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PROCEEDINGS OF THE 18TH INTERNATIONAL SHIP AND OFFSHORE STRUCTURES CONGRESS

Volume 1

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Volume 1

Edited by

Wolfgang Fricke

and

Robert Bronsart

Universität Rostock

Schiffbautechnische Gesellschaft e. V.

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PREFACE

This volume contains the eight Technical Committee reports presented and discussed at the 18th International Ship and Offshore Structures Congress (ISSC 2012) in Rostock, Germany, 09-13 September 2012.

Volume 2 contains the reports of the eight Specialist Committees whilst Volume 3 contains the report on the congress, the keynote lecture and the discussions of all the reports together with the replies by the committees.

The Standing Committee of the 18th International Ship and Offshore Structures Congress comprised:

Chairman: Wolfgang Fricke
Jørgen Amdahl
Yoo Sang Choo
Weicheng Cui
Chang Doo Jang
Segen F. Estefen
Carlos Guedes Soares
Mirek Kaminski
Merv Norwood
Michel Olagnon
Roberto Porcari
Manolis S. Samuelides
Ajit Shenoi
Jack Spencer
Yoichi Sumi
Secretary: Robert Bronsart

On behalf of the Standing Committee, we would like to thank Germanischer Lloyd, Det Norske Veritas, American Bureau of Shipping, Lloyd's Register, Nippon Kaiji Kyokai and Bureau Veritas for sponsoring ISSC 2012.

Wolfgang Fricke, Chairman
Robert Bronsart, Secretary

Rostock, September 2012

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18th INTERNATIONAL SHIP AND
OFFSHORE STRUCTURES CONGRESS

09-13 SEPTEMBER 2012
ROSTOCK, GERMANY

VOLUME 1

COMMITTEE I.1

ENVIRONMENT

COMMITTEE MANDATE

Concern for descriptions of the ocean environment, especially with respect to wave, current and wind, in deep and shallow waters, and ice, as a basis for the determination of environmental loads for structural design. Attention shall be given to statistical description of these and other related phenomena relevant to the safe design and operation of ships and offshore structures. The committee is encouraged to cooperate with the corresponding ITTC committee.

COMMITTEE MEMBERS

Chairman: Elzbieta M. Bitner-Gregersen
Subrata K. Bhattacharya
Ioannis K. Chatjigeorgiou
Ian Eames
Kathrin Ellermann
Kevin Ewans
Greg Hermanski
Michael C. Johnson
Ning Ma
Christophe Maisondieu
Alexander Nilva
Igor Rychlik
Takuji Waseda

KEYWORDS

Environment, ocean, wind, wave, current, sea level, ice, deep water, shallow water, data source, modelling, climate change, data access, design condition, operational condition, uncertainty.

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1 INTRODUCTION

This report is built upon the work of the previous Technical Committees in charge of Environment. The aim is to review scientific and technological developments in the field since the last Committee, and to set them in the context of the historical developments, in order to give a practicing engineer a balanced, accurate and up to date picture about the natural environment as well as data and models which can be used to approximate it in the most accurate way. The content of the present report also reflects the interests of the Committee membership.

The mandate of the 2009 ISSC I.1 Committee has been adopted and extended. It accords ice an equal status with traditional interests such as wind, wave, current and sea water level, and recognizes the importance of environmental data to the planning of operations and prediction of operability. Also in accordance with the ISSC mandate, this Committee has reported on the resources available for design and the operational environment. Additionally, in what represents an extension of the 2009 ISSC I.1 mandate, the Committee has initiated cooperation with the corresponding ITTC Committees.

The Committee consisted of members from academia, an oil company, research laboratories and classification societies. The Committee met three times: in Paris (24–26 February 2010), Madras (10–11 January 2010) and in St. Johns' (17–19 October 2011). Committee members also met on an ad hoc basis at different scientific conferences and industrial workshops. The Paris meeting was combined with a Fatigue Workshop organized by Ifremer and the oil company Total to which all Committee members were invited. A further meeting was arranged with the ISSC 2012 I.2 (Loads) Committee together with the ITTC Seakeeping and Ocean Engineering Committees in Portsmouth, 26 November 2010, which was attended by the Chairman and one Committee member. The Committees' reports were exchanged and it was agreed to hold a joint workshop on "Uncertainty Modelling for Ships and Offshore Structures" taken place 8 September 2012. The content of the ITTC reports was discussed at the ISSC 2012 Committee I.1 meetings.

The organisation of this report is an evolution of the outline used by the preceding Committee in their report to the 17th ISSC. Section 2 focuses on sources of environmental data for wind, waves, current, sea water level and ice. Section 3 addresses modelling of environmental phenomena, while Section 4 discusses some selected special topics. The design and operating environment is presented in Section 5. The most significant findings of the report are summarised in Section 6.

Furthermore three areas were considered as particularly important fields at the present time and were selected for special attention: climate change and variability, Computational Fluid Dynamics (CFD) applied to met-ocean modelling and statistical approaches.

Rogue waves have been a topic of increasing interest over the past two decades, and two international projects dedicated to these waves have been initiated by the industry CresT/ShortCresT and EXTREME SEAS during the period of the 2012 ISSC I.1 Committee. Following the previous Committee this Committee felt that the rogue waves could be adequately dealt with inside the normal wave sections: the wave data section (2.2) and wave modelling section (3.2).

Major conferences held during the period of this Committee include the 28th–30th International Offshore Mechanics and Arctic Engineering (OMAE) conferences held

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in Honolulu (2009), Shanghai (2010) and in Rotterdam (2011), the 19th - 21st International Offshore and Polar Engineering (ISOPE) conferences held in Osaka (2009), Beijing (2010) and Maui, Hawaii (2011). Also of great interest to the Committee were the 11th and 12th International Workshop on Wave Hindcasting and Forecasting held in Halifax, Canada (2009) and Hawaii (2011) respectively, the MARSTRUCT (International Conference on Marine Structures) conference which took place in Lisbon (2009) and in Hamburg (2011), the EUG (European Geosciences Union) conference in Vienna (2011), WISE (Waves in Shallow Water Environment) in Mexico (2009), Brest (2010) and Qingdao (2011), POAC (Port and Ocean Engineering under Arctic Conditions) in Luleå (2009) and in Montréal (2011), IWMO (International Workshop on Modelling the Ocean) in Qingdao (2011), and MARTECH (International Conference on Marine Technology and Engineering) conference in Lisbon (2011). Papers from those sources have been reviewed and those of particular relevance are cited here.

Success of the global and basin-scale ocean models development with data assimilation under the GODAE (Global Ocean Data Assimilation Experiment) program opened a new era of operational oceanography. GODAE ended in 2008 and continues as GODAE Ocean View: https://www.godae-oceanview.org/

A number of Joint Industry Projects (JIPs) are also contributing to the world's knowledge base on the met-ocean environment, with results released publicly in the form of academic papers. Several EU, JIP and ESA (European Space Agency) projects have reported during the course of this Committee, including: CresT and EXTREME SEAS (both on extreme and rogue waves), HAWAII and LoWish (both on shallow water), SAFE OFFLOAD (LNG terminals) and NavTronic (ship routing). A number of hindcast projects have also been in operation, notably CASMOS (Caspian Sea), NAMOS (NW Australia), SNEXT (North Sea), SEAFINE (SE Asia), BOMOS (Brazil, Atlantic waters) and a Chinese national project in the South China Sea. The present status of the GlobWave project initiated by ESA in 2008, making satellite derived data more widely available, is also reviewed here.

Climate change has also been a topic of continuing worldwide interest. The previous Committee reviewed this subject as a special topic and the current Committee has also done so, in Section 4. The present report makes an attempt to provide ISSC with the most up-to-date information from leading scientists on the main climate change issues of relevance to those working on the seas: storm intensity and frequency, sea-level rise, sea ice extent, and the debate on the contribution of natural variability to climate change. Particular attention is given to the Arctic environment and to tropical and extra-tropical hurricanes. The studies carried out by the Intergovernmental Panel on Climate Change have got particular focus, IPCC (2011).

Enhancing safety at sea through specification of uncertainties related to environmental description is also dealt with in the report. Uncertainty is being increasingly recognized by the shipping, offshore and emerging renewable energy industries.

Given such a wide ranging subject area and limited space as well as the boundaries presented by the range of specialisms and competencies of the Committee members, this Committee report cannot be exhaustive; however, the Committee believes that the reader will gain a fair and balanced view of the subjects covered. The Chairman endorses the work of the Committee members and has the pleasure to recommend this report for the consideration of Congress.

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2 SOURCES OF ENVIRONMENTAL DATA

This section addresses the sources of data for environmental descriptions. The nature and uses of the data are left to other sections.

Sea waves, wind, current, sea water level and ice conditions vary geographically and in time. Their variability can be approximated by physical and probabilistic models. If long records of measurements are available then the statistical procedures can be used to describe variability of met-ocean conditions. The issue of data ownership remains a general problem; the data are often of proprietary nature – for example, oil companies, ship owners, and agencies usually keep their data confidential. In some cases, government agencies make data freely available in the public domain, such as the NOAA, NIBCO data sources, but this is the exception rather than the rule.

Whilst the advantages of having data freely available to academia and industry are clear, the commercial sensitivity of some data sets is recognized. However, it is possible for organizations to make data available without compromising their confidentiality. An example of this is the SIMORC URL data base: http://www.simorc.org/, administered by the University of Southampton, as noted in the last report.

2.1 Wind

New needs for a detailed description of wind profiles and turbulence at regional and local scales, mostly required by the developing wind off-shore industry, appear to play a major role in the development of new sensors as well as the implementation of downscaled numerical models. The offshore wind industry especially not only needs data on suitable locations for the installation, but also on the changes in the wind profile. The wind profile in the large range from sea level to heights of more than two hundred metres will be important but as of now this type of data are not available.

2.1.1 Locally Sensed Wind Measurements

Meteorological data of good quality are important for understanding both global and regional climates. Local measurements, traditionally at $10\,m$ height, have been the standard way to record wind characteristics for decades and remain important particularly for verification of data from other sources. But as suitable measurement sites are scarce, and it is not possible to enlarge this number significantly, the advent of remote measurement techniques has allowed for much more detailed descriptions of wind in the offshore environment: large areas can be scanned yielding a more refined image of the environmental data.

Great efforts have been made to evaluate records of locally recorded environmental data. Jiménez *et al.* (2010) summarize the evaluations made to date of the quality of wind speed and direction records acquired at 41 automated weather stations in the northeast of the Iberian Peninsula. Observations were acquired from 1992 to 2005 at a temporal resolution of 10 and 30 minutes. A quality assurance system was imposed to screen the records for manipulation errors associated with storage and management of the data, consistency limits to ensure that observations are within their natural limits of variation, and temporal consistency to assess abnormally low/high variations in the individual time series. In addition, the most important biases of the dataset are analysed and corrected wherever possible. A total of 1.8 % wind speed and 3.7 % wind direction records were assumed invalid, pointing to specific problems in wind measurement. The study contributes to the science with the creation of a wind dataset of improved quality, and it also reports on potential errors that could be present in other wind datasets.

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Shimada *et al.* (2009) analyse long-term wind measurements made at the research platform of Shirahama Oceanographic Observatory, located $2\,km$ off the coastline in Tanabe Bay, Japan. Based on measurements of a propeller anemometer at $23\,m$ height, the authors describe annual- and monthly-mean wind speeds and directions, frequency distribution of wind speed, wind rose, energy density, atmospheric stability and turbulence intensity.

Similarly, Türk and Emeis (2010) evaluate data recorded at the offshore measuring platform FINO1 in the German Bight (Forschung in Nord- und Ostsee 1). They obtained the dependence of turbulence intensity on the wind speed from four years of 10-minute mean wind data. The investigated dataset is unique in so far as no high quality long-term measurements with a height resolution of $10\,m$ at heights between 33 and $103\,m$ and a minimum distance to the coast of $45\,km$ have been available so far. Wave height and therefore sea surface roughness and turbulence intensity increase with increasing wind speed. Türk and Emeis show how the influence of the surface roughness decreases with height and compare their findings with previous results.

A method for prediction of wind speed at a selected location based on the data collected at neighboring locations is described by Kusiak and Li (2010). The affinity of wind speeds measured at different locations compared with the location of interest is defined by Pearson's correlation coefficient. Five turbines with similar wind conditions are selected among 30 wind turbines for in-depth analysis and the wind data from these turbines are used to predict wind speed at a selected location. A neural network ensemble is used to predict the value of wind speed at the turbine of interest. The results demonstrate that a higher Pearson's correlation coefficient between the wind speeds measured at different turbines has produced better prediction accuracy for the same training and test scenario.

2.1.2 Remotely Sensed Wind Measurements

Past and present satellite programs dedicated to wind measurement using scatterometers, radiometers, altimeters and Synthetic Aperture Radars were described in the 2009 ISSC I.1 report where accuracy of satellite data was also reported. Since then new or updated surface wind data were made available. Most recent developments include improvement of high wind speed estimation and grid refinement of wind fields, using multiple mission observations.

The Remote Sensing Systems (RSS) QuikSCAT data have been completely reprocessed using a new Geophysical Model Function referred to as Ku-2011 (V4 QuikSCAT) (Ricciardulli and Wentz, 2011). The new processing has improved quality of high wind speeds (previously overestimated for winds greater than $20\,m/s$) and wind directions (especially at very low ($< 5\,m/s$) and high wind speeds ($> 15\,m/s$). A better agreement between radiometer and scatterometer winds in typically high wind speed regions is also pointed out.

A new model was proposed (Quilfen *et al.*, 2011) for estimation of near-surface wind speed in high wind conditions. The model was built using coincident observations made by instruments on board QuikSCAT and Jason during orbits crossovers and allows estimates of wind speed for values above $18\,m/s$.

Daily wind fields from Metop/ASCAT scatterometer retrievals are produced in near real-time over the global ocean with a spatial resolution of 0.25° from April 2007 to present, using the 'objective method' (Bentamy and Croize-Fillon, 2011). Data and documentation are available at CERSAT, the ERS data archive centre in Brest, France.

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In the framework of the MyOcean program, a data base of Global Blended Mean Wind Fields was also developed for the global ocean. Data include wind components (meridional and zonal), modulus of wind stress vector as well as associated error estimates. Evaluated from joint satellite observations (QuikSCAT and ASCAT scatterometers and SSM/I radiometers) and ECMWF operational wind analysis data, this data base offers a refined horizontal resolution of 0.25×0.25 degrees with a 6-hour time step for more than five years, starting from 1st April 2004 up to 22nd November 2009 (also available at CERSAT).

2.1.3 Numerical Modelling to Complement Measured Data

Numerically generated wind data are still commonly used in design and marine operations and for some ocean areas they are the only data available. They refer usually as the 10-minute average wind speed at the 10 m height above the ground or the still water level and include also wind direction. The wind data can be converted to a different averaging period as well as to the different heights by appropriate commonly used expressions (see DNV, 2010, 2011).

The recently updated or new developed met-ocean data bases like: ERA-Interim, NORA10, HIPOCAS, ARGOSS and Fugro-OCEANOR include information about both wind and waves and are discussed in detail in Section 2.2.3. Below only some additional information not given in Section 2.2.3 is provided.

Young *et al.* (2011) used a 17-year wind data base (1991-2008) of calibrated and validated satellite altimeter measurements and compare them with 12 deep-water buoys and numerical model predictions from NCEP (National Centre for Environmental Protection). The results are qualitatively consistent and are showing that the mean wind speed has stayed similar over the investigated period while the extreme wind speed has increased (see also Section 2.2.3 and 4.1.2).

Bertotti *et al.* (2011) have compared the model wind speeds (seven forecast systems were considered) versus the available measured values from scatterometer and found some inconsistencies in the results, model wind data were on average larger than the measured ones. Limited amount of data available and its different times and positions, at and off the centre of the storm, impede the drawing of any definite conclusion in this respect.

With increased interest in developing the offshore wind power plant, numerical studies have been conducted to estimate the wind speed profile and variability. Based on satellite derived surface wind (QuikSCAT), objectively analysed air-sea flux (OAFLUX) and reanalysis (NCEP-DOE AMIP-II), Capps and Zender (2009) extrapolated the surface wind speed to 80 m altitude incorporating stability effect. Such estimates are further combined with practical turbine characteristics and sitting to estimate the ocean wind power potential (Capps and Zender, 2010). The Wind Challenger Project is a joint industry project in Japan designing a bulk carrier propelled by hard wing sail. In this project, Nishida *et al.* (2011) has estimated the velocity profiles of the marine boundary layer based on downscaled NWP (numerical weather prediction) output. The study suggests shortage of in-situ observation.

A comprehensive review of offshore wind resource assessment was outlined by Sempreviva *et al.* (2008). The process involves site selection based on resource evaluation by models, and in-situ evaluation of wind climatology, vertical profile and turbulence. Recently, numerical models are becoming available tool for assessing wind profiles (e.g. Pushpadas *et al.*, 2010).

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2.2 Waves

Wave data from hindcast studies, discussed in Section 2.2.3, are the choice data sets for development of design criteria. However, measured wave data either locally (Section 2.2.1) or remotely (Section 2.2.2) remain important for development, calibration, and validation of numerical models, baselining, and specification of more detailed wave descriptions such as spectra and individual wave heights and crest elevations. This is particularly important in coastal areas where the prediction of waves is further complicated by shallow-water and coastal boundary effects.

2.2.1 Locally Sensed Wave Measurements

The status quo has essentially been maintained with respect to the collection of in-situ wave data, with most measurements undertaken as a part of on-going national coastal wave monitoring and by oil companies, particularly in more remote areas in support of exploration for new oil and gas fields. In the remote areas, wave buoys remain the instrument of choice, while wave radars are the choice instrument for permanent facilities with platforms for mounting the radars.

Measurements of significant wave height beyond $16\,m$ have been recorded both in deep as well as shallow water. The UK Met Office operating a network of marine Automatic Weather Stations (MAWS) around the UK has reported from the moored buoys (open-ocean deep water locations) west off Ireland and outside the Bay of Biscay (two buoys are operated jointly with Meteo-France) the maximum significant wave heights of $18.3\,m, 17.2\,m, 16.6\,m, 16.0\,m$ and $13.8\,m$ in the period from 7th to 10th December 2007; Turton and Fenna (2008). Babanin *et al.* (2011a) present the wave conditions in Typhoon Krosa prior to touching Taiwan in October 2007. The maximum wave height $H_{max} = 32\,m$ with significant wave height $H_s = 24\,m$ were measured at the water depth of $h = 38\,m$. The authors conclude that the measurement does not appear faulty and is physically realistic.

An extensive review of the performance of platform-mounted wave sensors was undertaken during the industry-sponsored CresT (Cooperative Research on Extreme Seas and their impacT) Joint Industry Project (JIP). The JIP had access to a very large dataset of water surface elevation measurements from various installations across the globe, provided by the participants in the JIP. The sensors were fixed-platform, absolute surface elevation measuring devices, including wave radars, a wave staff, optical lasers, and a step gauge, and some from floating systems. The vast majority of the data was from Saab wave radars, and the study concluded that this instrument also provided the most reliable data (Christous and Ewans, 2011).

Measurements made from floating systems require compensation for the vessel motions, and therefore involve a significant source of uncertainty, particularly in the case of ships, where the demand for accurate onboard wave measurements remains strong. In this respect, Simos *et al.* (2010) analysis of experimental data performed with a small-scale model of an FPSO platform under a wide range of sea state conditions is encouraging. Results showed that the sea conditions could be estimated with good precision.

Fu *et al.* (2011) gave an overview of ship borne systems and techniques, including a shipboard array of ultrasonic distance sensors for measuring directional wave spectra, a ‘Commercial Off The Shelf’ (COTS) wave radar system, and a COTS scanning LIDAR system. It was concluded that using ship-mounted LIDAR is a viable approach to measuring wave displacements from underway, high-speed vessels, but LIDAR performance is highly dependent on the wind and sea conditions. It was further concluded,

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in general, that the systems worked well for a fixed platform with a fixed incidence angle, but ship motion and a changing ambient environment present additional difficulties, and that Dynamic methods that perform real-time calibration of the systems may be required.

Fu *et al.* (2011) also trialed a WaMoS II X-band marine radar wave measurement system by OceanWaves GmbH, and concluded that such systems provide reasonable directional wave spectra when mounted at fixed sites, but exhaustive validation studies of the shipboard installations where the changing environment and ship motions need to be taken into account remains to be done. Story *et al.* (2011) discussed existing limitations with commercial incoherent navigation radar systems. Poor measurements resulted when there is little to no wind. Uncertainty with line-of-sight shipboard-based measurements effects due to low grazing angles effects, and limitations of wave radar in the cross-range direction, were also highlighted, associated with polarization effects. Additional limitations in sea states where nonlinear effects, such as wave breaking, and non-uniform surface wind drifts, were also mentioned, but these limitations are also common to other wave measuring devices.

Story *et al.* (2011) conclude that commercial systems require calibration of each installation in order to determine the correct values for these constants based on empirical data for height/incidence angle and hardware installation, and without them the wave height measurements perform poorly. Much of the validation data show that for a fixed platform in perfect conditions, wave radar can provide estimates of the frequency, direction, and wave height with an accuracy of around 10 %. Wave height values are significantly less reliable from shipboard platforms than those from fixed platforms. Advanced techniques addressing the impact ship motion has on these analysis techniques should be pursued further.

Wave measurement using stereo-photogrammetry type techniques continues to be the subject of much active research. Fedele *et al.* (2011a) present results from measurements with a Wave Acquisition Stereo System (WASS) deployed at the oceanographic tower Acqua Alta in the Northern Adriatic Sea, off the Venice coast in Italy. Their results produced accurate estimates of the sea state surface dynamics and associated directional spectra and produced wave surface statistics that agreed well with theoretical models. Bechle and Wu (2011) report the development of a virtual wave gauge (VWG) technique for processing stereo imaging data. Improved efficiency compared with traditional methods is demonstrated, and it is concluded that VWG has the potential to make real-time remote stereo imaging wave measurements a reality. de Vries *et al.* (2011) obtained good validation of stereo-photogrammetry measurements in both the laboratory with a pressure sensor and at a coastal location with buoy data.

Work continues on understanding the limitations of HF radar measurements and how these can be improved. In particular, Wyatt *et al.* (2011) identify aspects of measurements made at three coastal stations that require further improvement. These include modifications to the underlying theory particularly in high sea states, identification and removal of ships and interference from the radar signals before wave processing and some form of partitioning to remove these from the wave spectrum. The need to match the radio frequency to the expected wave peak frequency and wave height range, with lower radio frequencies performing better at higher wave heights and lower peak frequencies and vice versa, was also demonstrated.

The WMO-IOC Joint Technical Commission for Oceanography and Marine Meteorology (JCOMM) continues to make progress in the Pilot Project on Wave measurement

18th International Ship and Offshore Structures Congress (ISSC 2012) - W. Fricke, R. Bronsart (Eds.)

Evaluation and Test (www.jcomm.info/WET), which arose from the JCOMM/OGP workshop in New York, October 2008. In particular the collection and analysis of data from co-deployments of wave sensors continues. This has been undertaken at two Canadian sites and at locations in India, Korea and Australia. Efforts are underway in the USA in support of the Pilot Project, including the planned co-deployment of a directional waverider in Monterey Canyon, with the longer term goal of establishing a deep water evaluation test bed at that location, with a shallow water test bed at Duck, North Carolina.

2.2.2 Remotely Sensed Wave Measurements

The GlobWave project (www.globwave.org) is an interesting initiative funded by the European space Agency (ESA) to service the needs of satellite wave product users. A web portal provides a single point of reference for satellite wave data and associated calibration and validation information. A consistent set of satellite wave data from all available satellite altimeter data and from ESA synthetic aperture radar data is made available. The historical archive contains altimeter data from 8 satellites, ranging from Geosat (operating between 1985 and 1989) through to Envisat, Jason-1 and Jason-2. The historical data is continuous in time from 1991 to 2009, and near real-time data is made available from Envisat, Jason-1 and Jason-2 within a few hours of measurement time.

Some additional products are also made available, such as altimeter crossovers, computed for each pair of satellites, when crossing of their respective tracks is possible, providing a comprehensive dataset of coincident measurements that can be used to monitor the quality of each sensor and improve their calibration. Also made available are matching measurements between satellite and in-situ buoys, computed for various pairs of buoy networks and satellites providing a comprehensive dataset to assess, monitor and intercompare the accuracy of each of these sources of measurements.

For detailed description of satellite data accuracy reference is made to the ISSC 2009 I.1 Committee report.

2.2.3 Numerical Modelling to Complement Measured Data

Locations where high quality in-situ data are available are sparsely distributed, since buoy and platform data are geographically limited, and though satellite observations offer global coverage, they suffer from temporal sparsity and intermittency, making estimation of long term distributions and extreme analysis difficult. Hence hindcast data (or corrected hindcast) are often used and they remain to be the main source of met-ocean data for establishing joint environmental description as well as for design and operational planning. The corrected hindcast may be unbiased on average but still can be corrupted by other types of errors, which introduce a bias in the estimated return values of extreme sea states. In Mackay (2011) a deconvolution algorithm has been presented which reduces bias if the error CDF (Cumulative Distribution Function) is known.

The advantage of hindcast data is that they can be generated for a specific location world-wide and for a required time period, and three dimensional (frequency-direction) wave spectra as well as information on a spatial grid can be provided. Numerical wave models used for forecasting or building hindcast data bases are under constant evolution. In recent years attention has been given to improving resolutions of wave spectral models, implementing new or modified wind input and wave dissipation functions and including energy dissipation through wave breaking.

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Recently various hindcast and satellite data bases have emerged and the work of comparing and of assessing differences and uncertainty level involved in their use is not yet properly explored, although significant progress has been achieved for some data bases. The previous I.1 Committee report noted a lack of validation of numerical wave models with instrumented data beyond 12 metres, but some studies have included such extreme data since that time. Cardone and Cox (2011) demonstrated that the current 3G (3rd generation) models are capable of accurately hindcasting significant wave heights above 14 metres in very extreme storms. Similar studies are carried out at different met-offices world-wide.

Young *et al.* (2011) used a 23-year data base of calibrated and validated satellite altimeter measurements on a global scale and compare them to the 12 deep-water buoys and NCEP (National Centre for Environmental Protection) numerical model predictions. The results are qualitatively consistent and are reported in more details in Section 4.1.3.

ERA-Interim is the latest global atmospheric reanalysis produced by the European Centre for Medium-Range Weather Forecasts (ECMWF). The ERA-Interim project was conducted to prepare for a new atmospheric reanalysis to replace ERA-40, which will eventually extend the data base back to the early part of the twentieth century. The main improvement is the quality of data assimilation. ERA-Interim currently covers the period from 1st January 1979 onwards, and continues to be extended forward in near-real time. Gridded data products include a large variety of 3-hourly surface parameters, describing weather as well as ocean-wave and land-surface conditions, and 6-hourly upper-air parameters covering the troposphere and stratosphere.

The Norwegian data base NORA10 for wind and waves in the North Sea and Norwegian Sea, and the North Atlantic, has been developed at the Norwegian Meteorological Institute, with major support from a consortium of oil companies known as The Norwegian Deep Water Programme, see e.g. Aarnes *et al.* (2011). The NORA10 data base was validated extensively against satellite and buoy observations and gives higher spatial resolution than ERA40 from ECMWF albeit over a smaller area.

Campos and Guedes Soares (2011) have compared the HIPOCAS data base (44 years, covering the North Atlantic and the European seas) with NOAA/NCEP data for the whole North Atlantic. HIPOCAS is a result of the wave model WAM-cycle4 forced by REMO ((REgional Model) surface wind fields. The wave data set of NOAA/NCEP is a forecast that has been continually performed by WAVEWATCH III since 1997, forced by GFS surface wind fields. Small divergences between the two data sets are identified in standard weather conditions in the North Atlantic. Differences dependent on longitude were observed in both wave and wind fields.

In order to increase accuracy of wind and waves data bases the offshore industry has updated hindcast data sets for several basins, within proprietary joint industry projects, since the last reporting period.

The wind and wave hindcast data for the southern North Sea were updated in the Southern North Sea Extremes (SNEXT) JIP in 2009. This data set includes a 20-year hindcast with model grids to a resolution of 3 km and 1 km for resolving shallow water effects, (http://www.oceanweather.com/metocean/next/index.html).

A wind and wave hindcast for the Northwest of Australia was provided in 2010. The NAMOS (The North Australia Metocean Study Tropical Cyclone Wind and Wave Extremes) JIP provided estimates of wind and wave extremes based on new hindcasts

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of historical tropical cyclones affecting exploration and production areas offshore north Australia. This data base was updated under Phase 2 of the JIP, including data from analysis of an expanded historical tropical cyclone population.

The SEAFINE (SEAMOS-South Fine Grid Hindcast) JIP have commissioned an update to the current hindcast for the South China Sea, following a one year evaluation run of an improved current modelling scenario. The update will include an 18-year continuous production run, with results available in 2010.

The ARGOSS and Fugro-OCEANOR global wind and wave data bases described in the previous report are under continuous improvement. The new features of the ARGOSS data base (the version "15 June 2011") are reported on the ARGOSS website: http://www.waveclimate.com/clams/redesign/html/newfeatures.html. They include, between others, extension of the data up to 2010, updated and improved model calibration, directional roses and a more sophisticated shallow water model. The Fugro-OCEANOR databasis (http://www.oceanor.com/) includes new products like: a complete data-base/software package for providing wave climate data and statistics including full directional spectra time series anywhere globally both in deep and shallow waters at any time in the last 50+ years and right up to date, a modern-day Worldwide Wave Statistics (WWWS) equivalent of the old long standing volume Global Wave Statistics (GWS) atlas (British Maritime Technology, 1986), and wind and waves energy mapping (Barstow *et al.,* 2009).

Wave modelling tools are essential to assess energy generation resources. A nationwide survey of Australia was conducted by Hughes and Heap (2010) using the 3G wave model. Likewise a survey was made along the Spanish coast by Iglesias and Carballo (2009) and the information was further refined with coastal high resolution wave model (Iglesias *et al.,* 2010).

It should be noticed that the significant wave height provided by numerical wave models is calculated from the zero-spectral moment and is a slightly biased estimator of the one obtained from a sea surface time series as it includes an assumption of linearity of sea surface.

Further, when using wave model data a resolution of the model from which data are generated as well as an approach adopted for data calibration will decide the exact type of significant wave height the data represent, e.g. a 20-minute, 1-hour or 3-hour significant wave height; the topic remains insufficiently discussed in the literature.

2.2.4 Wave Description from Measured Ship Motions

Onboard sea state estimation based on ship motions, particularly when combined with other measurements with 'fusion' techniques, is becoming increasingly practical, for example the Decision Support System (DSS). It was introduced in the 2009 Committee report and it has seen further development: Nielsen *et al.* (2011), Nielsen and Jensen (2011). Wave description from measured ship motion utilises the analogy between a ship and a wave rider buoy, although the ship is moving with a forward speed. Using this methodology it is possible to obtain an estimate of the wave spectrum at the location of an advancing ship by processing its wave-induced responses in a similar way as for the traditional wave rider buoy. For a review on this development see e.g. Nielsen and Stredulinsky (2012). In this paper the authors compare 'wave buoy analogy' derived data from a large set of full-scale ship motion measurements with simultaneoss waverider buoys' measurements and wave radar system measurements. They found fairly accurate estimates of integrated sea state parameters when compared

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to corresponding estimates from the buoys, although there was poorer agreement of energy spectra. The wave buoy analogy, for the data considered, was said to provide, on average, slightly better sea state estimates than the wave radar system.

2.3 Current

Developments within renewable energy have brought the need for new current measurements as well as numerical current data. Several studies showing how tidal energy can be utilized can be found in the OMAE 2011 and ISOPE 2011 Conference Proceedings for example.

2.3.1 Locally Sensed Current Measurements

Not much work has been done in this area since 2009. Acoustic measurement techniques (both coherent and incoherent) for in-situ sensing of ocean current offer an excellent space-time resolution of the velocity profile. Another type of in-situ measurement of ocean current profile is based on autonomous underwater gliders. Accuracy of these in-situ measurements is discussed in the previous Committee report.

A joint effort between the USA's Minerals Management Service's (MMS) and Mexico's Centro de Investigación Científica y de Educación Superior de Ensenada (CICESE) to understand more on the dynamics of the Loop Current as it enters the Gulf through the Yucatan Channel was initiated in 2009. The particular objective is to measure currents in the Yucatan-Campeche area to provide data about the upstream conditions in the Loop Current and help improve forecasting of Loop Current eddy shedding and intrusions. CICESE has deployed eight moorings in Mexican waters east of the Yucatan Peninsula, where the Yucatan Current is found. The moorings will gather measurements and data in water depths up to $3{,}000\,m$ for two years.

The utilisation of the Kuroshio Current power is being studied in Japan and Taiwan (e.g. Falin, 2010). Observational study was conducted at the Miyake Island south of Japan for selecting potential sites for the power generation. Kodaira *et al.* (2011) conducted an Acoustic Doppler Current Profiler (ADCP) measurement around the island that revealed enhanced current speed of the Kuroshio Current under topographic influences. Concurrent measurement by SAR revealed strong radar scatter where the current shear is strong.

2.3.2 Remotely Sensed Current Measurements

Retrieving of currents features from remote sensing is mostly based on observation of Sea Surface Height (SSH) and requires cross-analyses with other parameters or data sources. Remote sensing also provides interesting data bases for identification of current structures and eddies and validation of models.

Hansen *et al.* (2010) use the European Space Agency (ESA) Advanced Synthetic Aperture Radar (ASAR) Doppler grid information to analyse the main current regimes in Norwegian waters. They show that in spite of the low velocity of the circulation, the method allows identification of patterns of the ocean currents driven by the topography in that area to be identified. They also show that the large scale circulation pattern obtained with high resolution current mapping compares qualitatively well with patterns obtained by other means (drifters).

The quality of remotely sensed SSH measurement has been enhanced by some researchers by combining the remote data with data from instrumented measurements. Focusing on the northern California current system, Saraceno *et al.* (2008) show that it is possible to improve the quality of the SSH in the coastal area (within $\sim 40\,km$

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from shore), poorly estimated by remote sensing, hence the assessment of geostrophic alongshore currents, by mixing offshore gridded SSH fields with time series of SSH measured by coastal tide gauges. Le Hénaff *et al.* (2011) use reprocessed Topex/poseidon altimetric data combined with sea surface temperature data to assess the interannual variability of the Navidad current along the Spanish coast.

2.3.3 Numerical Modelling to Complement Measured Data

An overview of the GODAE (Global Data Assimilation Experiment) project and the various products were introduced in the previous Committee I.1 report. In this report, we will introduce examples of numerical downscaling and the application of the GODAE products for ocean renewable energy and tracer tracking.

Ocean basin scale wind-driven ocean circulation is known to be most intense at the western boundary of the basin. The Kuroshio Current and the Florida Current (at the boundary of the Pacific and Caribbean Sea respectively) are considered to possess potential for hydro-kinetic power of the order of 20–30 GW. A number of numerical simulations have been conducted to estimate the available power resources, the velocity structure and temporal variations, at specific sites. Duerr and Dhanak (2010) have analysed the Hybrid Co-ordinate Ocean Model (HYCOM) reanalysis but had to adjust the transport to match the observed value. Often, the Global Circulation Models fail to reproduce the structure of the current that is locally modified by topographic effects and by local winds. The Kuroshio Current power is estimated based on numerical models and are reported as a government document and Japanese conference papers (e.g. Nishida *et al.*, 2011). Various other numerical studies about the estimation of ocean currents and tidal currents were reported at the 9th European Wave and Tidal Energy Conference which took place at the University of Southampton, UK, 4–9 September 2011.

An example of downscaling is the JCOPE2 (Japan Coastal Ocean Predictability Experiment); the reanalysis product is based on a nested Princeton Ocean Model (POM), downscaling from the Pacific model (1/4 degree resolution) to the 1/12 degree model near Japan (Miyazawa *et al.*, 2009). Isobe *et al.* (2010) further downscaled from the JCOPE2 reanalysis using the Finite Volume Coastal Ocean Model (FVCOM) to model the swift current at the Bungo channel between the Honshu Island and the Shikoku Island. The model successfully reproduced the rapid current called the Kyucho that branches off from the Kuroshio Current. The sensitivity of such downscaling techniques to the initial and boundary conditions were evaluated by simulating the Florida Current using the Hybrid Coordinate Ocean Model (HYCOM) (Halliwell *et al.*, 2009). The current field locally driven by wind was not influenced by the choice of the outer model whereas the alongshore current related to the Loop Current was sensitive to its realization in the outer model. Inter-comparisons among global models at different resolutions and nested regional models were conducted simulating the circulation in the Philippine Archipelago (Hurlburt *et al.,* 2011).

Ocean model outputs have been utilised after the incident at the Deepwater Horizon platform in April 2010 in the Gulf of Mexico to trace spilled oil in the Gulf Stream, and to trace debris and radioactive materials after the earthquake and tsunami incidents on 11 March 2011 in north east Japan. The oil was observed by satellites and the image showed an interesting pattern of stretching and advection by the Loop Current. The chaotic nature of the oil movement is described by Mezić *et al.* (2010) based on the diagnosis of fluid flows with invariant attracting and repelling manifolds. The motion of the debris from the disaster sites in Japan after the March 2011 tsunami was

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studied using both statistical ocean model and the satellite derived ocean current fields (Maximenko and Hafner, 2011). A number of studies have been made using various numerical models tracing the radioactive materials from the Fukushima Nuclear Power Plant but are not published.

We can also mention the Maximenko Hafner (2011) work in other current section 2.3.1.

2.4 Sea Water Level

Sea water level measurements have received special attention due to the ongoing debate about climate change. Section 4.1.4 summarised the main findings associated with climate change projections. Attention has been given to extreme sea levels caused by severe storms such as tropical or extratropical cyclones. An obvious source of error of long-term sea level trends from in-situ measurements is the change of the terrestrial reference frame.

Archiving of historical data sets, their quality control, and statistical analyses are the essential ingredients of the analysis of long-term sea level variations. A status report of the Global Sea Level Observing System (GLOSS) and community recommendation for the future role of GLOSS were given as a community white paper at OceanObs'09 (Merrifield *et al.*, 2009). The GCN (GLOSS Core Network) stations are being developed to have real-time distribution capability in view of flood warnings from storm surges and tsunamis.

The Australian Baseline Sea Level Monitoring Project (ABSLMP) collected and analysed the monthly sea level data up to June 2011 in the 16 locations around Australia. The quality-controlled data are available in electronic form from the Bureau of Meteorology website.

According to Cavaleri *et al.* (2010) current meteorological and oceanographic numerical systems for generating sea water level are able to predict satisfactorily severe sea water level events due to surge.

2.5 Ice

In recent years, changes in the Arctic Ocean weather as well as changes in Antarctica have received widespread attention. Sea ice constitutes a critical element of the arctic marine environment stability and any changes to the global sea ice regime result in changes to ocean ecosystem. This further influences global weather patterns, which will affect Arctic and Antarctic ice packs as well as intensity, frequency and duration of storms.

From the engineering point of view sea ice characteristics such as concentration, extent and thickness as well as physical-mechanical properties, age of ice and type of ice (level ice, broken ice) are important. Sea ice appears in many forms affecting ship, offshore structures and more recently offshore wind energy turbines.

Sea ice can be characterized by its age (from new, young, first year to multi-year ice), concentration (% of water surface coverage) and form. Sea ice can be found as level ice or broken ice in form of ridges, hummock field and landfast ice. In the marine environment there is also the problem of icing caused by sprayed or shipped seawater due to wind, ambient and seawater temperature.

Sea ice properties are determined by a number of factors. A number of studies have addressed sea-ice conditions and its variability, e.g. Fissel *et al.* (2009). The interannual variability of ice conditions in the Canadian Beaufort Sea was found by the authors

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to be very large, which leads to statistical uncertainties in the statistical significance of the derived trend results.

Marine icing is getting increasing attention. An ongoing research project MAR-ICE (Marine icing), sponsored by the Norwegian Research Council and the offshore industry, and coordinated by DNV, is dedicated to this topic. Some project results can be found in Kulyakhtin and Løset (2011).

2.5.1 Locally Sensed Ice Measurements

Sea trials, field and site measurements still provide the most reliable data on ice properties that could be used for climatological predictions and/or as engineering design parameters.

Ice thickness, ice coverage and extent, its growth and melting rates in specific geographic locations could be used for estimates and predictions of local or global weather/climate changes, to validate and calibrate numerical predictions models as well as design arctic structures and projection of availability of shipping routes.

Physical and mechanical properties of sea ice such as compressive strength, tensile/flexural strength, fracture toughness, friction, shear strength, elastic modulus and density, as well as, loads and local ice pressures could be used as engineering parameters in predictions of ice-structure interaction scenarios and establishing ice failure criteria, and in verification and validation of numerical tools. Those measurements can be carried out by various means from moving ships or submarines, by drill-hole techniques from stationary ice stations or by long-term measurements and observations from permanent structures.

The geometry of a ship hull and employed propulsion system constitutes its signature for operations in level ice that is expressed by the curve of level ice thickness vs. ship speed (h-v curve). The h-v characteristics could be used to determine level ice thickness from ship speed. In order to test the h-v relationship von Bock and Oilach (2010) performed full-scale trails aboard of MV Aranda. To determine and validate ice thickness obtained from the resultant ship velocity other ice properties possibly affecting ice resistance such as bending strength, crushing strength, ice temperature and salinity, were also measured at three stationary camps along the vessel trail path. The resultant ice thicknesses obtained from Aranda trials were very scattered and affected by the other measured ice properties. In the final conclusions the authors were skeptical if the employment of a vessel as a level ice thickness measuring sensor is feasible.

Indirect measurements of sea ice thickness from a moving vessel are presented by Suyuthi *et al.* (2010). The paper demonstares application of an electromagnetic device installed on both sides of a ship hull to measure ice thickness during operations in ice infested waters. The device is a part of the Ice Loads Monitoring (ILM) system that normally is used to collect information for prediction of extreme ice loads acting on the ship hull for short time duration. Similar technology was used by Lee and Jeong (2011). The electromagnetic induction instrument EM31-MK2 and updated the Cold Region Research and Engineering Laboratory (CRREL) empirical formula was used to obtain the ice thickness. The used updated formula was validated against drilled samples. The measured ice thickness was between 1.0 to 3.5 m.

Su *et al.* (2010) present an upward looking sonar (ULS) mounted on a submarine to observe ice thickness of ice less than 0.5 m. The technology is known and successfully

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employed to measure ice thickness since the 1990's, however; its application to measuring thin ice is relatively new. The system was validated and calibrated using digital camera images. Various types of flat jacks have been employed in destructive strength and non-destructive mechanical properties measurements for many years. They have been extensively used for in-situ fracture testing of sea ice in Arctic and Antarctica. Pennington and Dempsey (2011) investigated effects of initial pressure and opening distance on measured load when using a kevlar flat jack. The authors concluded that a single calibration factor cannot be assumed as it depends highly on the separation distance between loading surfaces and applied pressure. The calibration factor decreases as the distance increases, and appears asymptotic with increasing pressure.

Barrault and Strub-Klein (2009) investigated propagation of stress in ice in the Barents Sea by measuring the stress in six locations using stress sensors frozen in ridged ice. A borehole jack placed at known distances from sensors generated the stress. The observed stress propagation was inversely proportional to the distance from the source and decayed 4 metres from the source. Hutchings *et al.* (2010) conducted analysis of the relationship between internal ice strain-rate, stress and thickness redistribution of Arctic pack ice. The ice deformation observations were conducted using an ice drifting buoy instrumented with GPS. The trials were conducted in the Beaufort Sea. In-situ ice loads from fast and moving ice for design of wind-power generator foundations in ice-infested waters were investigated by Fransson and Bergdahl (2009). The authors noticed that the design effective pressure and compressive strength were independent of ice thickness, but design pressure was increasing with the ice drift speed.

Application and usefulness of conventional marine radars for ice detection has been recognised for some time. They are helpful in detection of multi-year ice and fragments of icebergs, but their range very often does not exceed one kilometre. Digitally enhanced radars can deliver higher resolution images allowing for better identification of ice characteristics allowing for avoidance of hazardous ice in the path of operating vessels. O'Connell (2011) presents a development of high-speed, cross-polarized, marine radar that will be able to make a distinction between various types of ice and enhance detection of smaller dangerous pieces in heavy see conditions. Gignac *et al.* (2011) applied high resolution radar data to assess ice conditions during freeze-up and break-up periods of 2009–2011 near the villages of Nunavik, Quaqtag and Umiujaq. The authors utilized RADARSAT-2 fine ($9\,m$) and ultra-fine ($3\,m$) images that were processed using the Multivariate Iterative Region Growing using Semantics technique. The resultant maps show ice formations classified as brash ice, multiyear ice, first year ice and open water. The results were validated against ground and air photos showing promising accuracy.

2.5.2 Remotely Sensed Ice Measurements

Sensors on board satellites (radiometers, scatterometers) allow a global and daily monitoring of various ice parameters such as: ice cover, ice concentration, ice thickness and ice drift.

Remotely sensed ice data is now regularly assimilated in ocean models such as TOPAZ (Nansen Environmental and Remote Sensing Center, Norway), FOAM (UK MetOffice), Mercator-Ocean (France), NCEP (USA), LIM (Belgium).

New data bases were recently made available. The United States NOAA's National Snow and Ice Data Center provides a data base of sea ice concentrations in daily time series from 9 July 1987 through to 31 December 2007. Sea Ice concentrations are obtained from gridded brightness temperatures from the Defense Meteorological

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Satellite Program (DMSP) series of Special Sensor Microwave Imager (SSM/I) passive microwave radiometers and are gridded on the NSIDC polar stereographic grid with $25{\times}25\,km$ grid cells. A data base covering 18 winters of ice drift was also made available at CERSAT.

Tournadre *et al.* (2008) developed an automated process for small iceberg detection from Jason's altimeter high rate wave form data. The large number of detected icebergs (up to 8000 for the year 2005, south of 45°S) appeared to be strongly correlated with sea ice extent.

Using this process and a six year data base of fields of small icebergs built from Jason-1 archive data (2002–2008) Ardhuin *et al.* (2011b) investigated, by comparison with wave model data, the influence of such icebergs fields on wave propagation. They find that in the southern ocean, icebergs distribution patterns appear strongly correlated with wave model error and propose a simplified parameterization of wave blocking by icebergs which induces a correction of the model's major errors.

Evolution of the sea ice extent is one of the major concerns of the studies related to climate change. Projections obtained from different models predict a possible total loss of sea ice cover in the arctic around 2030 (Wang and Overland, 2009). The September 2007 minimum sea ice extent was largely discussed and studied; Kauker (2009), Graversen *et al.* (2010), Giles *et al.* (2008).

Derivation of sea ice thickness from remote sensing alone appears not to be totally satisfactory. Ice thickness assessment requires simultaneous measurement of sea ice freeboard, snow cover and the densities of snow, ice and water (Kurtz *et al.*, 2009). These parameters are not always simultaneously available with homogeneous spatial resolution. Farrell *et al.* (2009) propose a new detection algorithm for the retrieval of altimeter sea surface height in the Arctic Ocean; they describe a procedure to calculate sea ice freeboard based on data from the Geoscience Laser Altimeter System (GLAS) onboard the ICESat mission. The authors produce a five years time series of freeboard elevation in the arctic, which in spite of uncertainties in snow thickness, indicates that overall sea ice freeboard has decreased during the considered observation period.

Based on the analysis of ICEsat data, Kwok *et al.* (2009) indicate that over the 2003-2008 period, an important decrease in volume and thickness of the multi-years ice cover over the Arctic Ocean could be observed.

Prinsenberg *et al.* (2011b) utilized three independent systems installed beneath of a helicopter to describe snow, and land-fast and mobile ice characteristics along the Labrador Shelf. The authors used a Ground-Penetrating Radar (GPR) to obtain the thickness of the snow layer on the ice and thickness of low salinity ice. The Electromagnetic-Laser (EM) system was applied to obtain ice thickness and surface roughness. The Video-Laser recorded the flight path. In their conclusions the authors indicate that the GPR and EM complement each other in interpreting ice and snow characteristics.

Johnston and Haas (2011) validated helicopter-base electromagnetic induction (HEM) system for measurement of ice thickness against drill-hole measurements of very thick ice. The measurements were taken in an area where drill-hole measurements are available for comparison. The HEM underestimated the average ice thickness on three floes by up to $1.9\,m$, and by as much as $3.1\,m$ on the fourth one. The authors finally indicate that application of HEM for measurement of very thick ice could be limited and suggest development of correction factors for future HEM applications.

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2.5.3 Numerical Modelling to Complement Measured Data

Numerical modelling based directly on measured data links the development of sensing-technology with sea-ice models. Such techniques are applied not only for the hindcast of sea-ice conditions for past decades, when relatively little measured data were available, they also give short-term predictions for sea ice build-up and prognoses for sea-ice extent under the influence of global warming.

Martin (2007) derives sea-ice ridges quantities from laser altimeter and airborne electromagnetic measurements. He then develops different numerical algorithms for the representation of ridges in a large-scale sea ice model. His study of sea ice drift focuses on the comparison of different sea ice-ocean coupled models and the validation with buoy and remotely sensed data from the period 1979–2001 on the basis of monthly averages. Martin found that all investigated models are capable of producing realistic drift pattern variability although differences are found between models and observations. He considers different causes for the discrepancies, which may lie in the wind stress forcing as well as sea ice model characteristics and sea ice-ocean coupling. Three different approaches to the simulation of pressure ridge formation are introduced and tested in idealised experiments and for realistic Arctic conditions. The model results show that the ridge density is mainly related to the sea ice drift whereas the mean sail height relates to the parent ice thickness. Most deformation occurs at coastlines. In general, all of the proposed algorithms produce realistic distributions of ridges.

Notz and Worster (2008, 2009) focus on the salinity of sea ice. They present data from in-situ measurements of the salinity evolution. The measured bulk salinity profiles show that during ice growth, sea-ice salinity is continuous across the ice-ocean interface and that there is no instantaneous loss of salt at the advancing front. The bulk salinity within the ice decreases continuously with time from the ocean water salinity. The findings showing that gravity drainage occurs for a critical Rayleigh number of around 10 are in close agreement with earlier theoretical and experimental studies. The authors also re-examine five processes that have been suggested to be important for the loss of salt from sea ice. These processes are the initial fractionation of salt at the ice-ocean interface, brine diffusion; brine expulsion, gravity drainage, and flushing with surface melt water. Their results from analytical and numerical studies, as well as from laboratory and field experiments, show that, among these processes, only gravity drainage and flushing contribute to any measurable net loss of salt. It should be mentioned that the salinity affects the ice mechanical properties and also the freezing/melting of ice and therefore it is important for ships and offshore structures.

3 MODELLING OF ENVIRONMENTAL PHENOMENA

The environmental description often employs a mixture of mathematical, probabilistic, empirical and statistical models. The following “decoupling” approach is commonly used.

One assumes that for a limited period of time and in a particular geographical region met-ocean conditions vary in a stationary way called sea state. Met-ocean conditions in a sea state can be described by means of mathematical models depending on a number of characteristic parameters. Changes of sea state parameters, which vary much slower than sea waves, wind, currents, sea water level and some ice characteristics, are modelled by means of probabilities. The final description of environmental conditions is obtained by combining the models for sea states evolution with the description of sea waves, wind, current, sea water level and ice in a sea state.

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3.1 Wind

Modelling the wind speed data has important implications in wind studies, providing valuable insight and parametric quantities for further engineering analysis. Wind not only acts on offshore and ship structures directly; it also constitutes the main driving force for waves, influences currents and also the drift of sea-ice. The classical modelling approach is to fit the probability distribution to a known model and estimate statistical parameters like mean and variance. Wind modelling considering multiple time scales is performed for different purposes. On long time intervals, the atmospheric circulation and embedded storm cells are affected by global warming. The long term predictions of extreme events give valuable information for the construction especially of fixed offshore structures. In the shorter term, wind forecasts for a few days are needed for operational planning, when steps in construction require calm weather conditions or a strait is unsafe to pass under strong winds. In the context of the increase of offshore wind energy, reliable forecasts of the order of hours or minutes are also become increasingly important since the complex electrical networks are sensitive to large fluctuations, which may occur at the onset of a storm.

The reports by Monteiro *et al.* (2009a, 2009b) give an overview of the activities with respect to wind energy in different parts of the world. Many countries and regions are introducing policies aimed at reducing the environmental footprint from the energy sector and increasing the use of renewable energy.

3.1.1 Analytical and Numerical Description of Wind

Wind power forecasting (WPF) is frequently identified as an important tool to address the variability and uncertainty in wind power and to more efficiently operate power systems with large wind power penetrations. In general, wind power forecasting can be used for a number of purposes, such as: generation and transmission maintenance planning, determination of operating reserve requirements, unit commitment, economic dispatch, energy storage optimization (e.g., pumped hydro storage), and energy trading. Monteiro *et al.* (2009a, 2009b) review and analyze state-of-the-art wind power forecasting models and their application to power systems operations. They give a detailed description of the methodologies underlying state-of-the-art models. The physical approach, which consists of several submodels, which together deliver the translation from the weather prediction forecast at a certain grid point and model level, to power forecast at the considered site and at turbine hub height. Every submodel contains the mathematical description of the physical processes relevant to the translation. They also consider the statistical approach which is emulating the relation between meteorological predictions, historical measurements, and generation output through statistical models whose parameters have to be estimated from data, without taking any physical phenomena into account.

Costa *et al.* (2008) give a brief review on 30 years of history of the wind power short-term prediction, since the first ideas and sketches on the theme to the current state of the art on models and tools, giving emphasis to the most significant proposals and developments. The two principal lines of thought on short-term prediction (mathematical and physical) are indistinctly treated because a standard for measurement of performance is still not adopted.

Most models are based on a combination of a numerical description of the underlying physical process or a statistical approach and external data from remote or local measurements. The models may apply iltering for a better prediction of wind speeds. For

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example, Louka *et al.* (2008) study the application of Kalman filtering as a post processing method in numerical predictions of wind speed. Two limited-area atmospheric models are employed, with different options/capabilities of horizontal resolution, to provide wind speed forecasts. The application of Kalman filter to these data leads to the elimination of any possible systematic errors, even in the lower resolution cases, contributing further to the significant reduction of the required CPU time. The authors show the potential of this method for wind power applications.

The work of Kavasseri and Seetharaman (2009) makes use of fractional-ARIMA or f-ARIMA models to describe, and forecast wind speeds on the day-ahead (24 h) and two-day-ahead (48 h) horizons. Results indicate that significant improvements in forecasting accuracy are obtained with the proposed models compared with the persistence method.

Since wind speed has a huge impact on the dynamic response of wind turbines, many control algorithms use a measure of the wind speed to increase performance, e.g. by gain scheduling and feed forward. As accurate measurements of the effective wind speed are in general not available from direct measurements, wind speed must be estimated in order to make such control methods applicable in practice. The technique described by Østergaard *et al.* (2007) estimates the rotor speed and aerodynamic torque by a combined state and input observer. These two variables combined with the measured pitch angle are then used to calculate the effective wind speed by an inversion of a static aerodynamic model.

A significant number of papers address the problem of the quality of high wind within tropical cyclone structures.

Hurricane Katrina of 2005 has been subject to deep analysis. Gathering and analysing an extensive multi-platforms observations data set, Powell *et al.* (2010) built a data base allowing a description with a 3 hours time step of Katrina's wind field evolution as the hurricane was travelling across the Gulf of Mexico. Therefore, the hurricane wind analysis system H*Wind was used which permits creating composite snapshots of the wind field based on all available observations over a given time window. Furthermore, the H*Wind fields were blended with peripheral data, using the IOKA system, then interpolated to the grids so as to provide forcing for the storm surge (ADCIRC) and wave models (WAM, Wave Watch, SDWave).

Based on analysis of observation data of wind fields measured for several days during seven hurricanes as well as on theoretical considerations, Stern and Nolan (2009) revisit some commonly accepted results regarding the vertical structure of tangential winds in tropical cyclones. Confirming previous studies, they show that the outward slope of the radius of maximum winds linearly increases with radius. On the other hand, they suggest that the slope of the radius of maximum speed is not related to intensity as was usually considered. This discrepancy seems to be mostly explained by the coarse sampling and data quality in previous studies.

Using a high resolution model (WRF), Uhlhorn and Nolan (2011) attempt to quantify the error made in estimating cyclone intensity as the maximum observed wind. They simulate the Hurricane Isabel of 2003 and reconstruct an observation data base as if measurement were made by a virtual aircraft equipped with a stepped frequency microwave radiometer flying a standard pattern. Analysis of the data suggests that the maximum observed surface wind typically underestimates the tropical cyclone maximum 1-minute sustained wind speed by about 7 to 10 %, on average whereas

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underestimation of the 10-minute averaged maximum wind speed is only about 1 to 3 %.

A large number of studies are dedicated to the development and analysis of regional models which allow assessment of smaller scale phenomena using higher resolution models by focussing on reduced areas. Leduc and Laprise (2009) investigate sensitivity of a regional climate model to the size of the numerical domain while Winterfeldt and Weisse (2009) assess the improvement in quality of the marine wind field induced by regional models when compared with those of a global reanalysis (NRA-R1) and point out interesting added value in coastal areas with complex topography.

3.1.2 Experimental Description of Wind

The experimental testing of structures in wind is often performed with scale models in wind tunnels. These tests are strongly linked to a specific structure. The geometry and the local installation need to be known in order to generate meaningful results in such experiments.

A method for modal wind load identification from across-wind load responses using Kalman filtering is presented by Hwang *et al.* (2011). They verify their findings using the wind tunnel test data.

Plain-air experiments, which are not focused on the wind forces on a specific structure often focus on certain weather phenomena. Choi (2004) investigates the variation of wind velocity with height during thunderstorms at five levels on a 150 m tall tower. Velocity profiles for more than 50 thunderstorms are studied and classified into four types according to the profile shape and the height of the highest wind speed. It is observed that wind profiles during thunderstorms are affected by several factors with the major ones being distance from the thunderstorm cell centre, intensity of the storm and ground roughness. Experimental studies on the simulation of thunderstorm wind using an impinging jet are also carried out to further investigate the effect of these parameters.

Cao *et al.* (2009) analyse the wind characteristics of Typhoon Maemi (2003) on the basis of 10-minute wind speed samples. The wind speeds were measured simultaneously by nine vane and seven sonic anemometers at a height of about 15 m. Turbulence intensity and scale, gust factor, peak factor, decay factor of the coherence function, probability distribution function, power spectrum, and their variations with wind speed are obtained. Wind-direction-dependent analysis is conducted on the wind characteristics. Turbulence intensity decreases with wind speed and remains almost constant when the wind speed becomes high. The averaged values of gust factor and peak factor are 1.6 and 3.3, respectively. The spatial cross correlation and decay factor of the coherence function increase slightly with wind speed. The probability density function of fluctuating wind speed of a strong typhoon follows a Gaussian distribution, and the power spectrum of strong wind can be expressed by a Karman-type spectrum at low frequency. The wind characteristics of the typhoon are shown to be very similar to those of non-typhoon winds.

The classical statistical description techniques have some drawbacks. They lack the time variation properties and ignore cross-dependencies between other meteorological data. Hocaoglu *et al.* (2010) developed a procedure to model the wind speed data using a dependent process of atmospheric pressure in the form of hidden Markov models. Consequently, the inherent dependencies between the wind speed and pressure are exploited. The models relate the two quantities in a framework which eliminates

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the necessity of direct sample-wise correlations, and avoid direct time-series analysis complications of the stochastic wind speed data at a marginal expense of easy pressure measurements. The experimental data were obtained from recordings of hourly atmospheric pressure and wind speed values for two cities in Turkey, namely Izmir and Kayseri.

3.1.3 Statistical and Spectral Description of Wind

To the Committee knowledge no changes to the statistical and spectral description of wind took place since 2009. Wind models commonly applied can be found in DNV RP-C205 (DNV, 2010) and DNV-OS-J101 (DNV, 2011). A joint fit of significant wave height and wind speed for the NW Australia location is presented in Bitner-Gregersen (2010) using the Conditional Modelling Approach (CMA) while for the Brasilian location by Sagrilo *et al.* (2011) applying the Nataf model.

3.2 Waves

Accuracy of the wave spectral models is under continuous improvement. The GlobWave project initiated by ESA in 2008 to improve the uptake of satellite-derived wind-wave and swell data is still continuing. A draft version of the GLOBWAVE Data Handbook is now available on the project web site (http://www.globwave.org/) and user feedback is requested.

The knowledge of extreme and rogue waves has significantly advanced recently. The predictions made by theoretical and numerical models compare well with experimental results.

Some progress has been made on long-term description of sea states, particularly on directionality of several wave systems and spatial-temporal models of sea surface characteristics.

3.2.1 Analytical and Numerical Description of Waves

The quality of numerical wave and surge hindcasts for offshore and coastal areas depends to a large extent on the quality and the accuracy of the upper boundary conditions, i.e. in particular on the quality of the driving wind fields. The WAM model and the WAVEWATCH-III model are the most generalized and tested wave prediction models used for both hindcasting and forecasting purposes. Although both WAM and WAVEWATCH-III are 3rd generation (3G) wave models, they now differ in a number of physical and numerical aspects and may give different predictions. This is an indication that a single "best" solution has not yet been accepted.

Since 2009 intercomparison among different forecast systems, i.e. meteorological model and wave model have been carried out. Bertotti *et al.* (2011) compared the model results versus the available measured wave data from altimeters and a small number of buoys and showed that on average model wave heights were lower than the measured ones; it was difficiult to reach firm conclusions however.

WAVEWATCH III™ version 3.14 (Tolman, 2009) was delivered in which some source term options for extremely shallow water (surf zone) have been included, as well as wetting and drying of grid points. A multi-grid or wave model driver was developed allowing the full two-way interaction between all grids at the time step level. Additionally, spectral partitioning was made available for post-processing of point output, or for the entire wave model grid (Hanson and Phillips, 2001). Spectral partitioning, allows identification of the various wave systems (swells and wind sea). This is useful for wave resource assessment and for design.

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Major contribution to the improvement of wave models based on the radiative transfer equation (RTE) is the development of new modified wind input and wave dissipation functions based on more physical description of the transfer mechanisms.

Recent developments with input (wind) and dissipation source terms have been made by Banner and Morison (2010). Babanin *et al.* (2010) (see also Babanin *et al.*, 2011b) proposed a new formulation for dissipation by breaking, based on observations that wave breaking only happens after an average background steepness exceeds a threshold value and that breaking probability depends on the excess of the mean steepness above this threshold. Other proposals for such semi-empirical dissipation functions were made and implemented in operational versions of WAVEWATCH III^{TM} (Ardhuin *et al.*, 2011a). Filipot *et al.* (2010) also propose a common parameterization of breaking wave height distribution which may be used from deep to shallow water.

One major interest in the implementation of these new dissipation terms is that these are based on observations and allow introduction of a more consistent description of the physics of the wind-wave interactions whereas previous approaches were mostly based on more parametric descriptions relying on the tuning of the various source terms to reproduce observed trends.

Tamura *et al.* (2010) studied the impact of non-linear energy transfer on realistic wave fields of the Pacific Ocean using the Simplified Research Institute of Applied Mechanics (SRIAM) model, which was developed to accurately reproduce non-linear source terms with lower computational cost than more rigorous algorithms, and the widely used Discrete Interaction Approximation (DIA) method. Comparison of the model with buoy observations revealed a negligible difference in significant wave heights but pronounced bias in peak frequency with DIA. The analysis of spectral shape indicated that the SRIAM method can quantitatively capture the overshoot phenomena around the spectral peak during wave growth.

Varieties of wind input source terms and dissipation source terms are implemented in operational wave models. One of the issues under debate is to set a cap on each source term rather than tuning the model so that the sum of input and dissipation source is realistic. Examples of implementations were presented at the 12th International Workshop on Wave Hindcasting and Forecasting held in Hawai (2011) and the nonlinear source term was discussed there.

Recently, in an attempt to improve the upper ocean mixing, various parameterization based on the concept of "wave induced turbulence" have been suggested; see Babanin *et al.* (2009), Dai *et al.* (2010). A number of works related parameterisation schemes such as BV parameterisation (Huang *et al.*, 2011), Stokes production term (Huang and Qiao, 2010), and modified K-profile parameterization (Qiao *et al.*, 2010), were presented. The wave induced turbulence is still under debate and active discussion supported by presentations took place in the WISE meeting at Qingdao in June 2011.

Classical topics of radiation stress and wave induced mixing are being revisited to improve the modeling of direct coupling of surface waves and ocean current. Different choice of the treatment of the free surface boundary condition and the coordinate system gives a different expression of the depth dependent radiation stress (Ardhuin *et al.*, 2008). Mellor (2008) corrected for some errors in the expression given in his 2003 paper which validity is being debated in the paper by Bennis and Ardhuin being in press. The issue was discussed in the WISE meeting in Brest, April 2010 and an attempt to include such effects in actual wave-current coupled model was presented at the International Workshop on Modelling the Ocean (IWMO) at Qingdao in June 2011 e.g. Tamura *et al.* (2010).

Dumont *et al.* (2011) consider the wave-ice interactions and their effects on sea ice–ocean models. The role of sea ice as a dampener of wave energy and the wave-induced breakup of ice floes are investigated. These two processes act in concert to modify the incident wave spectrum and determine the main properties of the marginal ice zone. The model predicts a sharp transition between fragmented sea ice and the central pack.

The code SWAN is commonly utilised to deal with shallow water wave climate. To describe wave transformations from deep water to shallow water depth the combined effect of the wave refraction, diffraction and reflection on the wave transformation has been considered by using the Mild-Slope Equation (MSE). Liau *et al.* (2011) proposed MSE including the higher-order bottom slope terms and ambient current effects into the wave action balance equation.

There has been further impetus to push exclusively non-stationary models such as WAM and WAVEWATCH-III closer to shore (e.g. Tolman, 2009) since this avoids learning, maintaining, and running multiple wave models at a given operational centre. Continuous attempts are made also to establish a stronger interaction between the wave and the circulation modelling community important for future development of the wave and circulation models.

A major initiative to improve wind wave predictions was launched under the umbrella of the National Oceanographic Partnership Program (NOPP) in 2009 (http://www.nopp.org/). The initiative is a four-year programme funded by the Office of Naval Research (ONR), the US Army Corps of Engineers (USACE), the National Oceanic and Atmospheric Administration (NOAA), and the Minerals Management Service (MMS). For some publications regarding improvement of the source terms in contemporary ocean wave models reference is made to the 12th International Workshop on Wave Hindcasting and Forecasting (http://www.waveworkshop.org/12thWaves/).

Wave models in deep and finite water describing short-term variations of water surface may be categorized into four classes: linear wave models, the Boussinesq, Kadomtsev–Petviashvili (KP) and the Korteweg-de Vries (KdV) models, second order wave models, and higher-order wave models. For extreme waves in extremely shallow water, the Boussinesq equation model (or KdV model, or its generalisation the KP equation) or its higher order extension is usually adopted with a relevant non-dimensional number, say Ursell number (ratio of wavelength, wave amplitude and water depth). For intermediate water depths the 2nd order shallow water theory is applicable whilst in deep water the 2nd order deep water theory may be applied; higher order theories may be needed for extraordinarily steep sea states. Nonlinear Schrödinger Equations (NLS), Modified Nonlinear Schrödinger Equations (MNLS), HOSM (Higher Order Spectral Method) have all been used to provide estimates of rogue waves.

Linear and second order wave models (e.g. the 2nd order Sharma and Dean finite-water wave theory) are well established and have commonly been used in design in the last years. Since 2009 increasing focus has been given to description of rogue waves (also called freak or abnormal waves) in shallow, intermediate and deep water.

When studying rogue waves the information given by the hindcast and the higher order solutions can be utilized and their use is encouraged. The complementary nature of two models has been pointed out by the ISSC 2009 I.1 discusser Prof. H. Tomita, see the ISSC 2009 Congress Proceedings Vol. III.

18th International Ship and Offshore Structures Congress (ISSC 2012) - W. Fricke, R. Bronsart (Eds.)

A number of physical mechanisms to explain the extreme and rogue wave phenomena have been suggested in the last decade; these include: linear Fourier superposition (frequency or angular linear focussing), crossing wave systems, wave-current interactions, quasi-resonant interaction (modulational instability) and shallow water effects. Since 2009 there has been increasing focus on further explanation of these mechanisms, development of numerical codes for description of extreme and rogue waves, as well as on comparison and validation of numerical nonlinear wave models with experimental and field data.

Three important review publications have been issued recently: Dysthe *et al.* (2008), Kharif *et al.* (2009) and Osborne (2010), gathering significant findings within the field of extreme and rogue waves. The paper of Pelinovsky *et al.* (2011) is also a valuable reference.

Didenkulova and Pelinovsky (2011) studied the formation of rogue waves in the framework of nonlinear hyperbolic systems with an application to nonlinear shallow water waves. It is shown that rogue waves can appear in nonlinear hyperbolic systems only as the result of non-linear wave–wave or/and wave–bottom interaction.

The transformation of a random wave field in shallow water of variable depth has been analysed by Sergeeva *et al.* (2011) within the framework of the variable-coefficient Korteweg-de Vries equation. It is shown that the characteristic wave height varies with depth according to Green's law, and this follows rigorously from the theoretical model.

Much attention has been given to quasi-resonance (modulation instability), one of the intermediate and deep water mechanisms responsible for generation of rogue waves. Wave breaking is not typically included in these studies except by simple parameterization e.g. Babanin (2011), and work continues in this area.

The deterministic theory of ocean waves, formulated as a nonlinear Schrödinger equation, has been shown to reproduce observed rogue waves very accurately when properly calibrated. The equations have also successfully been used to generate rogue waves, in a numeric and physical wave tanks, e.g. Babanin *et al.* (2011b), Toffoli *et al.* (2010a, 2010b), Slunyaev *et al.* (2011, 2012).

Toffoli *et al.* (2010b) have compared numerical simulations of a Boundary Modified Nonlinear Schrödinger equations (BM-NLS) and the potential Euler equations solved by Higher Order Spectral Method (HOSM) for long-crested and short-crested waves with different directional wave spreading and for the JONSWAP spectral parameter γ=3 and γ=6. Both models have provided similar results despite the bandwidth constraint of BM-NLS.

Mori *et al.* (2011) demonstrated by Monte-Carlo simulation of the NLS with various spectral geometries that the maximum attainable kurtosis as a result of quasi-resonance depends both on the frequency band-width and directional spreading. The result agreed well with the earlier experimental investigations by Waseda *et al.* (2009a, 2009b), and Onorato *et al.* (2006) showing increased occurrence of freak waves as the directional spectrum narrows.

Strongly nonlinear and fully nonlinear simulations of extreme wave events have been performed by Shemer *et al.* (2010a, 2010b) and Slunyaev (2010). In particular, the conformal 2D code has been employed for basic wave tests resulting in generation of steep and breaking waves. HOSM with the nonlinearity parameter M = 6, which corresponds to practically fully nonlinear wave simulations, was used to simulate 2D

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waves. Ruban (2010) investigated the formation of rogue waves in sea states with two close spectral maxima using a completely nonlinear numerical model for long-crested surface waves.

The Hilbert transform is a primitive method for obtaining the wave envelopes, which disregard wave nonlinearity, which is crucial when rogue waves are considered. Slunyaev (2009) examined different approaches and tested versus application to the in-situ data: 2-order and 3-order bound (Stokes) waves' consideration in a narrow-band assumption, and the Creamer transform approach. Although the difference in the surface elevation profile between the different envelope approaches is not visible, the distinctions between the vertical velocities and spectral tails are obvious.

Numerical simulations by using HOSM for solving the Euler equations have indicated that the number of extreme events increase when an angle between the two interacting wave systems was around 30–40 degrees, Toffoli *et al.* (2011b). This finding is supported by recent theoretical investigations of Onorato *et al.* (2010).

Impact of current in modifying the quasi-resonant wave evolution has been studied by Onorato *et al.* (2011a, 2011b) and Toffoli *et al.* (2011a, 2011c). A condition of partial opposition has been considered. The studies have shown that the current can trigger the formation of large amplitude waves. This conclusion has been confirmed by Hu and Ma (2011) who have shown that the physical properties of rogue wave are influenced significantly by the velocity of current. The authors established a spatial domain model of current modified nonlinear Schrödinger (NLSC) equations in one horizontal dimension for describing the deep-water wave trains in a prescribed stationary current field.

Some interesting developments have taken place on direct and indirect evidence on the specific meteorological conditions leading to the formation of narrow directional wave fields and occurrence of rogue waves, Waseda *et al.* (2011). Met-ocean conditions associated with occurrence of rogue waves were also studied, Bitner-Gregersen and Toffoli (2012). Rozhkov (2009) proposed a mechanism of generating a giant rogue wave in mid-ocean. The swell (steady wave) is the initial condition for the wave evolution at the beginning of which the wave is driven by the gust of wind, and then the wave runs free up to its overturning and may become huge. The time of the evolution is less than half of the swell period. In the course of the free evolution the wave height may also oscillate creating the "Three Sisters" effect.

A general consensus on the ultimate shape of waves has not been achieved yet due to the complexity of the breaking mechanism. A review book on breaking waves by Babanin (2011) outlines the state-of-the-art in understanding of wave breaking and presents the main outstanding problems. Dao *et al.* (2011) using an advanced numerical method, the Smoothed Particle Hydrodynamics enhanced with parallel computing, reproduced well the extreme waves and their breaking process. Babanin *et al.* (2011b) relate the wave breaking in oceanic conditions to features of two-dimensional breaking waves due to modulational instability. The authors argue that the physics of rogue waves is defined by the same processes as those leading to the onset of breaking with surface waves.

3.2.2 Experimental Description of Waves

Laboratory tests have been conducted world-wide to investigate extreme and rogue wave events, primarily through changing various wave spectral parameters and utilising a directional wave generator.

18th International Ship and Offshore Structures Congress (ISSC 2012) - W. Fricke, R. Bronsart (Eds.)

An interesting study with similar wave experiments conducted independently in two different facilities, the MARINTEK ocean basin (Norway) and the directional wave basin at the Australian Maritime College (AMC), is reported by Toffoli *et al.* (2011a). Although those facilities have different sizes and are equipped with different wave makers, the results obtained are very consistent. The modulational instability process is quenched when short-crested waves are considered.

Laboratory measurements of nonlinear wave group dynamics collected in the experiments in the Large Wave Channel (GWK) in Hannover have been carried out by Shemer *et al.* (2010a, 2010b) and compared with numerical simulations of the spatial version of the Dysthe model. Similar simulations within the spatial version of the NLS equation exhibit much worse agreement with the measured waves and thus the NLS equation is not efficient for this kind of modelling.

Cherneva and Guedes Soares (2010, 2011) have compared the results of experiments carried out in the DHI and MARINTEK basin and have shown that the observed maximum wave steepness systematically decreases with the band wide parameter.

An extensive investigation of the wave crest carried out in the MARIN basin is reported by Buchner *et al.* (2011). Particular attention in the experiment was the study of very steep crests. The study has confirmed earlier investigations; wave directionality suppressed nonlinear effects.

Latheef and Swan (2011) have performed an experimental study of wave properties in different sea states in the Imperial College facilities in order to study statistics of wave crest and height.

Investigation of crossing-wave systems has been carried by Toffoli *et al.* (2011b). HOSM was used for solving the Euler equations. Both numerical simulations and experimental data indicate that the number of extreme events depends on the angle between the two interacting wave systems.

Laboratory experiments of the wave field traversing obliquely an ambient current were carried out in the MARINTEK tank by Toffoli *et al.* (2011c). Tests on regular waves have shown that the current can trigger the formation of large amplitude waves. However, for the sea states considered this has resulted only in a weak deviation from the statistical properties observed in absence of a current.

Toffoli *et al.* (2010c) analysed a large sample of individual wave steepness data collected from measurements of the surface elevation in laboratory facilities and the open sea under a variety of sea state conditions. Observations reveal that waves are able to reach steeper profiles than the Stokes' limit for stationary waves. Direct measurements of instability-caused breaking in a directional wave tank with directional spread are discussed also by Babanin *et al.* (2011b).

Dai *et al.* (2010) have investigated mixing induced by nonbreaking surface waves in a wave tank by measuring the thermal destratification rate of the water column without waves and when waves are present. The study demonstrates that the mixing induced by nonbreaking waves may add an important contribution to the vertical mixing process in the upper ocean and suggests a way to parameterise wave-induced mixing in numerical ocean models.

The nonlinear dynamics of surface gravity is today reasonably understood, the focus is now on forcing terms like wind and current and wave breaking.

3.2.3 Statistical and Spectral Description of Waves

Short-term statistics. For Gaussian seas the crest distribution is often approximated by Rayleigh cumulative distribution function (CDF). For severe seas the Rayleigh CDF has been corrected in various ways often employing a Weibull distribution with empirically fitted parameters to capture very high crest heights.

Another approach to estimate the crest height is to employ a non-Gaussian model for waves and compute the crest height in the model. Normalized crossing intensity, given by the Rice formula, is often used to estimate of the crest height distribution. It is also a conservative estimate that fits well to the tail of the distribution. A new approach on evaluation of the Rice formula for second order wave models, based on a saddle point approximation, was presented in Butler *et al.* (2009). Further Laplace distributed processes have been used to model waves at fixed location, see Åberg *et al.* (2009). In Galtier (2011) an estimation method of crossing intensity for the Laplace process was given. Lindgren *et al.* (2010) give means to evaluate Rice's formula for Lagrange waves.

In Lindgren *et al.* (2010) the authors review work on a a spatio-temporal stochastic Lagrange wave model (an alternative to the Gaussian linear model) and give means to compute theoretical distributions of some wave characteristics, e.g. wave slope, see also Lindgren (2009).

Romero and Melville (2010) have studied spatial wave statistics, e.g. wave steepness and length of the crest extracted from LIDAR data and compared those with the theoretical distributions derived for Gaussian (linear) models. They concluded that the observed characteristics differ from the theoretical ones.

Several authors have studied extreme and wave rogue statistics in shallow, intermediate and deep water. Suggested simplified definitions of rogue waves, not sufficiently reflecting the physics of rogue waves, were noted in the previous Committee report. Recently Gemmrich and Garrett (2010) have proposed using an "unexpected wave", such as a wave twice as high as any of the preceding 30 waves, when studying extreme waves.

Sergeeva *et al.* (2011) have shown within the framework of the variable-coefficient Korteweg-de Vries equation that the skewness and kurtosis increase when the depth decreases, and simultaneously the wave state deviates from the Gaussian. The slope of the bottom influences the results. If the random wave field is represented as a soliton gas a number of large-amplitude (rogue) solitons increases when water becomes shallower.

Didenkulova (2011) has studied statistics of wave height in shallow water. Wave heights with high crests and deep troughs have been observed. The occurrences of rogue waves with high crests have been correlated with significant wave height when deep troughs were not present.

Latheef and Swan (2011) have performed a large experimental study of wave properties in different sea states. They compared observed crest and wave height with the models proposed in the literature and concluded that so called Glukhovskiy distribution gives the best fit; this confirms earlier findings.

Toffoli and Bitner-Gregersen (2011) have used the potential Euler equations to investigate comprehensively the effect of modulational instability on statistical properties of surface wave characteristics like water surface elevation, wave crest, wave trough, wave height, skewness and kurtosis in directional wave fields. The effect of modulational

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instability is gradually suppressed when the wave energy spreading increased and the second order wave theory is adequate to describe the statistical behaviour of ocean waves up to a particular probability level.

The statistics of wave height and crest based on numerical simulations carried out with 2D and 3D HOSM models, Boundary Modified-NLS (BM-NLS) model and the laboratory data have been compared with the 2nd order crest and height Tayfun distributions and the Rayleigh distribution by Toffoli *et al.* (2010b). There is good qualitative and quantitative agreement between the numerical and experimental statistics also regarding of the maximum kurtosis (important for practical applications), except for very narrow directional waves.

Several authors have pointed out that the kurtosis can be regarded as a suitable parameter to identify the presence of a rogue event in a short-term wave records, see e.g. Toffoli *et al.* (2011b), Mori *et al.* (2011). Toffoli *et al.* (2011b) found higher kurtosis values when analysing waves in bimodal sea states, with higher occurrences when there were directional differences between 20 and 40 degrees. Further investigations are needed to conclude whether the two peaks spectrum has larger impact on occurrence of rogue waves than the spectrum bandwidth and directional spreading.

It has been verified both theoretically and experimentally that the kurtosis depends on the square of the BFI (Benjamin Fair Index), Onorato *et al.* (2006). Mori *et al.* (2011) present two-dimensional Benjamin Fair Index (BFI-2D) and express the kurtosis as a function of it. Random waves are expected to become unstable when BFI>0.6, provided the wave field is long crested (i.e. unidirectional wave propagation); e.g. Toffoli and Bitner-Gregersen (2011).

Zakharov and Shamin (2010) studied the statistics of the occurrence of rogue waves on a surface of an ideal heavy liquid arising in the course of evolution of a statistically homogeneous random Gaussian wave field. The mean steepness of initial data varies from small to moderate values. The frequency of the occurrence of extreme waves decreases with an increase in the spectral width of the initial distribution, but remains relatively high even for broad spectra.

Results of an extensive tank investigation on the wave crest distribution at fixed location were reported in Buchner *et al.* (2011). The conclusion was that wave crests are higher than predicted by linear (Gaussian) sea models, and second- and third-order corrections are needed to better describe the crest height variability. The Forristall second order distribution was recommended as the model that most adequately fits the tank data but not the field data.

In Petrova *et al.* (2011) statistical properties of wave crest, height and trough were investigated using experiments in deep water basin with bimodal crossing seas. The observed distributions differed significantly from the theoretical one derived for Gaussian seas and the second-order corrected distributions. Modifications of parameters were proposed.

Gemmrich and Garrett (2011) showed that the occurrence rate of extreme wave crests can be displayed effectively by plotting ln(-lnP), where P is the probability of the wave or crest height exceeding a particular value, against the logarithm of that value.

The studies of wave statistics are mostly centered on individual waves, often extreme, however in many safety applications the properties of wave groups are at least as or even more important, as reported by Clauss *et al.* (2011a, 2011b). A review of work on wave groups in oceanography is given by Bassler *et al.* (2010). In this work several

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statistics of observed envelope properties are presented. Similarly in Cherneva and Guedes Soares (2011), the observed deep water basin wave group characteristics are compared with the theoretical crossing distributions derived for Gaussian processes. Their findings confirmed results, presented by many authors, that wave group dynamics are nonlinear, making the wave group process significantly non-Gaussian. Theoretical results on distributions of wave group characteristics for non-Gaussian waves or Gaussian spatio-temporal fields are as yet very limited; see e.g. Podgorski and Rychlik (2008) for some theoretical results on the envelope of Gaussian wave fields.

Somewhat different results were reported in Forristall (2011), where the author compared theoretical spatial distribution for crest height of a Gaussian wave field due to Piterbarg (1996) with measurements in the MARIN Offshore Basin and reported good agreement between measurements and the theoretical distribution.

A number of investigations have attempted to find relations between individual wave parameters and sea state characteristics identifying occurrence of rogue waves but have not succeeded in finding any strong correlation (see, e.g. Christou and Ewans, 2011a, 2011b). Recently Waseda *et al.* (2011) used the number of records containing a freak wave per certain time window as a proxy to estimating the enhancement of the tail of the probability density function. The authors have found that there is a notable increase of the probability of occurrence of freak waves when the sea level pressure gradient is strengthened and the directional wave spectrum is relatively narrow (directional spread about 30 degrees). Bitner-Gregersen and Toffoli (2012) demonstarte how sea state duration affects probability of occurrence of rogue waves.

A fundamental but often tacitly assumed condition upon which short-term characteristics are based is that sea states are stationary. Sea state stationarity was addressed by Ewans (in prep.) in the Safe Offload project who investigated the temporal behaviour of swell using the wavelet transform for Directional Waverider buoy data from Duck, North Carolina. It was shown that non-stationary sea states were usually associated with local wind-sea growth rather than significant changes in the swell component, which could be considered stationary for at least as long as the 160-minute records.

Long-term statistics. Computation of extreme wave parameters are often performed by a two-level procedure which requires a model for long term variability of sea states and a distribution of a wave parameter during a sea state. The long term variability of sea states can be specified by a long term CDF (Cumulative Distribution Function) of spectral parameters.

Fedele *et al.* (2010) employed the technique for studying the extreme wave amplitude in sea storms at a fixed point with attention to modeling storm shapes. Gaussian wave amplitudes were modelled by means of the Rayleigh CDF. The authors focused on extreme wave crests occurring in some region and time period in sea storms. The waves were Gaussian and for a fixed sea state Rice's method in three dimensions was employed, see Azaïs and Wschebor (2009), for theory behind of the method.

In Mao and Rychlik (2012) the spatio-temporal model of significant wave height due to Baxevani *et al.* (2008) combined with a transformed Gaussian model was used to estimate extreme ship response when sailing on a North Atlantic route.

In recent years increasing attention has been given to the importance of including wind sea and swell components in a joint environmental description. Olagnon and Guédé (2010) show how to model several swell components. Bitner-Gregersen (2010) demonstrates that two approaches suggested for joint modelling of wind sea and swell can give significantly different predictions of extreme swell values. Sagrilo *et al.* (2011) have shown, using Brazilian data, applicability of the Nataf transformation to describe joint probabilities for wave (wind sea and swell), wind and current parameters with direction The treatment of directional data using wrapped normal distributions is an innovative contribution to research on joint probabilities.

Liu *et al.* (2010) studied joint variability of significant wave height and wind speeds in the Bohai Sea.

Extremes in significant wave height from the NORA10 data were estimated by Aarnes *et al.* (2011) using the Generalized Extreme Value distribution and Generalized Pareto distribution/Peak Over Threshold model.

In Baxevani *et al.* (2009) a spatio-temporal model for significant wave height was presented; an improved model to the one given in Baxevani *et al.* (2008) and fitted to the satellite data. The model was used in Rychlik *et al.* (2010) to estimate the 100 years return value worldwide. Alliot *et al.* (2011) generalised the model of Baxevani *et al.* (2009) and fitted the model to hindcast data validated by satellite altimeter data and buoy measurements. Further generalization of the model is presented in Baxevani *et al.* (2011) where a general class of spatio-temporal models is introduced which may lead to new developments.

The Baxevani *et al.* (2009, 2011) approach to define spatio-temporal fields is convenient for generalizations of non-Gaussian spatio-temporal models, since the dynamics can be added to any significant wave height spatial surface. In Åberg and Podgorski (2011) a new class of Laplace distributed fields, which can be horizontally and vertically asymmetrical, has been proposed. By introducing movements to the field a spatio-temporal model can be obtained. Further research is needed to check the usefulness of Laplace fields to model space time variability of significant wave heights.

In Ailliot *et al.* (2011) the velocity field is modelled by hidden Markov chain estimated from meteorological data. In Schlather (2010) a related class of Gaussian fields with non-separable covariance structure has been presented.

Vanem (2011) gives a literature survey on different sea state modelling approaches, particularly about spatio-temporal models, citing 211 references. In Vanem *et al.* (2011) a Bayesian hierarchical model in space and time is fitted to hindcast data for significant wave height in an area in Northern Atlantic. It is a non-Gaussian model developed to study climatic changes in significant wave height. Further research is needed to improve effectiveness of the model. The model has been adapted to monthly maxima in Vanem and Bitner-Gregersen (2012).

Due to the spatial size considered for the significant wave heights field, the efficiency of simulations of spatio-temporal models is an important issue. In Lindgren *et al.* (2011) algorithms for efficient computations and simulations of Gauss-Markov fields were presented. The fields are useful tools for modelling of quantities varying in a non-homogenous way over large areas. The authors also derived a new class of random field models using nested stochastic partial differential equations (SPDE).

Loffredo *et al.* (2009) show that the main drawback of the Hanson and Phillips (2001) approach commonly used in design for splitting the 3D wave spectrum into separate peaks is when there are fully developed wind seas with small wind decay but still in the same direction of the wave field. If the wave systems under examination cannot satisfy the formulation adopted by Hanson and Phillips (2001), the old wind sea will be treated as swell and the new wind sea set to zero. This will have impact on statistics of wind sea and swells (Bitner-Gregersen, 2010).

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There are statistical techniques available that could be used to determine statistically similar ocean areas which have not been applied because of the low spatial resolution nature of the data available. Lucas *et al.* (2011) explore the capabilities of regional frequency analysis, which provides an appropriate statistical based method to deal with this problem.

Spectral description. The 2009 Committee I.1 reported that the Pierson-Moskowitz and JONSWAP spectra are most well known and widely applied along with wave spreading according to frequencies. This situation remains. Increasing attention has been given since 2009 to describe bi- and multi-model seas; wind sea and swell (or several swell components). In Norwegian waters, the Torsethaugen bi-modal spectrum suggested in 1993 and simplified in 2004 by Torsethaugen and Haver is the most common for design purposes.

Methods for partitioning of directional spectra into wave systems, such as the one proposed by Hanson and Phillips (2001), are now widely used and even implemented in wave models such as WAVEWATCH III^{TM} (Tolman 2009). The splitting of complex sea-states into their constituting wave systems, swells and wind-sea, allows a more accurate description of the energy distribution in the spectro-directional referential which is adequate for refined wave climate statistics (Saulnier *et al.,* 2011) and of major interest for resource assessment as described in the protocols for resource assessment provided by the EU funded project EQUIMAR (Equitable Testing and Evaluation of Marine Energy Extraction Devices in terms of Performance, Cost and Environmental Impact - http://www.equimar.org).

Bitner-Gregersen and Toffoli (2009) have compared the wind sea and swell components predicted according to the Torsthaugen partitioning procedure with the ones given by the hindcast data from three locations: West Shetland, NW Australia and off the coast of Nigeria. The results indicate that the Torsethaugen spectrum should be used with care outside the Norwegian waters. The Torsethaugen partitioning procedure is sensitive to inaccuracy in H_s and T_p (spectral peak period) estimates for the total sea. Uncertainties related to these estimates may result in predicting an incorrect sea state type (e.g. a wind dominated sea instead of a swell dominated sea) when the Torsethaugen model is applied.

Traditionally, the directional distribution of ocean waves has been regarded as unimodal, with energy concentrated mainly on the wind direction. However, numerical experiments and field measurements have demonstrated that the energy of short waves tends to be accumulated along two off-wind directions, generating a bi-modal directional distribution. Toffoli *et al.* (2010a) have used numerical simulations of the potential Euler equations to investigate the temporal evolution of initially unimodal directional wave spectra. The approach adopted does not include external forcing such as wind and breaking dissipation, thus spectral changes are only driven by nonlinear interactions. Simulations show that the nonlinear interactions spread energy outwards from the spectral peak along two characteristic directions in qualitative agreement with a simplified narrow-banded model proposed by Longuet-Higgins (1976). According to the latter, the energy redistributes on directions forming angles of ± 35.5 degrees about the dominant wave direction. As a result, the directional distribution develops a bimodal form as the wave field evolves. The results are somewhat consistent with the parametric empirical bimodal directional model proposed by Ewans (1998). For a fairly long crested wave field, the simulations fit the Ewans model. However, as waves become shorter crested, the side lobes tend to slightly concentrate over broader directions with a consequent deviation from the aforementioned bi-modal directional

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model. Toffoli *et al.* (2010a) have provided a parameterisation for the lobe amplitude derived directly from the parametric bimodal directional model of Ewans.

3.3 Current

Success of the global and basin-scale ocean models with data assimilation under the GODAE program opened a new era of operational oceanography. It needs to be mentioned that the GODAE product is global and it provides boundary conditions for regional and high-resolution models. It does not aim at covering all time-scales that are required for engineering.

The regional and coastal models can be forced by both astronomical tides and the basin-scale circulation. Therefore, phenomena related to external tides, storm surges, river plumes, coastal topographic waves, upwelling, downwelling and alongshore currents, mesoscale instability eddies and contour currents and standing meanders are in settlements, leaving the internal tides, surface fronts and submesosclae vortices, wakes and littoral currents as frontier phenomena (McWilliams, 2009). To best resolve these phenomena, modelling efforts are made at high-resolution, with wave-current interaction, and with realistic coastal and bottom topography. Operational ocean models need still improvements as they can fail to reproduce observed surface currents in the open ocean and particularly nearshore, see e.g. Breivik *et al.* (2011).

3.3.1 Analytical and Numerical Description of Current

The three dimensional hydrodynamic model COHERENS (COupled Hydrodymamic and Ecological REgioNal Shelf seas) http://www.mumm.ac.be/∼patrick/mast/ is a multi-purpose numerical model for coastal seas which can consider the effect of waves on current through introducing wave radiation stress. Recently, a coupled model COHERENS-SWAN was adopted to simulate tidal current distribution under waves. The current velocities and surface elevation are calculated simultaneously. In the coupled model COHERENS-SWAN (Zhang *et al.,* 2009), the mutual influence of wave and current are included through exchange of data of each model. SWAN is introduced into COHERENS as a subroutine. COHERENSE gets wave height, period and direction through calling SWAN. SWAN gets current velocity and surface elevation from COHEERENS to account for their effects on wave simulation. The effects of non-uniform currents on wave propagation and wave blocking are investigated by Zhan *et al.* (2010) using a new Boussinesq model, in which the non-linear interaction of wave and current are taken into account.

Hao *et al.* (2009) presented the numerical results of wind-driven current in a lake using the Princeton Ocean Model (POM) and showed that the orthogonal curvilinear the grid in horizontal plane and the sigma coordinate in vertical plane are most effective. Shan *et al.* (2010) modelled the current generated in the deep water offshore basin at Shanghai Jiao Tong University using unsteady Reynolds Averaged Navier-Stokes (RANS) code and compared the numerical results with experiments. Based on measured full-depth deepwater current data in the South China Sea (offshore from Borneo), Sheikh *at al.* (2010) analysed the current speeds using Empirical Orthogonal Functions (EOFs) and their extreme profiles derived using the inverse First Order Reliability Method (FORM).

High resolution submesoscale-eddy-resoving models are being developed and are applied to, for example, processes relevant to larval transports in regions connecting open ocean and coastal seas (Mitarai *et al.*, 2009). With further refinement of the model approaching the coast, the wave-driven current field plays a significant role interacting with submesoscale current variations e.g. Uchiyama *et al.* (2009). The so-called

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vortex-force formulation which is an alternate expression for the classical radiation stress of the nonlinear coupling of waves and currents was successfully implemented in this modelling. Uchiyama *et al.* (2010) further downscaled to resolve the surf zone dynamics where both vortex force and non-conservative wave effect on current due to breaking were significant in resolving the under-toe.

Schaeffer *et al.* (2011) investigate dynamics of mesoscale anticyclonic eddies identified by mean of HF radars in the Gulf of Lions in the Mediterranean Sea. The authors focus on identification of physical mechanisms for the generation of such eddies and especially the influence of wind forcing. Numerical studies point out two mechanisms for eddy generation which correspond to two identified meteorological conditions.

Considering the case of mesoscale eddies generation around the Hawaiin archipelago, Kersalé *et al.* (2011) assess the sensitivity of an ocean model to forcing and especially wind forcing. The study shows that in order to correctly reproduce the oceanic circulation, multiple combined forcing (wind, inflow topography) must be implemented. It also shows that the Quik-SCAT wind data, with higher spatial resolution captures the complexity of the atmospheric flow in the different channels between the islands and allows a more accurate reproduction of the oceanic circulation.

3.3.2 Statistical and Spectral Description of Current

Not much progress can be reported since 2009. Statistical properties of surface current have been investigated for three locations in the EC project SAFE OFFLOAD. Some results are presented in Bitner-Gregersen (2010). Modelling of vertical profiles of large ocean currents is discussed by Jonathan *et al.* (2011b). Statistics of wave–current interaction are reported in Section 3.2.3.

3.4 Sea Water Level

Several studies have been carried out to project future sea water level changes using GCM (Global Climate Model) or RCM (Regional Climate Model) models. Conclusions of these investigations are summarized in Section 4.1.4.

Assessment of the performance of state-of-the-art meteorological and oceanographic numerical systems in predicting the sea state (including surge) in the Adriatic Sea during intense storms has been carried out by Cavaleri *et al.* (2010). Two major storms that affected Venice are presented in the study. The results indicate the surge model should provide users with valuable forecasts.

3.5 Ice

Information about sea ice processes can come from field camps or aircraft and satellites, but data from these sources are limited. Sensors cannot account for all characteristics of sea ice anytime and anywhere. Furthermore, the record of sea ice data has a limited history. Satellite observations date back only to the mid-1970s; other observations, such as ship records, may go back as far as the late 19th Century, but they are sparse. Moreover, these data cannot predict the future of sea ice extent.

Sea-ice models allow for the reconstruction of historical patterns of sea ice and the prediction of future changes. Polar Regions are particularly sensitive to small changes in climate, and sea-ice models have undergone a significant development throughout recent years. Depending on the purpose of modelling, sea-ice models are used for short-term operational forecasts (one to five days) for ocean vessels in sea ice-covered regions, as well as for seasonal forecasts (one to three months) to aid in planning.

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The dynamics equations take into account winds, currents, and other forces that influence sea ice motion. They consider air and ocean temperatures, albedo, and other forces that influence the growth and melt of sea ice.

3.5.1 Analytical and Numerical Description of Ice

Timmermann *et al.* (2009) describe a global Finite Element Sea Ice–Ocean Model. The ocean component is based on the Finite Element model of the North Atlantic but has been substantially updated and extended. A finite element dynamic-thermodynamic sea ice–model has been developed and coupled to the ocean component. Sea ice thermodynamics have been derived from the standard Alfred Wegener Institute for Polar and Marine Research (AWI) sea ice model featuring a prognostic snow layer but neglecting internal heat storage. The dynamic part offers the viscous-plastic and elastic-viscous-plastic rheologies. The coupled model is run in a global configuration and forced daily atmospheric reanalysis data for 1948–2007. Results indicate that many aspects of sea ice distribution and hydrography are found to be in good agreement with observations.

Although most of the solar radiation is reflected back into the atmosphere by the sea ice, part of it is absorbed, and the rest heats the surface sea water by penetrating through the sea ice. Cao *et al.* (2011) consider the resulting Near Sea-surface Temperature Maximum, which appears at a depth of less than $40\,m$ in the Arctic sea ice covered region. Most of the heat in the sea water diffuses back upwards due to the existence of the pycnocline forming a temperature peak just above it. By heating the water below the sea ice, the heat accelerates the melting of sea ice. A thermodynamic coupled sea ice-upper ocean column model was used by the authors in order to examine the relationship between the solar radiation flux penetrating through the sea ice and maximum temperature of the Near Sea-surface Temperature Maximum.

The work of Gödert and Suttmeier (2009) presents a phenomenological constitutive flow model for polar ice derived from so-called mesoscopic considerations and its consistent implementation into an appropriate finite element scheme. A systematic investigation of the development of texture in isothermal polar ice is presented. From the viewpoint of numerics the flow of ice is considered as a stationary free surface Stokes flow fully coupled with the development of its texture. Boundary conditions at the free surface are accommodated in the course of the computation to the actual flow situation. It turned out that the choice of the velocity boundary conditions at the bottom (bed-rock) is the crucial point in modelling induced anisotropy of free surface flow.

The marginal ice zone is the boundary between the open ocean and ice-covered seas, where sea ice is significantly affected by the onslaught of ocean waves. Waves are responsible for the breakup of ice floes and determine the extent of the marginal ice zone and floe size distribution. When the ice cover is highly fragmented, its behaviour is qualitatively different from that of pack ice with large floes.

Ice loads have traditionally been estimated using empirical data and "engineering judgment". On the other hand, it is believed that computational mechanics and advanced computer simulations of ice-structure interaction play an important role in developing safer and more efficient structures, especially for irregular structural configurations. The work by Bergan *et al.* (2010) explains the complexity of ice as a material in computational mechanics terms. The paper points towards the use of advanced methods like the Arbitrary Lagrangian-Eulerian (ALE) formulations, meshless methods, particle methods, the Extended Finite Element Method (XFEM), and

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multi-domain formulations in order to deal with these challenges. Much research is still needed to achieve satisfactory reliability and versatility of these methods.

Ahlkrona (2011) addresses the topic of ice sheet modelling. It involves describing a system including the ice sheet, ice shelves and ice streams, which all have different dynamical behaviour. The governing equations are non-linear, and to capture a full glacial cycle more than 100,000 years need to be simulated. To reduce the problem size, approximations of the equations are introduced. The most common approximation, the Shallow Ice Approximation (SIA), works well in the ice bulk but fails elsewhere e.g. the modelling of ice streams and the ice sheet/ice shelf coupling. In recent years more accurate models, so-called higher order models, have been constructed to address these problems.

Modelling of the internal pressure field and effects of a finite ice strength on a new model for sea ice dynamics, based on a global optimisation problem, rather than a local rheology, are examined by Huntley *et al.* (2007) and Huntley and Tabak (2007). In both references the pressure is seen as emerging not from an equation of state but as a Lagrange multiplier that enforces the ice's resistance to compression while allowing divergence. This formulation leads to an analytic description that is also easily implemented in a numerical code, which exhibits marked stability and is suited to capturing discontinuities. In order to investigate the behaviour of the model under ice yielding, the equations are cast in an Eulerian framework, now allowing for variable thickness. The model is first tested under conditions of infinite ice strength, to ensure that the numerics behave as desired. A finite ice strength is incorporated into the model as a second optimisation step, minimising the change in ice thickness necessary to satisfy the upper bound on the pressure, whereby ice strength is taken to be a linear function of thickness, following typical parameterisations in the literature.

The Jacobian-free Newton-Krylov method is implemented by Lemieux *et al.* (2010) to solve the sea ice momentum equation with a viscous-plastic formulation. This method has many advantages: the system matrix (the Jacobian) does not need to be formed and stored, the method is parallelizable and the convergence can be nearly quadratic in the vicinity of the solution. The convergence rate is characterized by two phases: an initial phase with slow convergence and a fast phase for which the residual norm decreases significantly from one Newton iteration to the next. Because of this fast phase, the computational gain of the Jacobian-free Newton–Krylov method over the standard solver used in existing viscous-plastic models increases with the required drop in the residual norm (termination criterion). The method is between 3 and 6.6 times faster (depending on the spatial resolution and termination criterion) than the standard solver using a preconditioned generalized minimum residual method.

The growth of sea ice and the associated loss of salt are addressed by Notz (2005) experimentally as well as numerically. His findings show that in winter salt is only lost from sea ice by so-called gravity drainage and that the bulk-salinity and solid-fraction fields are continuous across the ice–ocean interface during ice growth. The concept of an effective distribution coefficient is therefore not warranted in the context of sea ice. It is further shown that so-called brine expulsion does not lead to any net loss of salt from sea ice, and that flushing with melt water during summer is the only other process that has any impact on the salinity evolution of sea ice. These results are obtained theoretically, using the so-called mushy-layer equations and an enthalpy-based numerical model. The theoretical predictions are confirmed by laboratory and field experiments, using a new instrument developed in this study, which allows the

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in situ measurement of the salinity distribution in growing sea ice with a very high temporal and spatial resolution.

A numerical dynamic-thermodynamic sea-ice model for the Baltic Sea is used to analyze the variability of ice conditions in three winter seasons by Herman *et al.* (2011). The modelling results are validated with station (water temperature) and satellite data (ice concentration) as well as by qualitative comparisons with the Swedish Meteorological and Hydrological Institute ice charts. Analysis of the results addresses two major questions. One question concerns the effects of meteorological forcing on the spatio-temporal distribution of ice concentration in the Baltic. Patterns of correlation between air temperature, wind speed, and ice-covered area are demonstrated to be different in larger, more open sub-basins e.g. Bothnian Sea than in the smaller ones e.g. Bothnian Bay. Whereas the correlations with air temperature are positive in both cases, the influence of wind is pronounced only in large basins, leading to increase/decrease of areas with small/large ice concentrations, respectively. The other question concerns the role of ice dynamics in the evolution of the ice cover. By means of simulations with the dynamic model turned on and off, the ice dynamics is shown to play a crucial role in interactions between the ice and the upper layers of the water column, especially during periods with highly varying wind speeds and directions. In particular, due to the fragmentation of the ice cover and the modified surface fluxes, the ice dynamics influences the rate of change of the total ice volume, in some cases by as much as $1\,km^3$ per day. As opposed to most other numerical studies on the sea-ice in the Baltic Sea, this work concentrates on the short-term variability of the ice cover and its response to the synoptic-scale forcing.

Liu *et al.* (2011) present a fine-resolution coupled ice-ocean model configured for the Bohai Sea and North Yellow Sea. Seasonal simulations were made from the winters of 1997/1998 to 2008/2009. By comparing of the simulation results and the remote sensing images, the ice-ocean coupled model reasonably reproduces the seasonal variations of the sea ice conditions in the Bohai Sea and North Yellow Sea. The predicted ice-freezing date, ice-ending date and ice periods are in fairly good agreement with observations, and some are even identical to measurements. The simulated maximum of the sea ice extent date and the observations match well. Normally, the sea ice thickness of the west part in Liaodong bay is less than that of the east part, which can be reproduced well by the ice-ocean coupled model.

Ji *et al.* (2011) modified a discrete elemental model (DEM) for sea ice dynamics based on granular material rheology. In the model, a soft particle is used with ability of self-adjusting its size. Each particle is treated as an assembly of ice floes characterised by adjustable ice concentration and thickness applying conservation of mass rule. The contact forces between ice floes are calculated using a viscous-elastic-plastic model and shear forces are obtained from the Mohr-Coulomb friction law. The model allows the simulation of ice piece dynamics in a channel and in an open domain with a vortex wind and current effects. The authors claim that the simulations show promising results.

Improvements to the sea ice forecasting tools are welcomed by the shipping and offshore engineering communities. All forecasts start from the observed initial conditions of ocean, land and atmosphere. Models are typically sensitive to the initial conditions, which are usually not known accurately, due to limited number of observing stations, imperfections of used instruments and other errors. Models are also sensitive to model formulations.

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The UK Met Office, Peterson *et al.* (2011), has recently upgraded its seasonal prediction system GloSea4 by implementing initialisation of the observed sea ice component in the forecast model HadGEM3/CICE. The upgrade improves the Arctic atmosphere locally near the ice edge and provides better forecast of ice extent in summer (minimum) and winter (maximum). The winter ice edge is particularly well predicted in Greenland, Norwegian and Barents Seas. Other areas like Labrador Sea, Bering Sea and Okhotsk Sea are less accurately forecasted. Further development is expected to include enhancement to the system horizontal resolution together with the ocean and sea ice assimilation scheme, and better quality of assimilated observations.

Increasing economic activities in ecologically sensitive Polar Waters increase the possibility of a devastating industrial pollution incident in these areas. An oil spill could be one of the possible disasters. Karlsson *et al.* (2011) conducted laboratory investigation of oil spills behaviour in the presence of sea ice in order to improve strategy of responses to oil spills in ice. The authors studied entrainment and upward migration of oil through the ice during growth and melt. They found that the oil can reach several centimetres into the ice through discrete brine channels where porosity is between 8 and 15 % even in the cold ice. The amount of oil absorbed by the ice will also depend on ice temperature.

Modern anisotropic plasticity ice dynamics models allow explicit descriptions of the formation and evolution of leads, rafts and ridges. The presence of these kinematic parameters can be very important for offshore operators. Pritchard and Tremblay (2011) present a preliminary idea for a new ice dynamic numerical model that describes the velocity and stress discontinuity explicitly. The analysis is limited to a quasi-static behaviour, for which temporal changes are resolved to a day or longer. Thus time does not appear in the momentum and constitutive equations at each time step. The scheme integrations are conducted along characteristic directions, so discontinuities appear naturally. So far, the authors use a new meshless model and have an anisotropic continuity law that describes lead formation and evolution, and derived the governing equation in characteristic coordinates. A numerical code is planned which will begin by solving the one dimensional problem.

3.5.2 Experimental Description of Ice

Full scale trials and model experiments are still the most reliable sources of information on ice properties and ice-structure interaction for designers and operators of offshore fixed and floating polar structures.

Two large ice model test campaigns were performed in the period 2007–2010 and are presented by Bruun *et al.* (2011) as a part of a Joint Industry Project. The objectives of the project were to investigate different floater geometries and ice model test set-ups e.g. with the model fixed to a carriage and pushed through the ice versus ice pushed towards a floating model moored to the basin bottom, also their influence on the ice failure mode and structure responses in the various tested ice conditions. This paper presents the objectives and motivations for the project, the models tested, the target test set-up for the various tested configurations and the test matrix. Initial results from a fixed model tested in three first-year ice ridges with similar target ice properties are also presented and compared.

Lee *et al.* (2011), Choi *et al.* (2011) and Lee and Jeong (2011) present results of the sea ice trails conducted with a Korean built icebreaker. The trials of the first Korean icebreaker “ARAON” were conducted in the Arctic Ocean in July–August 2010. Sea ice concentrations at the Arctic sea were 4/10 to 10/10 and sea ice thicknesses were

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roughly 1.0 to 3.5 m. During the trials characteristics and physical properties of sea ice and snow were measured, as well, icebreaking performance of the vessel in various ice and snow coverage conditions was evaluated. In situ measurements of the sea ice thickness distributions at the ice floe were conducted using drilling and electromagnetic induction instrument, EM31-MK2. Conductivity of the ice floes was measured and sea ice thickness was estimated applying empirical formula developed at the Cold Regions Research & Engineering Laboratory, CRREL. The results of sea ice thickness derived with the EM31-MK2 were compared with observations results and a new empirical formula for estimation of sea ice thickness through the analysis of apparent conductivity data is suggested.

One of the tasks when evaluating performance of ice class vessels and Arctic offshore structures in an ice model basin is to prepare a proper model of the ice with correct scaling of natural sea ice properites. Every ice model basin in the world has individually developed their own ice modelling technique and methodology. The EG/AD/S model ice which is a diluted aqueous solution of ethylene glycol, aliphatic detergent and sugar, may provide for the correct scaling of mechanical properties of columnar sea ice. The MOERI (Maritime & Ocean Engineering Research Institute) ice model basin of Korea which opened 2009, adopts the EG/AD/S type model ice, in collaboration with the IOT (Institute for Ocean Technology), Canada. Cho *et al.* (2009) presents a study that focuses on the evaluation of mechanical properties of the EG/AD/S model ice for the possible use in the new MOERI ice model basin.

Model tests on the Shoulder Ice Barrier (SIB) were performed in the large ice tank of the Hamburg Ship Model Basin (HSVA) during July 2007 as part of HYDRALAB III and are presented by Gürtner (2010). The main goal was to investigate the conceptual design of the SIB and assess ice forces and ice rubble build-up. Model test results showed that the SIB potentially could be utilised as an ice protection structure for future shallow water application. Based on the model tests performed a computational model for simulating ice-SIB interactions was developed. This computational ice-structure interaction model involves the simulation of ice rubble accumulations and accordingly the ice forces exerted on the structure.

3.5.3 Statistical and Spectral Description of Ice

Bekker *et al.* (2010a, 2010b) present a study where the problems of a statistical modelling of ice loads from drifting hummocky features and level ice fields on the reinforced gravity based structures in the Piltun-Astohsky and Lunsky fields offshore Sakhalin, north east Russia, are investigated.

Data collected by the Upward Looking Sonar (ULS) during a 5000 km submarine voyage between the Chukchi Sea, Beaufort Sea and North Pole are reported by Marcellus *et al.* (2011). They present a statistical approach used to extract key ice characteristics from ULS data that could be used in development of safe shipping routes in Polar Regions. The ice properties include floe size and thickness and ice ridge geometries for first year and multiyear ice.

4 SPECIAL TOPICS

4.1 Climate Change and Variability

The Intergovernmental Panel on Climate Change (IPCC) ARA5 report is under development (some members of the ISSC I.1 Committee have been reviewers of this report) and is planned to be issued in 2013/2014. The IPCC SREX "Summary for Policymakers" report was issued in November 2011 while the whole SREX (Special

18th International Ship and Offshore Structures Congress (ISSC 2012) - W. Fricke, R. Bronsart (Eds.)

Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation) report will be available in 2012.

Climate differs with geographic location and is influenced by amongst other factors latitude and distance from the open oceans. Climate has always changed over time, and the variations observed today are due to: natural variability (originating from the internal dynamics of the Earth's ocean and atmospheric system and occurring usually on time scales a few years from decadal to multi-decadal, but much longer cycles due to movement of poles may also occur, e.g. 23000 year cycles); climate change due to external forcing (such as changes in solar radiation and volcanic activity, varying on time scales from years to millennia); and anthropogenic climate change (caused by human activities, which takes place over a few decades to centuries), as stated by, for example, Bitner-Gregersen and Eide (2010).

The AR4 report (IPPC, 2007) concluded that there is very high confidence that the net effect of human activities since 1750 has contributed significantly to the global warming. This conclusion remains in 2012. It is pointed out by IPCC (2011) that assigning "low confidence" in a specific extreme on regional or global scale neither implies nor excludes the possibility of changes in this extreme. Many uncertainties remain in modern climate change projections.

Multi-decadal natural variability of climate (see ISSC 2009 I.1 report) due to the Earth's system dynamics, short term externally forced climate changes and short term changes (10–12 years) in solar radiation to some extend have been taken care of in design of marine structures by considering sufficiently long met-ocean data records (typically much longer than 10 years). Climate change due to long term external forcing such as solar radiation and caused by changes in the Earth's orbit is neglected in a design process because of the large time scale of its occurrence.

It is, however, important to be aware that the natural climate variability can be of the same order of magnitude as the anthropogenic climate change and may mask it for several years to come. Further, the anthropogenic climate change is affecting the natural climate modes. Palmer (2008) suggests that changes due to natural mode swap could be much larger than anthropogenic changes. Therefore the next 30–100 years' climate statistics may be affected strongly by it.

The Climate Change Conference which took place in Copehnagen in December 2009 raised climate change policy to the highest political level. It should also be mentioned that the credibility of the IPCC has been publicly called into question during the period of this Committee, in particular following mistakes in the AR4 glacial retreat projections.

4.1.1 Temperature

According to the IPCC SREX (2011) it is "virtually certain" ($> 99\,\%$ probability of occurrence) that increases in the frequency and magnitude of warm daily temperature extremes and decreases in the magnitude of cold extremes will occur in the 21st century on the global scale. The 20-year return period daily temperature will "likely" ($>$ $90\,\%$ probability of occurrence) increase by about 1–3 ^oC by the mid-21st century and by about 2–5 ^oC by late the 21st century, depending on the region and emission scenario (based on the B1, A1B and A2 scenarios, see ISSC I.1, 2009). The expected increase of the average Earth surface temperature will be twice as high in the Arctic compared to other parts of the Earth (IPCC, 2007).

Over the last two years, the Berkeley Earth Surface Temperature Project chaired by Prof. Richard Muller has deeply studied changes in global temperature. The changes

18th International Ship and Offshore Structures Congress (ISSC 2012) - W. Fricke, R. Bronsart (Eds.)

at the locations investigated have shown warming typically between 1–2 ^oC, much greater than the IPCC's (2007) average of 0.64 ^oC (http://www.berkeleyearth.org/).

The Copenhagen Climate Change Conference 2009 obtained strong convergence of the views of governments on the long-term goal of limiting the maximum global average temperature increase to no more than 2 degrees Celsius above pre-industrial levels, being subject to a review in 2015. No agreement on how to do this in practical terms, however, was reached. The 2011 UN Climate Change Conference held in Durban, South Africa, from 28 November to 9 December 2011 has agreed, however to prolong the Kyoto Agreement until 2015.

4.1.2 Wind

The review of the observed and projected changes of wind activities until 2010 is given by Bitner-Gregersen and Eide (2010). The IPCC SREX report (2011) concludes that average tropical cyclone maximum wind speed is "likely" to increase, although increases may not occur in all ocean basins. It is "likely" that the global frequency of tropical cyclones will either decrease or remain essentially unchanged. Further, there is "medium confidence" (about 5 out 10 chance) that there will be a reduction in the number of extra-tropical cyclones averaged over each hemisphere. There is "low confidence" (about 2 out of 10 chance) in the detailed geographical projections of extra-tropical cyclone activity while there is "medium confidence" in a projected poleward shift of extra-tropical storm tracks. "Low confidence" is associated with projections of small spatial-scale phenomena such as tornadoes and hail.

The recent study of Young *et al.* (2011) based on a 17-year satellite data base (1991-2008) shows, however, a clear global increase in the monthly mean, 90th-, and 99th-percentile values of wind speed for $2^\circ \times 2^\circ$ regions. The study reports that the mean and 90th percentile wind have increased by at least 0.25 to 0.5 % per year with stronger trend in the Southern than in the Northern Hemisphere, apart from the central north Pacific. At the 99th percentile extreme wind speeds are increasing over the majority of the word's oceans by at least 0.75 % per year.

4.1.3 Waves

The review given by Bitner-Gregersen and Eide (2010) identified that the global climate models in IPCC AR4 did not include wave conditions. Available studies have used statistical relationships between wave heights and sea level pressure (statistical downscaling) or the winds from the global models to run wave models (dynamic downscaling) in order to predict the future wave climate and uncertainties are related to these predictions. This situation remains.

Studies carried out before 2009 have reported increases of 0.35–1.15 m in the seasonal maxima of H_s by 2080 and of 0.2–0.8 m in the 20-year H_s in the 50-year period (2001–2050) in the northeast North Atlantic. These positive trends have also been confirmed by later studies, e.g., Dragani *et al.* (2009), Wang *et al.* (2009), and Dodet *et al.* (2010).

Several investigations have also shown an increase in extreme H_s in the North and Norwegian Sea, however, this is very regionally dependent. Grabemann and Weisse (2008) found increases in the 99 % percentile of the long-term H_s as an average over four climate model/emission scenario combinations to be 0.25–0.35 m from the present to the end of the 21st century in the North Sea. However, the range for the northern North Sea varied from 0.10 m to 0.6 m and the authors assign an uncertainty to the mean value of 0.6–0.7 m. Debernard and Røed (2008) found that the annual 99-percentiles of significant wave height increase 6–8 %, and 4 % or less in the North and

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Norwegian Seas and west of the British Isles by the end of the 21st century (2071–2100). The results indicate also more frequent strong wind and wave events in the future with higher extreme surge but high uncertainty is attributed in these estimates.

Young *et al.* (2011) have found using the 23-year (1985–2008) data base of calibrated and validated satellite altimeter measurements a general global trend of increasing values of wave height over this period, but to lesser degree than wind speed. Large regions of the north Pacific and north Atlantic show a weak negative trend (0.25 % per year), as do much of the equatorial regions of all oceanic basins. However, the southern hemisphere has a consistent weak positive trend of approximately 0.25 % per year. The 90th percentile and the 99th percentile wave height trends are progressively more positive, with the higher latitudes (greater than 35°) of the both hemispheres showing positive trends of approximately 0.25 % per year at the 90th percentile and 0.50 % at the 99th percentile. The buoy and wave model data support these conclusions.

Vanem and Bitner-Gregersen (2012) using the Bayesian-Hierarchical model and the North Atlantic C-ERA-40 data (1958–2002), have predicted an increase of the significant wave height up to $2.0\,m$ by the end of the 21st century.

Babanin *et al.* (2009) and Dai *et al.* (2010) have shown, based on the concept of "wave induced turbulence", how to improve climate change predictions by improving the upper ocean mixing modeling.

4.1.4 Sea Water Level

A new climate model (ECHAM5/MPL-OM1) considering changes of sea level due to increased CO2 in the atmosphere and developed for IPCC AR4 has been applied to simulate the climate changes under different increased CO2 scenarios (Mu *et al.,* 2010). The sea surface temperature and salinity structure, the sea level variation and the changes of sea ice in the northern hemisphere have been analysed.

The degree to which climate models (Global Climate Model, GCM, or Regional Climate Model, RCM) have sufficient resolution and/or internal physics to realistically capture the meteorological forcing responsible for storm surges is regionally dependant. For example current GCMs are unable to realistically represent tropical cyclones

According to IPCC SREX (2011) it is "very likely" that mean sea level rise will contribute to upward trends in extreme coastal high water levels in the future but they will be geographically non-uniform. Changes of sea water level remain as reported by IPCC (2007); on average up to $0.5\,m$ of sea level rise can be expected by the end of 2100 although some recent investigations seem to indicate that these numbers can be higher.

Sea level variations due to surge and tide in future climate have been investigated by several researchers, e.g. Debernard and Roed (2008), Sterl *et al.* (2009), Harper *et al.* (2009). Harper *et al.* (2009) studying tropical cyclones off the east coast Australia have shown that there is a relatively small impact of 10 % increase in tropical cyclone intensity on the 100-year storm tide.

Taking into consideration the change of the terrestrial reference frame, Collileux and Wöppelmann (2010) reported a bound of 1.2 to $1.6\,mm/year$ global sea level rise for the past century whose upper bound is slightly lower than the IPCC AR4 estimates of $1.8\,mm/year$. The geodetic requirements to improve the prediction of the sea level rise and its variability is reviewed by Blewitt *et al.* (2010). For example, Wu *et al.* (2011) have estimated the earth radius expansion rate to be $0.2\,mm/year$.

18th International Ship and Offshore Structures Congress (ISSC 2012) - W. Fricke, R. Bronsart (Eds.)

Based on global tide gauge records, Merrifield *et al.* (2009) estimated an acceleration of sea level rise since 1990 as $3.2 \pm 0.4\, mm\ yr^{-2}$, higher than the average values of 1.5 $\pm\ 0.5\, mm\ yr^{-2}$ in 1962–90. Ray and Douglas (2011) have shown the large sea-level trends of the satellite era (post-1992) may not be unique. However, Woodworth *et al.* (2011) provided evidence of a century of sea-level-rise acceleration which is still under debate (Bojannowski, 2011, Rahmstorf and Veermeer, 2011, Houston and Dean,2011). Church and White (2011) updated their earlier analysis and estimated a statistically significant acceleration of $0.009 \pm 0.003\, mm\ yr^{-2}$ and $0.009 \pm 0.004\, mm\ yr^{-2}$ since 1880 and 1900 respectively.

Gu and Li (2009) show with long-term tide gauge records that decadal sea level oscillations along the Pacific coast are significantly affected by the Pacific Decadal Oscillation with a 2–3 year lag and its variation may influence long-term trends. Menendez and Woodworth (2010) analysed worldwide tide gauge data and have shown that a trend in extreme sea levels globally is more pronounced since the 1970's. This is supported by Haigh *et al.* (2010).

Merrifield (2011) showed that strengthening of the trade wind contributed to the sea level rise of the tropical Pacific since the early 1990s. Influence of natural climate variability such as an Indian Ocean Dipole has been observed as well (Han *et al.*, 2010; Dunne *et al.,* 2011). Recent regional decadal trends are largely due to wind pattern change (Timmermann *et al.*, 2010).

4.1.5 Ice

Sea ice characteristics such as concentration, extent and thickness are considered to have a profound impact on global climate. Sea ice in the Arctic has shown dramatic changes over the last 30 years. The extent of summer ice (September) has declined by 8.9 % per decade between 1979 and 2009 and the winter ice (March) by 2.5 % per decade. September 2007 had the smallest ice extent on record (see e.g. Budikova, 2009) but although the extent and area increased through 2008 and 2009 it is likely that the total Arctic sea ice volume had its minimum in 2009. The decrease of sea ice (http://arctic.atmos.uiuc.edu/cryosphere/) and resulting unusual conditions, such as the North-East and the North-West Passage being open simultaneously for the first time in recorded history in August 2008, has raised alarm.

Some model projections predict a possible total loss of sea ice cover (at a September datum) in the Arctic around 2030 (Wang *et al.*, 2009) while other ones show seasonal ice coverage of Arctic by the end of 21st century. Recent observations indicate, however, that the simulation models under predict the Arctic ice decline (Budikova, 2009).

Golubeva and Platov (2009) based on model calculations show a significant reduction of the ice area in the Canadian waters. Stroeve *et al.* (2011) show how a range of climate models project future September ice extent in the Arctic Ocean, along with observed ice extent. Note that the models do not reproduce the historic ice data well. The study indicates that the ice cover in summer may practically disappear before 2050 (before 2020 has even been suggested by some investigations). However, an ice free Arctic winter is not predicted by any model, though the ice may be limited to first year ice and, therefore a likely maximum thickness of 2.0–2.5 m.

The EC project Developing Arctic Modelling and Observing Capabilities for Long-term Environmental Studies (DAMOCLES, 2010) suggests that the Arctic Ocean could be ice-free in summer in as little as 10 to 15 years from now, much sooner than had been predicted by most of the IPCC models.

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4.2 CFD

CFD (Computational Fluid Mechanics) methodology is getting increasing attention in modelling of water waves and it is expected that this will continue.

As opposed to the analytical description of wave fields, another approach is the discretised space and time method of Computational Fluid Dynamics. Commercially available suites with turbulence based on Reynolds Averaged Navier Stokes (RANS) methods have dominated the maritime market, but open source packages such as OpenFOAM are beginning to find some acceptance. Although the idea of the 'Numerical Towing Tank' including ship-wave interaction has been suggested for many years, CFD work requiring high power computing was typically limited to very localised flows and short time frames. Sufficient processing power is now much more affordable so that many research centres have multiple processor facilities available and limited scope studies may even be performed with desktop computers. The EU '6th Framework' project VIRTUE (www.virtual-basin.org) adopted a co-operative approach.

Typically CFD has been applied to specific fluid-structure interaction problems. There has been limited focus on the wind-wave interaction and wave propagation modelling. Wu and Oakley (2009) presented a study on the generation and evaluation of progressive regular waves with the commercial code STAR-CCM+. Virtual wave gauges at several locations in the numerical tank were compared with first and second order Stokes waves; they found that the dissipation of wave amplitude down the tank was higher than observed in experiments, but lower than had been shown by other researchers. They were able to show wave profiles that were close to 1st and 2nd order Stokes descriptions, with 2nd order fitting better for higher amplitude (steeper) waves. The behaviour of the CFD waves could have been higher order still. Denchfield *et al.* (2010) compared numerical and physical tank realisations of superposed regular wave trains with the aim of creating 'rogue' waves; success was limited, but the CFD was restricted to a laminar flow model which clearly did not capture breaking mechanisms observed in the tank. Clauss has presented several papers in this area, for example Clauss *et al.* (2008). The authors discuss methods for numerically reproducing nonlinear waves by physical tank methods with both potential flow and RANS codes. Using several different scenarios such as regular and irregular long crested waves with embedded wave packets, they show the importance of a nonlinear approach to accurately produce the desired wave and thus the fluid-structure loads.

Choi and Yoon (2009) developed an internal wave generation scheme using momentum source to produce the target waves. The scheme was applied to the RANS equation model in the CFD code FLUENT. Ko *et al.* (2011) continued the study on internal wave generation by combining the previous approach with the VOF scheme of the Lin and Liu one of 1999. The numerical experiments were applied with the aid of the CFD code Flow3D.

The application of CFD models was not restricted during the reporting period only to gravity waves. A relevant example is the work of Das *et al.* (2009) who followed numerically the generation of a tsunami wave using two different approaches, namely a RANS and a VOF method as well as a numerical model based on the so-called Smoothed Particle Hydrodynamics (SPH).

Indeed the methods for studying wave generation and propagation problems are characterized by diversity. This is manifested by the existence of alternative to CFD models. Indicative examples are the work of Kim *et al.* (2006) who developed techniques for the generation of random waves by solving the so-called mild-slope equations of

18th International Ship and Offshore Structures Congress (ISSC 2012) - W. Fricke, R. Bronsart (Eds.)

Suh *et al.* (1997) and the study of Kim and Lee (2011) that was based on the Control Volume Approach.

Despite increasing interest, RANS CFD methods cannot rival the flexibility of analytical approaches in representing high order and non-linear waves, and are therefore not favoured by the leading edge wave dynamics researchers. Neither do they yet rival the established potential flow based ship/marine structure wave response models. Nevertheless, this kind of CFD offers a conceptually straightforward way to approach the wave-structure interaction that is becoming much more accessible to the engineering community and may be the only choice for modelling particularly complicated situations.

4.3 Statistical Approaches

Publication of statistical and artificial intelligence methods especially for predicting ocean waves has accelerated over recent years. These are the so-called soft computing techniques, which do not assume any mathematical model *a priori*. Such methods are based on analysis of recent historical data, to make predictions about the future, and in this respect are dependent on the availability of recent and accurate time series estimates of the parameters concerned. By comparison dynamical models are based on predictions based on an understanding of the physics and an implementation of these into a numerical model. The publications reported work involving the application and validation of various methods for the prediction of meteorological and oceanographic parameters. Londhe (2008) provides a good summary of these methods, and a number of recent papers are summarized in this section.

Recent examples of the application of various soft computing approaches in terms of wave parameter predictions are given by Reikard and Rogers (2011), Malekmohamadi (2011), Özger (2010), Herman *et al.* (2009), Cañellas *et al.* (2010), Sylaios *et al.* (2009), and Etemad-Shahidi and Mahjoobimodel (2009), and Mahjoobi and Mosabbeb (2009). All showed reasonable success, primarily for relatively short projection periods. Golestani and Zeinoddini (2011) also showed that these methods could also accurately fill data gaps in wave parameters and also to predict wave spectra.

An interesting use of Artificial Neural Network (ANN) for transferring pressure transducer measurements to surface elevation is given by Tsai and Tsai (2009). They employed ANN to convert the pressure signal into significant wave height, significant wave period, maximum wave height, and spectral peakedness parameter using data obtained from underwater ultrasonic acoustic transducer measurements at various water depths. Their results showed that, for water depths greater than $20\,m$, the wave parameters obtained from the ANN were significantly closer to those obtained by the acoustic measurements recorded by using a linear pressure transfer function. This was not the case for wave heights greater than a significant wave height $4\,m$, but improvement was expected when the training data set contained more records with large wave heights.

Wahle *et al.* (2009) discuss work involving a novel approach to parameterising the exact nonlinear interaction source (Snl) term for wind wave spectra. They mapped discrete wave spectra directly onto the corresponding Snl-terms using a neural net (NN), training the NN with modelled wave spectra varying from single mode spectra to highly complex ones. They found that the NN approach performed well in mapping the wave spectra onto the corresponding Snl-terms, emulating the WRT-method calculations of the exact nonlinear interaction source terms for single and multi-mode wave spec-

18th International Ship and Offshore Structures Congress (ISSC 2012) - W. Fricke, R. Bronsart (Eds.)

tra with a much higher accuracy then the approximations implemented in present operational wave-models.

Delavari *et al.* (2011) used Fuzzy Inference System (FIS) and Adaptive Neuro-Fuzzy Inference System (ANFIS) methods to estimate breaking wave height and the water depth at the breaking point, finding that the ANFIS model to provide more accurate and reliable estimation of breaking wave height, compared with semi-empirical equations, but that some semi-empirical equations provided better predictions of water depth at the breaking point compared to the ANFIS model.

Aydogan *et al.* (2010) predicted vertical current profiles in the Strait of Istanbul. The used an artificial neural network (ANN) model built on thousands of hours of concurrent measurements of current profiles, meteorological conditions, and surface elevations. The model predicted 12 outputs of East and North velocity components at different depths in a given location. Predictions from the model had an average root mean square error of $0.16\,m/s$ when compared with observations. They also found good overall agreement with observations when used to predict current velocities 1–12 h into the future, and concluded that the technique can be used as a reliable tool for forecasting current profiles in straits.

Neural Networks have also been used to estimate regional and global sea level variations through the 20th century, based on long-term tide gauge records (Wenzel and Schröter, 2010). The neural network technique is used to connect the coastal sea level with the regional and global mean via a nonlinear empirical relationship, solving the difficulties with both the vertical movement of tide gauges over time and the problem of choosing the weighting function for each individual tide gauge record. Neural networks are also used to fill data gaps in the tide gauge records. The global mean sea level for the period January 1900 to December 2006 is estimated to rise at a rate of $1.56 \pm 0.25\,mm/yr$ which is reasonably consistent with earlier estimates, but no significant acceleration was detected. While most of the basins showed a sea level rise of varying rate, a mean sea level fall in the southern Indian Ocean was found. No significant trends were found for the tropical Indian and the South Atlantic, but they were the only basins to show significant acceleration. At shorter timescales, oscillations with periods of 25 years and between 50–75 years were found to be dominant and consequently there were strong rise rate correlations (but with phase lags) between the different basins.

To conclude this section, it is clear from the summary that there exists a host of soft computing techniques, with wide application although most effort appears to be focused on wave predictions. Data gap filling and short-term prediction appear obvious applications. The success of various techniques in terms of forecasts is largely only for short projection times; so it is the relatively short computation time associated with these techniques, where the major advantage over traditional, physics-based approaches lies. This would suggest an operational application, but much more experience is needed with these techniques before they could be applied in critical operational situations.

5 DESIGN AND OPERATIONAL ENVIRONMENT

5.1 Design

New designs and operational decisions must be assessed/made relative to recognised codes and standards, for which the responsible authority, perhaps a classification society or the user himself, will depend on the design and its application. To achieve recognition, an environment parameter's climatology must be demonstrated as robust

18th International Ship and Offshore Structures Congress (ISSC 2012) - W. Fricke, R. Bronsart (Eds.)

and of adequate accuracy and consequently such codes and standards may lag behind the state-of-the-art.

The majority of ocean-going ships are designed currently to the North Atlantic wave environment, which is regarded as the most severe. The traditional format of classification society rules is mainly prescriptive, without any transparent link to an overall safety objective. In 1997 and 2001 IMO has developed Guidelines for use of the Formal Safety Assessment (FSA) methodology in rule development which will provide risk-based goal–oriented regulations. Although environmental wave data and models are not explicitly used by classification society rules for general ship design they are used in rule calibration when FSA methodology is applied. For some less typical designs, classification society rules require or recommend some type of dynamic load analysis that makes use of wave climate data.

Classification rules, in fact, permit the design of ships for restricted service (in terms of geographical zones and the maximum distance the ship will operate from a safe anchorage); in which case reduced design loads apply. Many aspects of the design, approval and operation require a detailed knowledge of local weather conditions. While in principle open to all ship types, the use of such restricted service is in practice mainly confined to high speed vessels.

Unlike ship structures, offshore structures normally operate at fixed locations and often represent a unique design. As a result, platform design and operational conditions need to be based on location specific met-ocean climate. Note that Floating Production Storage and Offloading (FPSO) systems are designed for the North Atlantic wave environment if location specific wave climate cannot be proved more appropriate.

In the comparatively nascent field of operational analysis techniques, it is more frequently the responsibility of the user to select a climatology that they feel is most suitable to the task. Such decisions are taken based on a risk assessment.

5.1.1 Met-Ocean Data

Visual observations of waves collected from ships in normal service and summarized in the BMT Global Wave Statistics (GWS) atlas (British Maritime Technology, 1986) are still used for ship design and operations. The average wave climate of four ocean areas in the North Atlantic, with some correction introduced due to inaccuracy of zero-crossing wave period (Bitner-Gregersen *et al.,* 1995), is recommended by the International Association of Classification Societies (IACS, 2000) for design.

The necessity of replacing that historic, (essentially subjective) observation based wave data base for ship design with instrumentally collected (objectively measured) data bases, or by a combination of numerical and measured data, has become a subject of increasing discussion within classification societies in recent years, which has intensified because of the climate change debate. Predictions of extreme met-ocean parameters based on the new wave data bases have shown large discrepancies making still difficult reaching firm conclusions, as discussed by Bitner-Gregersen and Skjong (2011).

The offshore industry uses location specific data in specification of design and operation criteria and generally regards instrumentally recorded data as superior to model derived data. However, due to limited availability of instrumental data, hindcasts are also commonly used. Increasing attention has been given since 2009 to the uncertainties in hindcasts, and in particular to energy partitioning procedures used to separate wind sea and swell contributions e.g. Loffredo *et al.* (2009), Bitner-Gregersen

18th International Ship and Offshore Structures Congress (ISSC 2012) - W. Fricke, R. Bronsart (Eds.)

(2010). The offshore companies are following the met-ocean research findings on climate change, but as with the shipping industry there have been no changes in the standards as a consequence so far.

Since the last reporting period, both research organisations and the offshore industry have updated wind and waves hindcast data sets for several basins, within proprietary joint industry projects (see Section 2.2.3).

5.1.2 Design Environment

In the design process, international standards are followed to calculate ship structural strength and ship stability during extreme events, with an occurrence of once every 20 years - the Ultimate Limit State, ULS, corresponding to the maximum load carrying resistance. Recently, an increase in the return period to 25 years has been adopted by IMO. Checks in the Accidental Limit State, ALS, (corresponding to the ability of the structure to resist accidental loads and to maintain integrity and performance due to local damage or flooding) cover grounding, collision, and fire and explosion. An extreme weather event check is not included in ALS.

Offshore structures (including FPSOs) follow a different approach to ship structures and are designed for the 100-year return period (ULS). The Norwegian offshore standards (NORSOK Standard, 2007) take into account extreme severe wave conditions by requiring that a 10000-year wave does not endanger the structure integrity (ALS).

Long-term distributions of sea states are often employed in the prediction of met-ocean characteristics or various responses that a marine structure will experience. It is recognized that uncertainties/errors in the estimated long-term distributions often leads to gross errors in the predictions. Hence, since 2009 a lot of research effort has been put into refining models and estimation procedures of the long-term sea state description.

Joint long-term environmental models are required for a level III reliability analysis (Madsen *et al.*, 1986). A review of joint long term probabilistic modelling of wind, waves, and current and sea water level can be found in Bitner-Gregersen (2012). The joint met-ocean statistical models were originally developed for design purposes but Bitner-Gregersen (2010) has proposed a procedure allowing also application of these models to operational conditions. Utilisation of a joint fit for fatigue calculations is given by Olagnon and Guédé (2010).

Joint met-ocean models are commonly used with the environmental contour concept due to Winterstein *et al.* (1993), IFORM, (see also Haver and Winterstein, 2009; DNV, 2010) for specification of design criteria. Recently, Jonathan *et al.* (2011a) have proposed an alternative technique based on the 'Heffernan and Tawn 2004' approach to modelling conditional extremes and demonstrated its use for hindcast data from the Northern North Sea, the Gulf of Mexico and the North West Shelf of Australia. An advantage of this technique is that it does not depend on an a priori model for the joint distribution, it can easily be extended to multi-dimensions (e.g., Jonathan *et al.*, 2011a), and it offers flexibility in the specification of the form of the probability contours (Jonathan *et al.*, 2011a). Comparison with the IFORM concept and a discussion of uncertainties related to both approaches needs still further investigations.

In Hagen *et al.* (2010) wave storm history combined with Weibull distributed wave heights was used to derive the long term CDF of wave heights acting on an offshore structure.

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Since 2009 increasing attention has been given to directional effects and combined seas (see Bitner-Gregersen, 2011; Loffredo *et al.*, 2009). Consensus has still not been reached within the industry concerning directional criteria. For reliability calculation the Forristall procedure is recommended to be used by DNV RP-C205 (2010).

Effort continues relentlessly in the quest to reduce the uncertainties associated with the estimation of extreme environmental parameters for design, mainly through improvements in the extremal modelling. In recognition of this, Mackay (2011) proposes a method for correcting bias in return values of wave heights caused by hindcast uncertainties. Gibson *et al.* (2009) demonstrate uncertainties related to extreme crest predictions. Forristall (2011) has proposed a procedure for correction of extreme wave crest due to spatial variability of seas surface in a sea state. Applications for design are reported by e.g. Bitner-Gregersen (2011).

Jonathan and Ewans (2011a) describe the application of a spatial model for establishing extreme wave conditions in the Gulf of Mexico. The model allows for dependency between adjacent locations and allows for a natural variation of the extremes in space. It is an alternative, and perhaps a superior approach, to site averaging in which data from surrounding locations are pooled on the assumption that the extreme climate is homogeneous over the pooling space.

Recognition of the consideration of the spatial variation in extreme value analysis is an example of the need to consider covariates when performing analysis. The importance of this with specific examples for seasonality is shown by Jonathan and Ewans (2011b) and is also emphasized by Menéndez *et al.* (2009).

Vanem and Bitner-Gregersen (2012) suggest how to link the Bayesian hierarchical space-time model allowing projections of future climate changes to a joint met-ocean model.

The Peaks Over Threshold (POT) method is probably the most widely used approach to calculating extremes, for which the Generalized Pareto Dstribution (GPD) asymptotic distribution. A problem with the method is the need to set a threshold which needs to be high enough in order to justify use of the GPD, but low enough so that enough data remain for analysis. This is discussed by Mazas and Hamm (2011). MacDonald *et al.* (2011) describe an extreme value mixture model combining a non-parametric kernel density estimator with an appropriate tail model. Thompson *et al.* (2009) propose an automatic approach to threshold selection. Næss (2011) recommends using the upcrossing rate methodology instead of POT in design.

Mackay *et al.* (2011) evaluate the performance of several estimators for the parameters of the GPD from Monte Carlo simulations and conclude that the likelihood-moment (LM) estimator is close to the lowest bias and variance over a wide range of sample sizes investigated.

Gaussian models to describe met-ocean phenomena are still used in applications. If the observed Probability Density Function (PDF) differs significantly from the Gaussian model then some researchers transform the data so that the observed CDF matches the transformed Gaussian CDF, see e.g. Azaïs *et al.* (2011a) and references therein. An application of such an approach for the estimation of extreme responses of a container ship is presented in Mao *et al.* (2012). Another interesting approach to compare more complex properties of waves with those predicted by an adopted model is presented in Ortega *et al.* (2011).

For design for ice operations, satellite Earth Observation (EO) are expected to being play a more and more important role in the future as discussed by Partington *et al.*

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(2011). Adoption of the International Standards Organization (ISO) standard number 19906 – Arctic Offshore Structures standards for cold regions, which has a probabilistic approach, requires quantification of ice environment behaviour in probabilistic maner.

ISO 19906 presents recommended procedures on protection of people, environment and property when operating in polar conditions. The standards were developed by the ISO Technical Committee 67 (TC67), Sub-Committee 7 (SC7 – Offshore Structures), Working Group 8, and approved by ISO member countries in December 2010. Spring *et al.* (2011) present history of standards development, editing and review process as well as its acceptance by ISO and participating members. ISO 19906 standards constitute unification and harmonization of existing local national codes into a single international standard.

Moslet *et al.* (2011) present ISO 19906 related projects at DNV in Norway. DNV is managing two related JIP projects, Barents2020 and IceStruct. The Barents2020 project focuses on Russian-Norwegian development of common rules for safe exploration in the area of Barents Sea; the goal of the IceStruct project is to help a non-specialist designer to comply with the normative provisions of ISO 19906 and address design issues not covered by the standard.

5.1.3 Design for Climate Change and Rogue Waves

To be able to design for climate change time-dependent statistical descriptions need to be adopted. Statistical extreme value analysis, as currently used in the met-ocean community, has to be upgraded to take into account the non-stationary character of current climate, in terms of both climate change trends and natural variability cycles. These changes need to be incorporated in the risk based approach used currently in design as proposed by Bitner-Gregersen and Eide (2010).

The marine industry has initiated studies on potential impact of climate change on design of marine structures, e.g. Bitner-Gregesen *et al.* (2011), Bitner-Gregersen and Skjong (2011), Vanem and Bitner-Gregersen (2011); others still not publicly available.

Observed and projected changes in waves and wind climate are expected to have the largest impact on marine structure design in comparison with other environmental phenomena. Changes in sea level combined with storm surge have little potential to affect ship design directly but may impact offshore and coastal installations, depending on how significant they are. Secondary effects, such as changes in sea level range, harbour depths and offloading heights may need to be taken into account. The predicted increase in marine growth may increase loads on marine structures in some ocean regions, e.g. the Baltic Sea.

It is also important to be aware that changes, like increase in storm activity (note intensity, duration and fetch) in some regions (still low confidence in these projections, IPPC, 2011), may lead to secondary effects such as increased frequency of occurrence of extreme wave events. The frequency of occurrence of combined wave systems like wind sea and swell/swells may increase also in some ocean areas due to the increase of storm intensity and change of storm tracks. This may consequently lead to more frequent extreme events (Toffolli *et al.,* 2011).

The risk associated with rogue waves has attracted the attention of the shipping and offshore industry, which has recently initiated two international research projects: the JIP project CresT (Cooperative Research on Extreme Seas and their impact) coordinated by MARIN in The Netherlands, and its second phase ShortCresT, and the EC project EXTREME SEAS (Design for Ship Safety in Extreme Seas) coordinated

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by DNV of Norway. Rogue waves are not explicitly included in classification societies' rules and offshore standards today due to lack of consensus about their definition and probability of occurrence.

Some recent investigations regarding probability of occurrence of extreme and rogue waves e.g. Baschek and Imai (2011), Rozhkov (2009), Bitner-Gregersen and Toffoli (2012) seem to indicate, however, that rogue waves may need to be considered by ship and offshore standards; although further investigations are still called for to reach firm conclusions.

5.2 Operations

Marine operations require more detailed description of sea state variability than long-term sea state distributions used for design can provide, e.g. optimal ship routing Mao *et al.* (2010a), estimation of variance in accumulated fatigue damage Mao *et al.* (2010b), construction of warning systems for high sea levels, extreme waves and planning of marine operations. These applications use correlations between sea state parameters at different locations and moments in time. Such information is often a part of spatio-temporal models of sea state variability.

Signing of the delimitation treaty between Norway and Russian Federation in September 2010, has opened new opportunities for the shipping and offshore industry in the Barents Sea and brought the need for further research of met-ocean and ice conditions in the Arctic regions.

5.2.1 Planning

The EC SAFE OFFLOAD project has proposed a procedure utilising information about wind sea and swell in specification of a risk-based approach for safety of offloading operations from the LNG terminals to shuttle gas tankers.

McGonigal *et al.* (20011) show results of JIP investigating the presence of EIFs (Extreme Ice Features) in the area between Ellesmere Island and Prince Patrick Island. The data was collected in August 2008 from satellite images. Roughly 200 EIFs were identified, including 40 ice islands, 93 ice island fragments and 67 multi-year hummock fields. Ice island fragments were defined as less than 1 km in the longer dimension, ice islands had an average diameter between 1.6 and 5.2 km, and multi-year hummock fields between 1.7 and 13.8 km.

Mudge *et al.* (2011) analysed Canadian Ice Service (CIS) records from 1982 to 2010 and studied two passages of Viscount Melville Sound (VMS) by CCGS Amundsen in order to assess feasibility of navigation if Canadian Arctic. The authors observed a high degree of spatial and temporal variability in ice conditions in the area of Northwest Passage with large seasonal variations. The study indicates the importance of timely and accurate ice information in making the Northwest Passage feasible for trade as numerical models are not inaccurate.

5.2.2 Warning Criteria and Decision Support Systems

Several authors have studied relations between spectral parameters and occurrence of extreme or rogue waves and the topic is also investigated in the EC EXTREME SEAS project. Mori *et al.* (2011) have used Monte Carlo simulations on the Nonlinear Schrödinger equation in two horizontal dimensions and found that increasing directional spread decreases kurtosis, a parameter accepted to be related to higher probability of rogue wave occurrences. On the other hand Toffoli *et al.* (2011b) found

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higher kurtosis values when analysing waves in bimodal sea states, with higher occurrences when directional differences were between 20 and 40 degrees.

The distribution of encountered wave slope was used to predict risks for capsizing of vessels, see Leadbetter *et al.* (2011) and Åberg *et al.* (2008) for the theoretical background of the method.

The development of decision support systems remains in focus. As proposed by Nielsen *et al.* (2011) and Nielsen and Jensen (2011), they require the collection of relevant data e.g. met-ocean, ship response, on board. These types of data can also be used for self learning (see the EC project NavTronic for example).

Search and Rescue operations require specific decision support systems. Their planning relies on accurate forecasting of the drift of objects under search. The most widely used approach for drift assessment is based on the Leeway method in which Leeway coefficients taking into account combined action of wind and waves are experimentally identified for various classes of objects allowing assessment of drift velocity and direction as a function of wind speed. Breivik *et al.* (2011) propose a standardised method for assessment of Leeway coefficients from field experiments. Uncertainties in forcing fields (wind and currents) as well as other information such as initial date and location of the drift are accounted for when introducing a stochastic approach used a on MonteCarlo technique for the computation of an ensemble of equally probable perturbed trajectories (Breivik *et al.*, 2008).

Accuracy of drift prediction is highly dependent on the quality of the forecasting of environmental data. It was pointed out during the 4th International Workshop on Technologies for Search And Rescue and other Emergency Marine Operations (2011, Brest, France) that the use of HF-radar and Lagrangian floats (SLDMBs) data for assimilation or correction of current can provide efficient improvement of the accuracy of the drift prediction.

Iyerusalimskiy *et al.* (2011) present state-of-the-art ice load monitoring and alarm system that was installed on a large icebreaking tanker operating between the Barents Sea and Murmansk. The system is designed to measure and record in real time the ice pressure and loads and calculates structural responses in selected locations on the hull.

6 CONCLUSIONS AND RECOMMENDATIONS

Accuracy of wind and waves hindcast data bases for several ocean basins has been improved since 2009. The issue of met-ocean data ownership remains a general problem. Whilst the advantages of having data freely available to academia and industry are clear, the commercial sensitivity of some data sets is recognised. However, it is possible for organizations to make data available without compromising their confidentiality. An example of this is the SIMORC URL data base administered by the University of Southampton, as noted in the last Committee report.

Owing to many research efforts, the occurrence of rogue waves, their mechanism, and detailed dynamic properties are now becoming clear. The state of the art development on rogue waves are well summarised at three Rogue Wave Conferences, held in 2000, 2004, and 2008 by Ifremer, and the publications reviewed in Section 3.2. Consistency between numerical models and experimental data has been documented. The focus is now on forcing terms like wind and current and wave breaking that are not typically included.

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Despite recent achievements, consensus on the definition of rogue waves and particularly their probability of occurrence has not been reached yet. Such consensus, however, is essential for the evaluation of possible revision of offshore standards and classification society rules, which currently do not include rogue waves explicitly. The Norwegian offshore standards take into account severe wave conditions by requiring that a 10000-year wave does not endanger the structure integrity (Accidental Limit State, ALS). But it still lacks guidelines for model predictions of extreme and rogue waves and design scenarios to be included in a possible ALS procedure. Recent investigations seem to indicate that rogue waves may well need to be considered by ship and offshore standards. However, further investigations regarding the probability of occurrence of rogue waves and their impact on marine structure responses are still called for before firm conclusions can be drawn.

Attention has been given to accounting for directional effects, modelling of wind sea and swell, seasonality, spatial and non-stationary statistics and their applications in design. The importance of these effects on extreme met-ocean statistics has been demonstrated.

With the increase of offshore wind energy installations, reliable forecasts of the order of hours or minutes are also becoming increasingly important since the complex electrical networks are sensitive to large fluctuations, which may occur at the onset of a storm. In addition, more information on the wind profile in the lower atmospheric layer is needed for the design and analysis of these structures. Long-term trends, not only in the occurrence of extreme events but also other statistical properties will remain an important research topic in wind analysis in forthcoming years.

On a positive note for the marine community is the emergence of potential opportunities for seasonal shipping on the Northern Sea Route, the Northwest Passage and a potential Transpolar Route, improving access to many offshore resources in the Arctic region. On the negative side, the increased intensity of tropical cyclones has caused devastating damage to the offshore industries in the Caribbean in the past 8 years; the link with the warming climate is debatable but if so these effects would be anticipated to continue as warming continues. The observed trends and projected climate changes indicate that significant impact on marine structure design may be expected for some locations. It is noted that there is large uncertainty associated with the projections.

Extreme value estimates of wind and waves needed for design work may be more affected by climate changes than the average values although there are some examples where they were less affected. Not many publications are written from the viewpoint of the designer; too often they focus on too low return periods.

Economic markets and environmental changes in northern areas give projections of further and progressive availability of Arctic seas. Decreasing ice cover extent and thickness will allow pioneers to operate closer to calving glaciers but also increases the probability of encountering icebergs, bergy bits and other ice formations in areas where they were not previously experienced.

6.1 Advances

Utilisation of wave information collected by satellites in wave models has increased significantly through the GlobWave project initiated by the ESA in 2008. Access to wind and waves remote sensing data bases has improved.

A major improvement of wave models based on the radiative transfer equation (RTE) is the development of new modified wind input and wave dissipation functions (for

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breaking) based on more physical description of the transfer mechanisms. A common parameterisation of breaking wave height distribution which may be used from deep to shallow water has been proposed. Exclusively non-stationary models such as WAM and WAVEWATCH-III have been pushed closer to shore.

The knowledge of extreme and rogue waves has significantly advanced since 2009 and the nonlinear dynamics of surface gravity is now reasonably understood. The predictions made by theoretical and numerical models compare well with experimental results. New investigations include the effect of current and wave breaking. Indirect evidence on the specific meteorological conditions leading to the formation of narrow directional wave fields has been shown.

Significant progress has been made on development of spatial and temporal models. Recognition of the need to consider covariates when performing extreme value analysis has been shown.

The increased use of renewable energy sources, especially offshore wind energy, has triggered many new research activities. With the limited number of profitable locations came a trend towards higher structures up to some two hundred metres. But it is not the wind energy industry alone that focuses on more accurate wind data in lower layers of the atmosphere; both academia and others industrial sectors are also interested in it. The trends in the development of new sensors and data acquisition techniques are expected to continue.

As the effects of global warming have been closely monitored, results from a variety of local and remote ice measurements are available, ranging from satellite data on the extent of ice, ice thickness from moving vessels to various mechanical properties obtained from ice probes.

The observed trends and projected climate changes have been used to demonstrate their impact on marine structure responses.

6.2 Recommendations

The need for improving the availability, quality and reliability of met-ocean data bases was reported by the previous Committee. This situation is unchanged, and any effort to address this concern is recommended. Further utilisation of remote sensing data by the marine industry should continue.

The importance of including wave breaking and external forcing (wind) when modelling rogue waves requires increasing attention. Detailed investigations of meteorological and oceanographic conditions in which extreme and rogue waves occur together with analyses of field wave time series (uncertainty due to sampling variability may be a problem here) are needed to reach a consensus about probability of occurrence of rogue waves; this being mandatory for evaluation of possible revision of classification society rules and offshore standards. Further, a consistent approach combining new information about extreme and rogue waves in a design perspective needs to be proposed.

Focus needs to be given to properly accounting for directional effects in design, assuring consistency between omnidirectional and directional criteria, to seasonality, spatial and non-stationary statistics as well as modelling of wind sea and swell for design and operational purposes.

Work on enhancing safety at sea through specification of uncertainties related to the environmental description should continue. The shipping industry lags the offshore industry in these studies but has made significant progress since 2009. Further development of decision support systems should support this work.

The 2012 ISSC I.1 Committee recognises the significance of the IPCC (2007, 2011) findings and the conclusions drawn by the Panel. However, as pointed out by the IPCC Panel (2011), there are still significant uncertainties associated with climate change projections making it difficult to drawn firm conclusions. Reducing these uncertainties requires attention. The adaptation process to climate change should continue by the shipping and offshore industry. The projected climate changes open new opportunities for Arctic development and challenges when shipping the goods to main economic centers. To take advantage of these opportunities new technologies will be required to safely operate in polar ice environments which need to be based on reliable met-ocean and ice data, and models.

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09-13 SEPTEMBER 2012
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VOLUME 1

COMMITTEE I.2

LOADS

COMMITTEE MANDATE

Concern for environmental and operational loads from waves, wind, current, ice, slamming, sloshing, weight distribution and operational factors. Consideration shall be given to deterministic and statistical load predictions based on model experiments, full-scale measurements and theoretical methods. Uncertainties in load estimations shall be highlighted. The committee is encouraged to cooperate with the corresponding ITTC committee.

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KEYWORDS

Ships and offshore platforms, cables and risers, damaged ship structures, wave loads, slamming and springing, sloshing, ice loads, fatigue loads, design waves, hydroelasticity, CFD, model and full scale tests, uncertainties.

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CONTENTS

18th International Ship and Offshore Structures Congress (ISSC 2012) - W. Fricke, R. Bronsart (Eds.)

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1 INTRODUCTION

The content of this committee's report is dictated by its mandate, as well as the expertise of its membership. Its structure and content follow along similar lines to those adopted in previous ISSC reports (e.g. ISSC 2009). Wave-induced loads on ships are dealt within two different sections, namely 2 and 3. Section 2 focuses on two- (2D) and three-dimensional (3D) methods, dealing with linear and nonlinear methods and including applications of the so called CFD (Computational Fluid Dynamics) methods. Section 3 reviews specialist topics such as slamming and green water loads as well as loading on damaged ships. Wave-induced loads on offshore structures are reviewed in sections 2 and 4, the former dealing with single and multi-body interactions, including a note on the effects of current and bathymetry. On the other hand section 4 focuses on specialist topics, such as cables and risers, vortex-induced vibrations (VIV), offshore lifting and installation and submersibles. As with previous reports, current state of progress in short- and long-term predictions and fatigue loads is examined, focusing on applications to ships and offshore structures. Finally, uncertainties in experimental and full-scale measurements and computational methods are discussed.

2 COMPUTATION OF WAVE INDUCED LOADS

2.1 Zero Speed Case

2.1.1 Body Wave Interactions

Traditionally the prediction of wave loading of zero speed body wave interactions has been based on potential flow solutions (ISSC 2009). Consideration of viscous effects has been commonly restricted to specific problems such as, the calculation of slow drift motion of offshore structures, the evaluation of rolling response close to the roll resonance of ships or barges or the evaluation of the resonant motions of the confined fluid between side-by-side arrangements of floating bodies.

Pescoa *et al.* (2011) presented an experimental investigation of the first and second order wave exciting forces acting on a body of simple geometry subjected to long crested irregular waves. The body is symmetric about the vertical axis, like a vertical cylinder with a rounded bottom, and it is restrained from moving. Second order spectral analysis was applied to obtain the linear spectra, coherence spectra and cross bi-spectra of both the incident wave elevation and of the horizontal and vertical wave exciting forces. The linear and quadratic transfer functions (QTF) of the exciting forces were obtained from the analysis of irregular wave measurements. The results have been compared against experiments in bichromatic waves and with numerical predictions from a second order potential flow code. Whereas the agreement of the experimental and numerical results was shown to be satisfactory for the linear forces, it was concluded that the measured wave exciting forces include a significant non linear contribution for the low frequency range.

Recent research results have been presented in the area of bottom founded structures (e.g. single or multi-array cylinders, wind turbine foundations, gravity support structures (GBS) etc.) show a trend toward the use of CFD simulations and approximate nonlinear diffraction models. For example, Morgan and Zang (2010) investigated the use of the open source CFD software suite OpenFOAM for the simulation of focused wave packets interacting with a vertical bottom mounted cylinder. Wave elevation in the vicinity of the cylinder was compared to experimental data. In a parent paper, Zang *et al.* (2010), investigated the higher-order diffraction effects on the loading and demonstrated that the method leads to reasonable agreement with experiments.

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Bredmose and Jacobsen (2010) reported investigations on a typical bottom-mounted offshore wind turbine foundation, also using the OpenFOAM suite. In this study special emphasis was attributed to the wave generation process. The fluid loading obtained from the CFD calculations was compared to results given by a combination of the 'Wheeler stretching technique' for the incident wave kinematics, and 'Morison equation' for the fluid loading. Comparisons between empirical and computational results were shown to be satisfactory. Roos *et al.* (2009, 2010) reported on the experimental study of wave impacts on elements of a GBS composed of submerged storage caissons combined with four surface piercing vertical cylinders, in relatively shallow waters. The authors indicate that larger impact loads to those measured on the underside of the deck (e.g. wave in deck impact loads, loads on vertical columns etc.) may be recorded successfully.

The recent expansion in the market of Floating Offshore Installations (FOIs) has introduced the need to direct research towards understanding the effects of varying water depths and associated high frequency responses of such structures in waves using advanced methods. For example, Johannessen (2011) revisited the problem of the high frequency resonant response of offshore structures in irregular waves, using approximate nonlinear diffraction models. The author concluded that provided the incident wave spectral properties are carefully represented, such models allow for a good representation of the resonant response of stationary large offshore structures. Yan *et al.* (2010) conducted fully nonlinear analysis of a moored FPSO vessel in shallow water waves using the Lagrangian-Eulerian finite element method. Investigations were also carried out on the effects of water depth on forces and wave run-up. The numerical results suggest that the induced forces decrease. However, the nonlinear components may be more significant as the water depth decreases. Lee and Kim *et al.* (2010) calculated motions of two floating bodies (FSRU and LNGC) in shallow water. The authors concluded that whereas the horizontal surge motion is significantly affected by the wave deformation, the surge motion is considerably amplified in low frequency waves by nonlinear wave-wave interactions.

Park *et al.* (2010) studied the motions and loads of a LNG-FPSO considering the effects of sloshing. The methodology is based on a coupled model of sloshing and motion in the time domain. It was confirmed that the sloshing impact pressure depends on the wave period, the number of filled tanks and the tank filling level. Ryu *et al.* (2010) studied sloshing loads in partially filled LNG tanks for an FLNG at different headings and sea states. They described the effect of wave heights on the sloshing loads, especially for partially filled LNG tanks.

2.1.2 Effects of Varying Bathymetry

When shallow water operation is considered, the influence of the seabed bathymetry variation on the loads acting upon the floating body needs to be examined. De Hauteclocque *et al.* (2008) presented a method to eliminate the interference caused by the wave reflection on the boundaries of the truncated bathymetry using the classical diffraction theory. Their method applies semi-transparent panels to the region of the bathymetry boundaries. The radiation coefficients were compared with those obtained when only an opaque bathymetry is considered. The wave kinematics calculated by the diffraction code were compared to those obtained by a shallow water code based on Green-Naghdi theory. The study concluded on good comparisons against semi-analytical solutions (e.g. GNWave) of wave kinematics along a slopped seabed. Further numerical studies for the case of a barge floating over a horizontal bathymetry

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and for a LNG over a slopped seabed demonstrated that the interference effect of variable bottom on the wave loads may be important.

Molin *et al.* (2010) and Liu *et al.* (2011) addressed the problem of determining apriori whether the shoaling of the accompanying long wave to an irregular wave system may lead to significant corrections with regards to the flat bottom model. These studies assume that the bathymetry is constrained in way of a constant depth zone that is followed up by a rectilinear ramp. The authors compared their results with those of a flat bottom. It was concluded that low frequency second order loads are strongly reduced as compared to their flat bottom reference values.

Athanassoulis *et al.* (2009) studied the problem of transformation of the spectrum of an incident wave system over a region of strongly varying bottom topography within the context of linearity. This work focused on cases where the typical wave length and the characteristic length of the bottom profile variations are comparable and the waves propagate in intermediate-to-shallow water depth. It was concluded that the approach permits the consistent transformation of the full incident wave spectrum over variable bathymetry regions and the calculation of the spatial evolution of point spectra of all interesting wave quantities at every point in the domain. Belibassakis (2010) presented a nonlinear hybrid domain decomposition method with application to the problem of roll response of ship-hull sections of general shape floating in general bathymetry regions. The idealisation is based on a BEM for the representation of the nonlinear potential wave motion around the floating body and a vortex particle method for the generation of vorticity in way of the boundary layer. Results of reasonable accuracy are presented. It is concluded that in those cases where the viscous effects associated with boundary layer separation may be significant, mixing of boundary integral and particle methods may be useful in the evaluation of ship-hull characteristics in rolling motion.

Ferreira *et al.* (2009) discuss the importance of modelling the effects of significant variation in bottom depth along the length of large LNG carriers. In this work, comparisons between simplified and advanced numerical models idealising in detail the bathymetry changes due to a sloping bottom in way of the ships' parallel body are generally speaking small. Hence, reasonable estimates of the heave and pitch motions were obtained using the average depth along the length of the ship. The authors concluded that differences in depth at the bow and stern do have a substantial effect on the cross-coupling coefficients. Thus, the phases of the heave and pitch motions and associated loads are not as well approximated by computations assuming constant depth.

De Hauteclocque *et al.* (2010) formulated a radiation - diffraction theory to calculate the wave kinematics, motions and loads of a floating body in areas of varying bathymetry. The method presented could be useful in the context of LNG terminals where the depth is quite shallow and the bathymetric variations significant. The bathymetry is modelled as a second body. A modified formulation of the BEM is introduced to model accurately the opaque bathymetry. Numerical results are shown to be satisfactorily compared to a 3D shallow water code based on Green-Naghdi theory. The differences with the constant depth calculations are shown to be significant, due to the modified incident wave field, modified added mass and radiation damping terms. More recently, Pinkster (2011) also addressed the same problem by introducing a modified diffraction method based on a multi-domain approach capable of handling different water depths in each domain. In this work it is shown that the multi domain approach can also be used for subdividing large domains.

2.1.3 Multi-body Interactions

Multi-body hydrodynamics became a relevant topic of research over the last years as the offshore activities grow and diversify. Many of the developments have been motivated by the operation of side-by-side, or tandem, offloading of LNG from the floating production unit to a shuttle tanker. Other examples of multi-body systems include the classical problem of multiple surface piercing vertical cylinders, very large floating structures and wave energy converters. The calculation of the hydrodynamic interactions is important in order to assess the operability of the coupled systems, estimate the loads on the structure and on the mooring lines (e.g. lines connecting the bodies and on the articulations). The current practice is to use frequency domain potential flow linear BEM to calculate the wave-body interactions. For computational economy the Higher Order Boundary Element Method (HOBEM) is preferred for multiple bodies. If nonlinear mechanical interactions need to be included, frequency domain results are used to calculate hydrodynamic linear impulse response functions. The equations of motions and loads are consequently solved in the time domain by combining linear and nonlinear forces. There are specific problems which require nonlinear hydrodynamic methods (e.g. resonant free surface motions in a narrow gap between two fixed or floating structures).

Lewandowski (2008) presented a systematic investigation of the hydrodynamic coefficients, free surface elevation and motions of two side-by-side rectangular barges. The author confirms that standing waves between the hulls occur at critical frequencies and they may have a significant effect on the hydrodynamic forces and loads. Different methods to reduce the standing wave elevations have been proposed as reported by ISSC I.2 (2009). However, some energy dissipation in the form of a damping term, must be assigned by the analyst. Since the loading calculations of moored floating structures often need to be carried out in the time domain, the author discusses the effects of the critical frequencies on the floater motions by memory functions. Such functions become inherently lightly damped, which leads to truncation errors in the evaluation of the convolution integrals. Bunnik *et al.* (2009) proposed a variation of the damping lid method introduced by Chen (2005) to reduce the unrealistically high resonant wave elevations between two floating structures positioned side-by-side. The damping lid method was chosen as it adds some damping to the free surface between the vessels. The results from the new method were compared with experimental data for two similar LNG ships in head regular waves. It was concluded that the new approach compares well with available experimental data for the in-gap wave motion and the wave induced drift forces.

Kristiansen and Faltinsen (2009) applied 2D linear and nonlinear BEM to investigate the pumping mode induced by incoming waves on an LNG carrier berthed near a gravity based structure in shallow waters. The results were compared with experimental data to conclude that both the linear and nonlinear predictions overestimate the resonant free surface elevation, although nonlinear results are closer to the experiments. In a more recent publication from Kristiansen and Faltinsen (2010) the flow separation of bilge keels was modelled by an inviscid vortex tracking method. It was concluded that while the nonlinear free surface effects have a small effect on the resonant free surface elevation prediction, the damping effect from the flow separation is large and in fact the predictions of the complete nonlinear model are quite good.

A 2D viscous flow numerical method has been applied by Lu *et al.* (2010a, 2010b) to calculate the wave motion in the narrow gap between rectangular cross sections, restrained from moving when subject to harmonic waves. In this work the Navier-Stokes

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equations are solved with a finite element method, while the free surface is captured with a VOF method. The viscous flow results are compared against experimental data for the wave elevation in the gap showing good agreement. It is concluded that a 2D linear potential flow method is able to predict correctly the resonant frequencies but overestimates the free surface elevation amplitudes.

Hansen *et al.* (2009) presented an analysis of the motions, mooring lines and fender forces on two LNG carriers moored side-by-side in irregular seas and shallow water. The motions are calculated in the time domain accounting for the nonlinear mooring effects, while the multi-body hydrodynamic problem is solved with WAMIT. The Boussinesq wave model is applied to simulate the irregular sea states in shallow water. The comparisons with experimental data show good agreement for the first order motions and reasonable agreement for the forces on the mooring lines and fender connecting the ships. On the other hand, de Wilde *et al.* (2010) presented an experimental investigation with scaled models of the LNG stern-to-bow offloading with a shuttle tanker behind a weather vaning platform in irregular waves, wind and currents. Different options were assessed, namely passive tandem mooring, taut hawser and full dynamic positioning (DP). It was concluded that the DP shuttle tanker option significantly reduces the relative motions between the vessels.

The operability of the LNG offloading with tandem configuration can be assessed with the support of commercial computer codes. For example, Wang *et al.* (2010) used the software ARIANE 7.0 to carry out a systematic investigation of the time domain responses of a floating production platform and a tanker in tandem configuration. Clauss *et al.* (2009) presented an LNG transfer system based on new flexible cryogenic pipes where the shuttle tanker is towed between the mooring wings of a turret moored platform. The system was analyzed with WAMIT and related impulse response functions and with AQWA in the time domain, to calculate the relative motions and mooring forces. Excellent operability in the North Sea environment was reported. Brake *et al.* (2009) proposed to separate the floating LNG production platform in two vessels, the first for the production, process and storage of crude oil and the second for the storage of LNG and LPG. The vessels were moored with spread lines and connected with a yoke system in a tandem configuration. The relative motions and forces on the mooring lines were calculated with WAMIT for the multi-body hydrodynamics and OrcaFlex for the nonlinear coupled mooring analysis.

Within the reporting period new linear and nonlinear methods have been proposed to calculate the hydrodynamic interactions between vertical cylinders. Siddorn and Taylor (2008) presented an exact algebraic method to solve the diffraction and radiation of linear waves by arrays of independently moving truncated cylinders. This method is an alternative to BEM and since it does not require discretization of the boundaries, the solution is fast. Mavrakos and Chatjigeorgiou (2009) solved the second order diffraction problem of two concentric surface piercing cylinders subjected to harmonic waves with a semi-analytical formulation. Wang and Wu (2010) applied a finite element method to calculate the potential flow fully nonlinear interactions between incident waves and arrays of fixed cylinders in a numerical tank. At each time step the FEM was used to determine the velocity potential and then a finite difference method was implemented to calculate the velocity of the free surface and track its movement. A structured mesh was used near the wave maker. This was combined with an unstructured mesh around the cylinders.

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2.2 Foreword Speed Case - Overview of Methods

A large variety of different nonlinear methods for the forward speed problem have been presented in the past three decades. One may distinguish between methods based on potential theory and those solving the Reynolds-Averaged-Navier-Stokes (RANS) equations. The majority of methods for ships at forward speed still belong to the first group. Within this group there is a large variety of methods ranging from linear theories to fully nonlinear methods. Between these two extremes there are many partially nonlinear, or blended, methods, in which one aims at including the most important nonlinear effects. As per ISSC 2009 in the subsequent discussion these methods are classified using 6 different levels namely: Level 1(linear); Level 2 (Froude-Krylov nonlinear); Level 3 (Body nonlinear); Level 4 (Body exact - weak scatterer); Level 5 (Fully nonlinear - Smooth waves) and Level 6 (Fully nonlinear).

2.2.1 Level 1: Linear Methods

In linear methods, the wetted body surface is defined by the mean position of the hull under the corresponding position of the free surface where the free surface boundary conditions are applied. The hydrodynamic problem is solved in the frequency domain by either 2D, 2.5D or 3D idealisations. One may distinguish between three levels of refinement in representing the steady flow field when the equation system for the unsteady flow is established. Those are:

- The Neumann-Kelvin (NK) method where the base flow is approximated by a uniform flow with velocity equal to the ship speed (U).
- The Double-body (DB) method where the base flow is approximated by the flow obtained when a mirror condition is imposed on the plane defined by the mean free surface.
- The Complete method where the complete steady flow, including the steady wave elevation, is used.

In problems with low speed and relatively high frequencies, the interaction with the steady flow in the Free-Surface Boundary Condition (FSBC) can be neglected and the only interaction appears as a U-term in the Body Boundary Condition (BBC). The solution of the boundary value problem can then be divided into a zero-speed solution and correction due to the forward speed. Such a speed correction approach is used in the classical strip theory (Salvesen *et al.*, 1970) and it is also quite common in 3D methods. One example is the so-called pulsating-source (PS) Green's function methods.

A recent comparison of frequency-domain 3D Green's function methods based on pulsating source (PS) and translating-pulsating source (TPS) is presented by Chapchap *et al.* (2011a). The authors studied the heave and pitch motions of the S175 container ship at Froude number 0.2 - 0.275 in head regular waves. The PS method produced better results than the TPS for this case; a trend that has also been observed for other hull forms at relatively high Froude numbers (Bailey *et al.*, 1999). The forward speed Green's function is significantly easier to evaluate in time-domain than in frequency domain, and many linear 3D methods utilise this fact. For example, Datta *et al.* (2011) have increased the robustness and the overall efficiency of the method of Datta and Sen (2007) to enable calculation of motions of fishing vessels. The simulations were compared with results from the 3D WAMIT code (Korsmeyer *et al.*, 1988) and a strip theory code for the zero-speed and forward-speed cases, respectively. The method compares generally well with WAMIT for zero speed

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for 3 fishing vessels, while the agreement with strip theory varies depending on the Froude number (in the range 0 to 0.42) and the hull form.

A systematic study of the influence of various degrees of refinement in the modelling of the forward speed-effects has been presented by Zhang *et al.* (2010). The authors compared hydrodynamic coefficients, excitation forces and heave and pitch motions calculated by three interaction scenarios between (a) uniform flow in BBC and FSBC (Neumann-Kelvin method) (b) double-body (DB) flow in BBC and uniform flow in FSBC and (c) DB flow in BBC and in FSBC (Double-body method). Comparisons against experimental measurements were carried out for the Wigley I hull of Journee (1992) at Froude number 0.3 and a Series 60 hull at Froude number 0.2 (Gerritsma *et al.*, 1974). It was concluded that for the hydrodynamic coefficients, A35, A53, A55 and B55, including the DB-flow in the BBC gave the most significant improvement. For B35, including DB-flow in the FSBC was the most important, while for B53, including DB-flow in BBC and in FSBC were of almost equal importance. For the excitation forces, the effect of including the DB-flow was small. For heave and pitch motions the double-body method produced significantly better results than the Neumann-Kelvin method.

In order to accurately compute the m-terms, involving interactions between the base flow and unsteady flow fields in the BBC, Qiu and Peng (2007) introduced a panel-free method for frequency domain forward speed problems. More recently, Peng and Qiu (2009) have applied their method to the Wigley III monohull of Journee (1992) at Froude numbers 0.2 to 0.4 in head seas. The calculated heave and pitch motions generally compare well with the experimental results; except for pitch at the highest Froude number. The heave resonance peak of the Wigley III at Froude number 0.3 was well predicted by the Neumann-Kelvin method of Peng and Qiu (2009), while Zhang *et al.* (2010) demonstrated that the Neumann-Kelvin method gave a relatively large overestimation of the heave resonance peak of the Wigley I at the same speed. This indicates that it is still difficult to draw firm conclusions regarding the required refinement level when including forward speed effects in the boundary value problem.

Shao and Faltinsen (2011) presented a time domain Higher Order Boundary Element Method, which is based on cubic shape functions, to study the linear seakeeping problem. Their validation results include the amplitudes and phase angles of a Wigley hull subject to heave and pitch motions in head seas, and the corresponding added resistance. Finally, they studied the 2nd order wave diffraction problem of the Wigley hull and showed that the second order velocity potential is dominating over the quadratic terms in the wave induced excitation of nonlinear ship springing.

Du *et al.* (2011) discussed the problem of irregular frequencies in forward speed seakeeping analyses with singularity distribution methods. For the majority of ship-like structures these irregular frequencies lie outside the range of practical interest for rigid body motions but they may create difficulties for the analysis of flexible bodies, multi-hulled vessels and when using frequency-domain data to create impulse-response functions for subsequent simulation of vessel responses in the time-domain (Bailey *et al.*, 2001). A rectangular box and a Series 60 hull form were analysed at zero and non-zero forward speed. It was concluded that more practical numerical approaches are required to overcome the problem of irregular frequencies.

Wu *et al.* (2010) applied the VERES/WINSIR strip theory based hybrid hydroelastic method of Wu and Moan (2005) to study the heave/pitch motions and vertical bending moments (VBM) for an ultra large container ship progressing at the Froude number

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0.22 in head seas. Comparisons were made with results from model tests and with the 3D WASIM code. For RAOs of heave, pitch and VBM, both computer codes agreed quite well with the experimental data. However, it could not be concluded that one code is superior to the other.

Some linear seakeeping methods have recently been modified to enable analysis of special vessels, such as high speed craft (HSC), multihulls, air-cushion vehicles (ACV), foil-assisted craft and SWATH-like vehicles. De Jong and Van Walree (2009) extended the work of Lin and Yue (1990) and van Walree (2002) to present a linearised time-domain Green's function method for analysis of HSC. Predicted heave, pitch and vertical accelerations are compared with experimental data for two high speed monohulls in head irregular waves. Results in terms of standard deviations compared well, but the numerical method tends to underpredict the extreme vertical accelerations. Milewski *et al.* (2009) presented a practical simulation model for seakeeping analysis of air-cushion vehicles. Saito and Iwashita (2009) applied a frequency domain Rankine panel method to calculate the motions, pressures, vertical shear forces (VSF) and VBM for a slender high speed vessel with aft outriggers in head seas. The Froude numbers 0.31, 0.5 and 0.69 were studied. Good agreement with experiments was reported, but the strip theory method was shown to give almost as good results for the heave and pitch motions. For VSF and VBM at the two higher speeds, the 3D method provided better agreement against experiments. Experimental results for a trimaran, a monohull and two SWATH types at Froude numbers 0.43-0.50 were given by Kihara *et al.* (2009). Comparisons against strip theory calculations for the monohull and the SWATHs has shown that additional damping due to lift and drag may be accounted for in a quasi-steady manner as suggested by Lee and Curphey (1977). Hydrodynamic interactions between hulls were neglected in their calculations. However, the strip theory calculations generally agreed well with the experiments for hydrodynamic coefficients, excitation forces and heave/pitch motions.

2.2.2 Level 2: Froude-Krylov Nonlinear Methods

In Level 2 methods, the disturbance potential is calculated as in the linear case. The incident wave forces are evaluated by integrating the incident wave pressure and the hydrostatic pressure over the wetted hull surface defined by the instantaneous position of the hull under the incident wave surface. Level 2 methods are very popular, since they capture many important nonlinear effects with only a fraction of the computer time required for the Level 3 methods. It is common to use linear analysis to calculate the frequency response or Retardation Functions (RF). The linear frequency response functions are transformed to time domain, yielding the RFs. The time domain response will contain a convolution integral with the RF to account for the memory effects. Another common starting point is to solve the problem directly in the time domain using the time-domain (transient) Green's function, which also involves convolution integrals (e.g. Lin *et al.*, 2007; Weems *et al.*, 2007). In the next step, various nonlinear modification forces can be included in the time domain equations of motion in addition to nonlinear Froude-Krylov and restoring forces in order to account for slamming and green water.

Within the reporting period the Level 2 time domain 3D formulation LAMP-2 has been applied to a semi-displacement mono-hull by Ibrahim *et al.* (2009). The authors incorporated lift and damping effects from the hull by adopting a formula from Thwaites (1960). Lift and drag forces due to trim tabs were also included. It was demonstrated that these lift-effects are small for Froude numbers below 0.3. On the

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other hand, at higher Froude numbers the effects of including these additional forces become noticeable. However, when comparing against experiments it is not yet clear that lift and drag force idealisations give more accurate results.

Bruzzone *et al.* (2009) applied a Level 2 method to a hard-chine and a round-bilge catamaran, running at Froude numbers 0.5 and 0.3, respectively. A 3D Rankine panel method was used to calculate the steady flow and linear radiation and diffraction forces in the frequency domain. Interaction with the steady flow was included in the FSBC. Relatively good agreement with experiments was obtained for the vertical motions. Liu and Papanikolaou (2010) presented a hybrid, time-domain domain potential theory method and applied it to a variety of seakeeping problems. The validation included steady flow, wave resistance calculations and studies of nonlinear motions and loads in waves. Their results agree well with experimental data for the wave making resistance of a Wigley hull, heave and pitch motions of the S-175 container ship in head sea under different wave conditions and the added resistance of various ship hulls. In a more recent publication the efficiency of calculations was enhanced by use of a Chimera-type, overlapping grid schemes on the free surface (Liu and Papanikolaou, 2011).

The hybrid hydroelastic nonlinear strip theory of Wu and Moan (2005) was applied for the case of a 294 m long container ship by Drummen *et al.* (2009). Numerical results were compared against experimental results derived from a flexible model in head seas. The nonlinear strip theory agreed quite well with the experimental results. It was demonstrated that sagging and hogging moments in head seas increase and become more nonlinear when the high-frequency vibrations due to hull flexibility are accounted for. It was also shown that springing is often excited by nonlinear wave loads that oscillate at a frequency that is an integer multiple of the wave encounter frequency. The same theory was applied to a 366 m container ship by Wu *et al.* (2010) and compared with experimental results from a flexible model in head seas. The calculated hogging and sagging moments generally agreed quite well with experiments. However, it was concluded that the wave-frequency sagging moments are over predicted, while the whipping sagging moments are under predicted. Hence the 2D momentum slamming model could be replaced by a more refined model in order to predict the whipping moments more accurately.

Another nonlinear hydroelastic analysis of a 336 m container ship was reported by Lee *et al.* (2011a, 2011b). The calculated VBM were compared with results from model tests with a flexible model in head seas. The time-domain analysis used linear hydrodynamic coefficients obtained with a 3D panel method. Momentum-based slamming forces were included in addition to the nonlinear Froude-Krylov and hydrostatic forces. The theoretical method captured the springing and whipping vibrations reasonably well, but it was shown that there are some regular wave periods for which the vibration magnitude is not correctly predicted.

2.2.3 Level 3: Body-nonlinear Methods

In Level 3 methods, the disturbance potential is calculated for the wetted hull surface defined by the instantaneous position of the hull under the mean position of the free surface. This requires regridding and recalculation of the disturbance potential for every time step. The computational costs will therefore increase dramatically as compared to Level 2 methods. No publications regarding the Level 3 methods appeared during the reporting period.

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2.2.4 Level 4: Body-exact Methods (Weak Scattered Methods)

These methods are similar to Level 3, but the wetted hull surface is defined by the instantaneous position of the hull under the incident wave surface. For Green's function methods, this increases the complexity, since the commonly used time domain Green's function satisfies the free surface condition on the mean free surface and not on the incident wave surface. The later can be circumvented by mapping the geometry into a computational domain where the incident wave surface becomes a flat plane (e.g. Lin *et al.*, 1994). Level 4 methods are sometimes referred to as "weak scatter methods", since the disturbed, or scattered waves, caused by the ship are disregarded when the hydrodynamic boundary value problem is set up. It is assumed that the scattered waves are small compared to the incident waves and the steady waves.

Recently, Mortola *et al.* (2011a,b) presented a time-domain method where the restoring, Froude Krylov and diffraction forces are calculated at each time-step for the exact position of the hull under the incident wave surface. The diffraction forces were calculated with the strip theory approach (Salvesen *et al.*, 1970). Hydrodynamic coefficients for the correct instantaneous draft for each section were applied during the simulation. These coefficients were calculated beforehand by strip theory for relevant combinations of section immersions and heel angles. This approach implies that forward speed effects are accounted for only in a simple manner. It is shown that the method predicts RAO-values of heave, pitch and midship VBM for the S175 in head regular waves that, for the zero speed case, compare quite well with predictions from linear 2D and 3D frequency-domain codes.

2.2.5 Level 5: Fully Nonlinear Methods (Smooth Waves)

In these fully nonlinear methods, the scattered waves are no longer assumed to be small, and they are included when the boundary value problem is set up. In the MEL (Mixed Eulerian-Lagrangian) method the Eulerian solution of a linear boundary value problem and the Lagrangian time integration of the nonlinear free surface boundary condition is required at each time step. These methods assume that the waves are "smooth", i.e. there is no wave breaking or fragmentation of the fluid domain. Computations are typically forced to stop based on a wave breaking criterion. The stability of the free surface time-stepping can also be a problem (e.g. Bandyk and Beck, 2008).

Lin and Kuang (2009) applied the 3D fully nonlinear method presented by Lin and Kuang (2006) to a fast vessel. Heave and pitch motions seem to agree well with experimental results in head irregular waves, but only short time-series for two different speeds have been presented. Sun and Faltinsen (2009) extended their fully nonlinear 2.5D theory to account for non-prismatic hull forms. Only calm water results have been presented, but the theory is also applicable to the problem of forced heave and pitch motions. Yan and Liu (2010) presented a fully nonlinear 3D method. An efficient MEL-based time-domain computational method was developed using the pre-corrected Fast Fourier Transform algorithm based on a quadratic BEM. The method was used to study wave radiation of a heaving sphere, wave diffraction of a fixed vertical cylinder, and wave generation of a forward moving ship hull. Calculated results generally compared well with available experimental data, although discrepancies still remain in the predictions of the wave elevation near the bow of the ship hull. More recently, in order to overcome some of the problems associated with the MEL description of the fluid flow and enhance its applicability, Chapchap *et al.* (2011b) described the geometric domain by means of signed distance functions, which considerably simplify the mesh generation procedure.

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2.2.6 Level 6: Fully Nonlinear Methods

The boundary integral methods used in potential theory cannot handle breaking waves, spray and water flowing onto and off the ship's deck. Moreover, viscous forces are not part of the solution and must be obtained by other methods. With the increasing power of modern computers, methods solving the RANS equations are becoming increasingly popular. In these methods, the water/air volume is normally discretised, and a finite difference, finite volume or a finite element technique is used to establish the equation system. Within the reporting period particle methods, where no grid is used, have also been applied to solve the Navier-Stokes equations. Examples are the Smoothed Particle Hydrodynamics (SPH), the Moving Particle Semi-implicit (MPS) and the Constrained Interpolation Profile (CIP) methods, with the latter believed to be more suitable for violent flows.

The unsteady RANS code CFD Ship-Iowa V.4 has been applied to a catamaran advancing in head regular waves by Castiglione *et al.* (2009). In this code the free surface is captured using a single phase level set method and turbulence is modelled by a blended $k-\epsilon/k-\omega$ model. The equations are discretised using a finite difference approach. The authors concluded that calculated amplitudes and phases of heave and pitch motions agree well with experimental results at Froude numbers 0.45, 0.6 and 0.75. A modal hydroelastic analysis, using CFD Ship-Iowa V.4 for the fluid calculations and the commercial FEM code ABAQUS for calculation of mode shapes, was presented by Paik *et al.* (2009). The S175 container ship at Froude number 0.2 in head regular waves was studied. Different ways of fluid-structure coupling were investigated. Heave, pitch and VBM compared quite well with experimental data obtained with a flexible segmented model (Ramos *et al.* 2000).

Lin *et al.* (2009) used the FANS (Finite-Analytic-Navier-Stokes) code developed by Chen and Yu (2006) together with the Froude-Krylov nonlinear 3D potential theory code LAMP-2 to calculate motions and wet deck slamming loads on a high-speed catamaran. In this work LAMP was used for the flow solution in the outer region and FANS was used to model the local flow region immediately around the ship for nonlinear free surface and 3-D impact effects. FANS uses a level-set method for interface capturing. The paper presents some computational results obtained with this new hybrid method but no comparison is made with experimental data.

Hu *et al.* (2010) applied the CIP-based code RIAM-CMEN to a post-Panamax container ship at Froude number 0.179 in head and bow regular waves. RIAM-CMEN uses a Cartesian grid covering the whole computation domain, the CIP combined and unified procedure as the flow solver, a VOF-like Tangent of Hyperbola interface capturing technique and a Lagrangian method for solid body motion, in which the fluid structure interaction is treated by an immersed boundary method. Calculated heave, pitch, pressures, VBM, horizontal bending moments (HBM) and torsional moments (TM) were compared against experimental results for a segmented model (Miake *et al.*, 2004) and with results from a linear Rankine panel method and a linear strip theory. The results from RIAM-CMEN generally compared better with experiments than do the potential theory codes. This was particularly the case for hydrodynamic pressures on the hull and for heave and pitch motions. For HBM strip theory results compared equally well with the experiments, and for VBM amidships strip theory seemed to compare slightly better than RIAM-CMEN. None of the methods could predict the torsional moments in bow waves with good accuracy.

The same CIP method was applied to a 270 m container ship at Froude number 0.24 in head regular waves by Huijsmans *et al.* (2010). Calculated heave, pitch, VSF and VBM were compared with results obtained with a segmented model. The CIP-method predicted pitch motions with quite good accuracy, while heave motions were underestimated. Generally, for VBM and VSF the discrepancies between computed and experimental RAO's were relatively large, although for the peak RAO-values of the VBM amidships and the VSF at the fore quarter length the agreement was fairly good.

2.3 Offshore Wind Loads

Wind loads are often considered as secondary with regards to the overall loading of marine structures. This may be considered acceptable as long as the magnitude of the mean wind forces and moments are only a fraction of the total loading. For situations such as cyclonic storms (e.g. hurricane Katrina), for offshore offloading and operations or helicopter landing the magnitude of wind loading is considered critical and should be accounted for in the design.

Wind coefficients used in offshore structures load analysis are often taken from literature or from wind tunnel measurements. Engineering studies are usually focused on the prediction of the global motion analysis and not in the definition of the wind load itself. Accordingly, the wind, wave and current combined motion analysis effects are analysed by numerical models and validated by model tests. The approach used in model tests may be either used to generate wind directly by fans or to simulate wind loads using a dynamic winch. Wind load time series are then derived based on wind tunnel tests as reported by Liapis *et al.* (2010) for the Perdido spar.

With the advancement of computers complex computational methods (e.g. CFD) are used as a cost-effective alternative to wind-tunnel tests. For example, Wang *et al.* (2010) performed a wind load analysis for a semi-submersible platform using CFD analysis and compared the results with wind tunnel experiments. The model used was a semi-submersible drilling unit with a length of $114\,m$ and a main deck height of about $38\,m$. The analysis was performed for a 1:192 size model. The platform was modelled by using the FLUENT commercial CFD algorithm and standard turbulence models were investigated by Large Eddy Simulation (LES). It was concluded that the dynamic sub grid scale (SGS) model provides best results regarding pressure coefficients, drag and lift forces as compared to model tests. The $k-\epsilon$ model results showed acceptable force prediction but could not predict exactly the effects of turbulence. Wnęk *et al.* (2012) presented an analysis of the aerodynamic forces acting on a floating LNG platform and an LNG carrier. The investigation focused on understanding the approach manoeuvre of the ship to the platform. This is the effect of platform shadow on the vessel during operation under wind conditions. Results from using the commercial CFD ANSYS CFX code were compared with experimental measurements performed in a wind tunnel. Numerical and experimental results, presented in a form of coefficients for the drag, lift components and yaw moment, reached approximate agreement. The biggest discrepancy occurred for lateral forces, where CFD underpredicts by about 50 % the experimental results.

Within the reporting period special interest has been attributed to loads emerging from extreme events (e.g. cyclonic tropical storms, hurricanes etc.). For example, Jang *et al.* (2010) identified the effects of damages on wind turbines due to tropical storms and analysed these effects on a wind turbine tower. Yang *et al.* (2009) analysed the loads on drilling rig tie down systems during hurricane conditions. The authors attributed special effort in analysing the dynamics of the structures. The wind force time series were calculated in a classic manner and applied as collinear to the wave and

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current actions. In a similar type of work Mücke *et al.* (2008) and Mücke *et al.* (2010) have analysed high frequency wind speed time series measured at the GROWIAN site at the German North Sea coast. In comparison with the standard models used for load analysis of structures and wind turbines their models have shown a higher probability of extremes. The analysis of probability density functions of wind speed amplitudes showed a non-Gaussian distribution with flatter tails. Adjusted wind turbulence models as the one proposed by Kleinhans (2008) were used to numerically analyse loads on wind turbines resulting in significantly higher load fluctuations.

In those cases where the wake behind a simple object may be roughly estimated using wind coefficients coming from experiments or empirical formulas, CFD simulations can be valuable to simulate the wake field astern complex ship structures. For example, Koop *et al.* (2010) investigated the applicability and accuracy of CFD analysis to derive wind loads for an FPSO tandem offloading configuration. This work was performed within the OO1 Joint Industry Project and analysed the wind load on a fully-loaded barge-shaped FPSO with 5 square blocks on the deck and a ballast loaded shuttle tanker at a distance of 450m. For the tandem configuration the FPSO was modelled with a 30° misalignment to the mean wind direction while the shuttle tanker was fully aligned to the wind direction. The analysis was performed using the MARIN inhouse CFD code ReFRESCO and the CFX commercial software on block structured and unstructured computational grids. Steady state forces on the structures were derived. Computational results were compared against wind tunnel measurements using segmented models. For FPSO or shuttle tanker standard configurations different numerical analysis codes provided force coefficients within a bandwidth of the order of 15 % to 30 % of the measurements. However, in the tandem configuration numerical analysis showed large differences compared to wind tunnel measurements. Trends in forces and moments were opposite from measurements, a fact that led to an unexpected increase in the drag force of the shuttle tanker. It was concluded that model scale effects may influence the wake behaviour and grid adjustments. CFD models therefore should capture more accurately the vortices generated by the FPSO boxes.

A similar type of analysis was performed by Tannuri *et al.* (2010) on a typical shuttle tanker when offloading an FPSO moored in a spread mooring system. In that work shielding effects when the shuttle is shifted to a tandem position, aligned to the FPSO, were analysed. Two identical FPSO and shuttle tanker structures (length 300 m) were tested for wind directions of 15° and 30°. The steady state condition was analysed using the commercial CFX algorithm and the model was calibrated using wind tunnel measurements. The results showed accuracy of the order of 10 % to 40 % depending on the load components and conditions. For yaw moments large discrepancies were observed for those cases where the absolute value of the moment is very small.

De Carvalho (2010) simulated the flow over a helideck in way of the complex topsides geometry of an FPSO. The numerical investigation was performed using CFX for a typical Brasilian FPSO of about 340 m length. During the preliminary tests comparative simulations were carried out using the $k - \epsilon$ and Shear Stress Transport (SST) turbulence models. SST results were in line with the wind tunnel experiments performed for a 1:200 scale model. Particle Image Velocimetry (PIV) and hot wire measurements compared well against the flow field numerical analysis measurements. Comparisons against modelling guidelines resulted in the conclusion that new turbulence criteria may have to be developed in the future.

A special topic in wind load analysis is the loading of offshore wind turbines. Currently, numerical schemes accounting for the coupled dynamics of the wind inflow,

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aerodynamics, elasticity, and controls of the turbine, along with the incident waves, sea current, hydrodynamics, and foundation dynamics of the support structure are being developed. Jonkman *et al.* (2010) and Vorpahl *et al.* (2010) reported some of the results from a benchmark study carried under the International Energy Agency (IEA) Wind Task 23 on aero-servo-hydro-elastic codes. In this work complex load cases were defined and run to trace back differences against simulation results. Different phases analysing the response of a 5 MW turbine on (a) a monopile with fixed foundation, (b) a monopile with flexible foundation, (c) a tripod and (d) a floating spar buoy were studied and an adaptation of the codes to those developments was enabled. The comparisons, in general, agreed quite well. All codes used blade element theory to account for rotor aerodynamics and the Morison equation to consider the wave actions. The structural dynamics were modelled by FEM methods or multi body formulations that are acknowledged to have influence on higher order eigen-frequencies. Some differences in the results obtained from different structural or hydro-structural models were identified.

The influence of wakes within a wind farm may significantly influence wind turbine loading. The standard approach is to artificially increase wind turbulence intensity to account for added vorticity and wind speed decay due to upwind wind turbines as shown by Frandsen (2007). Madsen *et al.* (2010) proposed the use of a dynamic wake meandering (DWM) model. Accordingly, by using CFD computations simplified engineering equations were derived considering basic physical mechanisms in the wake i.e., the velocity deficit, the meandering of the deficit, and the added turbulence. The model has been validated by Hansen (2009) and implemented in the HAWC2 and the Bladed codes by Schmidt *et al.* (2011).

In the field of floating offshore wind turbines the coupling of the rigid body motion (due to wave forces) and the elastic behaviour of structure/blade with the aerodynamic loading may be significant. Jonkman (2009) described the dynamics of offshore wind turbines for load analysis. Cordle (2010) and Matha *et al.* (2011) provided a complete overview of the state of the art and existing codes as well as the requirements for floating offshore wind turbine load analysis. Regarding aerodynamic loading one interesting finding is that the large low frequency platform motions experienced by floating wind turbines may result in complex flow conditions in those cases where the rotor is traversing back over its own wake.

2.4 Loads from Abnormal Waves

In the field of abnormal or freak (or rogue) waves some investigations deal with the nature, as well as physical and numerical generation of these waves, whilst others with the effects of waves on floating structures. The former falls within the remit of Committee I.1; hence, the focus of this section will be on the latter.

The concept of rogue waves and their effect on ships and offshore structures was first brought to prominence by Draper (1964, 1971) through observations of the addition of many wave components to form a larger wave during a world voyage. In more recent decades the phenomenon has grown in consequence in the marine industry as a result of high-profile encounters recorded by vessels. For example, Haver (2000) reported on the effects of a $30\,m$ high rogue wave that broke over the superstructure of the Queen Elizabeth 2 during gale conditions in 1995. Stansberg (2000) discussed the case of the FPSO Schiehallion that suffered plate deformation of the order of $15-20\,m$ above the mean waterline, due to severe bow slamming experienced as the result of an impact from a $20\,m$ high wave crest. Haver and Andersen (2000) reported on the event that

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occurred at the Draupner oil platform on 1st January 1995 when a 26 m high rogue wave occurred in a 12 metre sea state, causing damage to the accommodation deck on the platform. More recently, Berlotti and Cavaleri (2008) discussed the incident where the passenger ship Voyager encountered a rogue wave in 2005. This event caused severe roll motion, control room flooding and a loss of electrical systems. From these known encounters information about rogue waves is available in the form of crew observations and, in the case of the Draupner platform, a wave record from a downward facing laser. Unexplained ship losses have also been attributed to rogue wave encounters. For example, Kjeldsen (2000) reported on the cases of M/S Anita and M/S Norse Variant; Kharif and Pelinovsky (2003) discussed the effects of rogue waves in relation to the loss of MV Derbyshire.

The effect of freak waves on marine structures, in general, has also been focused on the effect on stationary offshore fixed structures. For example, Guedes Soares *et al.* (2008) presented an approach to determine the global load effects induced on ship structures by abnormal, freak, or episodic waves. The authors refer to a procedure that can be used for the determination of extreme values of wave-induced responses, including the recent advances of adopting time series of wave elevation, as reference design condition to calculate the wave-induced structural loads on ships in heavy weather. It is shown how this procedure can be extended to account for abnormal or episodic waves. It is suggested that at the present stage of knowledge it is possible to determine the loads induced by abnormal waves similar to ones that have been measured at various ocean locations and that are thus realistic. Although this information cannot replace the wave-induced loads calculated with the presently established procedures, it can serve as guidance for the design. Fonceca *et al.* (2010) investigated the vertical motions and bending moments of an Floating Production Storage and Offloading FPSO platform in several design storms with duration of three hours which correspond to the 100 years return period of the North Sea. Experimental data were systematically compared with numerical results from a nonlinear time domain strip method and they were found to underestimate the relative motions at the bow. The authors concluded that the discrepancies were related to the nonlinear effects on the incident waves, resulting in larger crests than troughs, and the run-up of the wave as it encounters the hull. The maximum bending moments obtained experimentally in the design storms were compared with the Rule reference values and they were found to surpass the later by around 30 %.

Following the work of Clauss and Henning (2004) on the assessment of rolling and capsising of ships in large waves, more recent investigations focused on understanding the behaviour of moving vessels in severe random seas. For example, Dramen *et al.* (2009) and Clauss (2009) addressed an experimental and numerical studies for a Container Ship, a bulk carrier and a Ro-Ro ship responses in severe seas. In these works it is recognised that having chosen a rogue wave type, known repeatable rogue waves need to be produced in an experimental towing tank. It is also addressed that nonlinear fluid structure interaction techniques including the physics of wave formation and the wave kinematics should be developed and validated. The later may include the nonlinear Schrodinger equation introduced by Onorato (2005) and the numerical wave tank approach suggested by Clauss *et al.* (2005). Recently, Rajendran *et al.* (2011) present direct comparisons between experimental time records and linear and nonlinear time domain simulations for a 117 m container ship in extreme sea conditions. Predefined wave traces, corresponding to the New Year Wave and a freak wave measured at North Alwyn, were reproduced in the tank. It is shown that the calculated response motions

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compare well with the experiments. However, the VBM amidships calculated using a linear method tend to underestimate the sagging peaks and overestimate the hogging peaks.

The work by Denchfield *et al.* (2009, 2010) concentrated on investigating the encounter between a rogue wave and a Lender Class Frigate in irregular head waves, including the influence of forward speed, through a combination of experimental investigations and numerical models incorporating the effects of hull flexibility. Predicted motions were compared with test measurements from a rigid model and two options for generating rogue waves, namely the first order optimisation approach and the New Wave approach. Results have shown that as the significant wave height and hence the rogue wave height increases, the experimental wave traces exhibit greater second order characteristics in the vicinity of the rogue wave peak. Comparisons in terms of heave and pitch motions become more severe with the introduction of a rogue wave into a seaway. The 2D linear model shows good agreement at low and mid-range speeds but at high speeds it shows some considerable discrepancies against experiments. It was concluded that this is likely to be due to the extreme "tunnelling" motions usually observed at high speed and in large seas during experiments.

2.5 Hydroelasticity Methods

Wu and Cui (2009) presented an overview of the developments and achievements of linear and nonlinear 3D theories of ships and the corresponding numerical and experimental techniques. In the proceedings of the 5th International Conference on Hydroelasticity in Marine Technology Temarel and Hirdaris (2009) presented a number of theoretical developments and applications of hydroelasticity methods on the design of ships and offshore structures. Hirdaris and Temarel (2009) discussed a number of recent applications of 2D and 3D hydroelasticity theories for ship design along with future ideas on the development and implementation of fully nonlinear fluid-structure interaction models, including CFD based methods, for the improved modelling of ship wave load predictions.

Following some initial work by Uğurlu and Guedes Soares (2008), Uğurlu and Ergin (2009) proposed a 3D hydroelasticity method for studying the response of surface piercing elastic structures using a higher order BEM approximation. The effects of approximation order and boundary surface discretisation on the removal of irregular frequencies were investigated by applying the extended boundary integral equation method of Lee *et al.* (1996). The frequency dependent hydrodynamic coefficients were calculated for a freely floating half-submerged elastic circular cylindrical shell. It was shown that the process of removing the irregular frequency effects becomes inefficient for higher frequency values. Notwithstanding, repeating the analysis with a higher number of free surface elements or by using a higher order approximation may be useful.

Mikami and Kashiwagi (2008) derived a nonlinear hydroelastic strip theory capturing the geometric nonlinearities in the hydrodynamic restoring and Froude-Krylov forces in waves. The frequency dependence in the radiation and diffraction forces was accounted for by using convolution integrals. The hull was modelled using a Timoshenko beam approach. The calculations were performed for a 716 TEU container ship and comparisons against model test results were shown to be satisfactory for symmetric distortions.

Kim *et al.* (2009a) studied the springing response of the flexible S175 ship using a Vlasov beam finite element method for the motion of the flexible structure and a

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higher-order Rankine panel-based boundary element method to simulate the fluid motion around the flexible body. The solution was sought by strongly coupling these boundary integral equations and FEM implicitly in the time domain. The structural domain was modelled by beam finite elements, able to capture the coupling effect between torsion and bending as well as warping distortion. Comparisons between symmetric wave loads derived by the Rankine-panel based time domain approach and a Green-function based frequency domain approach compared generally well (Kim *et al.*, 2009c).

Hirdaris *et al.* (2009b) discussed a method for the dynamic analysis of beam-like ships with large deck openings and associated structural discontinuities. The authors employed different numerical models to assess the influence of the discontinuities and the effect of other structural parameters. They concluded that the inclusion of structural discontinuities may have an important influence on natural frequencies, mode shapes and modal internal actions. However, it is difficult to establish a pattern of influence in terms of torsion or bending dominant mode shapes or a particular modal characteristic. In a similar type of work, Senjanović *et al.* (2009) investigated the hydroelastic responses of a 7800 TEU container ship by coupling a beam structural model with a 3D hydrodynamic model. The analysis demonstrated reasonably good results for symmetric wave loads. However, the structural responses in way of the hatch corners were underestimated.

Riyansyah *et al.* (2010) employed the Euler-Bernoulli beam theory and boundary element method to solve the beam equation of motion and the governing equation of fluid motion, respectively, for the hydroelastic response behavior of a two floating beam system. The authors investigated the relative beam stiffness on the hydroelastic response behavior. They observed that an increase in the flexural rigidity may change the characteristics of the floating beam system. It may also change the pressure distribution along the floating beam system.

Kaydıhan *et al.* (2010) presented a hydroelasticity study investigating the response of six bulk carriers with different load carrying capacities. The ships selected for this investigation were two Handysize, one Panamax and two Capesize bulk carriers. The authors calculated dry and wet natural frequencies and associated modes as a function of the non-dimensional parameters. They also presented hydrodynamic modes, such as generalised added mass and hydrodynamic damping, as a function of wave frequency, and wave excited responses.

Tian *et al.* (2009) investigated the rigid body motions and structural responses of an 180,000 dwt bulk carrier traveling in regular and irregular head waves. The numerical predictions were obtained by using the programs THAFTS and NTHAFTS that are based on linear and non-linear 3D hydroelasticity theories respectively. The predicted linear hydroelastic responses are illustrated, together with the investigation and discussion of the forward speed effect on the hydroelastic responses. The successive second order nonlinear hydroelastic analysis was also performed. It was shown that the springing behavior is clearly exhibited by the linear and nonlinear predictions. The influences of the forward speed effect and the nonlinear hydroelastic actions on the motions and structural loads of this large bulk carrier were quantitatively discussed.

Itamura *et al.* (2009) studied the hydroelastic vibrations including springing and whipping of an ore bulk carrier, and their influences on fatigue damage. A fully 3D time-domain method was employed to analyze the hydroelastic response. That is, shell finite elements were employed to account for the complex deformation behavior of the

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ship to predict global and local stress distributions while linear and nonlinear forces were considered with an extension of 3D potential flow theory. Springing responses in regular and short-term irregular waves were discussed by different ship speeds and wave heights.

Taghipour *et al.* (2009) presented an alternative method for hydroelastic analysis of marine structures by using state-space models. The method was applied to a very flexible barge, and the dynamic response of the barge due to regular waves as well as its transient response after release from an initial displacement was simulated. It was concluded that state-space models may replace the convolution integrals.

2.5.1 Slamming Loads

The hydrodynamic loads imposed upon the water entry of a flat plate were investigated by Iafrati and Korobkin (2008). The authors developed a 2D potential flow theory accounting for variable entry velocity. A theoretical estimate of the loads during the early stage of the water impact by the method of matched asymptotic expansions compared well against numerical predictions.

Dessi and Mariani (2008) implemented the Von-Karman theory with a water up-rise correction to calculate the sectional loads acting on the V-shaped bow of a fast-ferry. The authors considered the effects of variable water-entry speed, the presence of knuckles and the contribution of 3D terms given by the variation of ship sections by implementing a BEM. The theoretical load prediction used seakeeping experimental data as input for the calculation. The sectional loads were spatially integrated along the ship length and compared with the vertical force measured on the physical model segments in order to avoid errors on the relative body motion derived from the theoretical analysis.

Tveitnes *et al.* (2008) investigated the constant speed water-entry of wedges at different dead rise angles. The authors measured both loads and wetted length uprise during impact. They concluded that careful investigation of results in way of water entry and exit conditions may be useful for the refinement of 2D slamming load theories. In a subsequent publication, Sun and Faltinsen (2009) dealt with the 2D water entry of a bow-flare ship section with constant heel angle by means of a BEM. Non-viscous flow separation from the knuckles of the section or from the curved bottom was taken into account. The numerical calculations were compared with drop tests available in literature. It was shown that as long as the heel angle is increased, high localised pressures arise on the impacting flare area. Thus, the flow separation for large heel angles may significantly affect the pressure along the impacting bottom and its relevance seems much more related to non viscous than to viscous effects.

Lee and Park *et al.* (2010) exploited the moving particle semi-implicit method to study the effects of an incompressible violent flow over structures. The method exploits a more efficient algorithm and is used for solving various highly nonlinear free-surface problems, to evaluate the slamming loads on rigid plates with various incident angles. It was shown that without using the Eulerian approach or the grid system, the convection terms and time derivatives in the Navier–Stokes equations can be calculated more directly without any numerical diffusion, instabilities or topological failure. The method also allows for the derivation of numerical results that are in good agreement with available experimental data.

Greco *et al.* (2010a, 2010b) analysed the problem of bottom slamming for very large floating structures using 2D potential flow theory without and with coupling between the global behaviour of the platform and local actions. Whereas a linear solver was adopted to investigate the global behaviour, a nonlinear approach was implemented to predict locally the slamming forces. For large platform motions an iterative time-decomposition strategy was developed to examine the resulting coupling. The effect of air entrapment was taken into account along with a detailed description of pressure and stresses on the platform bottom using beam theory to model the equivalent floating structure.

Korobkin (2011) discussed a refinement of the well-known generalized Wagner model to improve the hydrodynamic forces measured on 2D impacting bodies. Wagner models provide higher accuracy with respect to other semi-analytical methods (e.g. modified Logvinovich Model) as they are able to predict better the pressures on the body contour. However, they fail to integrate correctly the pressure distribution due to lack of adequate numerical treatment. To avoid this drawback, Korobkin (2011) employed rigorous analytical calculations by separating the singular components of both the flow velocity and the pressure. By reducing the original problem to two non-linear integral equations, where one of them serves to evaluate the conformal mapping and the second one to compute the position of the contact point, improved prediction of the pressure and hydrodynamic forces was achieved.

Another interesting application of Wagner's water impact theory was provided by Qin and Batra (2009). They investigated the local slamming problem of a deformable sandwich wedge by taking into account hydroelasticity effects. The novelty of their work resides upon the use of a sandwich panel theory, that incorporates the transverse deformations of the core, with the Kirchhoff plate theory for modelling of the face sheets. A numerical procedure to solve the nonlinear system of governing equations, from which both the fluid load and the structure deformations can be simultaneously computed, has been developed and verified. The hydroelastic effect on the hull deformations appears to be noticeable and the core shows to absorb a considerable part of the strain energy due to transverse shear deformation implying that the core can be effectively used for slamming impact alleviation.

Maki *et al.* (2011) highlighted the need to develop a practical tool for the computation of slamming loads. Taking advantage of the method developed by Paik *et al.* (2009) the authors recommended using an one-way coupling method to model fluid structure interactions. Accordingly, the open source CFD solver OpenFOAM and the dynamic finite element method were employed and the exchange of numerical data was facilitated by a grid matching algorithm. The fluid-dynamic simulation was carried out on a rigid body in the time domain and the modal equations of motion were numerically integrated to yield the structural response in time. Acoustic elements were used to account for the added mass due to flexible modes. The procedure allowed solving the impact of a rigid and an elastic wedge. Hanbing Luo *et al.* (2011a,b) studied the hydroelastic responses of complex stiffened panels. A steel wedge with complex stiffened panels was designed with a dead rise angle of 22° and a series free-drop model tests were carried out. The explicit FEA commercial algorithm LS-DYNA was used to simulate this coupled hydroelastic impact problem. Comparisons of the numerical and the experimental results have shown generally good agreement on the acceleration and stress responses. However, more research is required to understand the influence of high frequency oscillations on the measured accelerations and the local hydroelastic effects.

18th International Ship and Offshore Structures Congress (ISSC 2012) - W. Fricke, R. Bronsart (Eds.)

2.5.2 Experimental Hydroelasticity

Over the last three years two major international Joint Industry Projects (JIPs) concentrated on the validation of the effects of springing and whipping on Container Ship Structures. In the first one Classification Societies, CeSOS and MARINTEK carried out model tests with the ultimate aim to investigate how wave induced vibrations affect the fatigue and extreme loading at different cross sections (Storhaug *et al.*, 2010a, and Storhaug *et al.*, 2010b). The second international project namely WILS currently enters its third phase; it is led by the Korean industry (KORDI and Korean Shipyards) and is supported by all major Classification Societies (Kim *et al.*, 2010, Lee *et al.*, 2011a,b). To date the main conclusions of both JIPs can be summarised as follows:

- With regards to the impact of the wave-induced vibrations on structural design, the tank test results seem consistent with each other to the point that the fatigue damage is increased due to the wave-induced vibration when the fatigue damage is estimated by using the Rainflow counting method and the Palmgren-Miner's rule. However, the validity of the fatigue damage estimation method for the combined load is yet to be confirmed against fatigue tests under combined high-frequency and low-frequency loads that may be used to clarify the effects of wave-induced vibrations on fatigue damage;
- The scaled model techniques for the wave-induced vibrations of hull girder in torsional mode have been developing and there is still space for improvement. Scaled models need to have similarities in modal shapes as well as the natural frequencies. The consideration of the position of the shear centre, which is normally located lower than the keel, and measurement methods of the torsional moments seem to be some of the directions where fundamental understanding needs to improve;
- Numerical simulation methods need to be validated in further against tank tests and full scale measurements until they become an established tool for predicting the wave-induced vibrations of a ship's hull girder;
- Slamming impacts seem to be a source of large uncertainty.

Drummen *et al.* (2009) presented an experimental and numerical study of the responses of a container ship in severe head seas. In this work it was demonstrated that hull flexibility could increase the vertical bending moment by up to 35 %. Comparisons of experimental bending moments against nonlinear hydroelastic strip theories provided reasonably good agreement. Kim *et al.* (2009b) (see Kim, 2009a,b,c) investigated the responses of a floating and flexible barge. The experimental measurements were carried out in different wave heading angles, from head waves to beam waves with angle increments of 30 degrees. different irregular waves were generated based on the JONSWAP spectrum with different significant wave heights and wave periods. Resonses were obtained by processing the irregular motion time history using Fourier analysis.

Coppotelli *et al.* (2008) determined the operational vibration modes of an elastically scaled ship using the frequency domain decomposition method. By exploiting the ambient mode excitation in head waves they have determined the mode shapes as well as the associated frequencies and damping. In furthering this work, Dessi *et al.* (2009) presented the preliminary results relative to the correlation of model scale and full scale tests, for determining the bending response of a naval vessel in waves. The tests were carried out at the INSEAN towing tank with a segmented-hull elastic model

18th International Ship and Offshore Structures Congress (ISSC 2012) - W. Fricke, R. Bronsart (Eds.)

scaling the mass, sectional moment of inertia and shear area. The vertical bending moments measured on board the ship during the full scale trials were compared with those determined with the segmented-hull tests and with the simulations using 2D and 3D FEA models of the ship structure.

Dessi *et al.* (2010) also explored the bow and stern slamming events experienced by a cruise ship comprising of five-segments. The authors demonstrated that slamming intensity occurring in way ot the ship stern in following wave conditions may be potentially larger than the one relative to the bow in head waves. The response level was evaluated as the time average of the envelope of the high-pass filtered bending moment, obtained experimentally from the strain-gages for different sea states, wave directions and forward speeds. The mean bending moment was then related to the number of impacts per minute and to the impact severity. Some global trends between the observed variables were identified and were found to be similar to those determined for other ship types. More recently, the underlying requirement of broad-band excitation has been clarified by Dessi (2011). The author applied the proper orthogonal decomposition under the same hypothesis to determine not only the modal shapes of the same physical model but also the energy associated to each identified mode in the response. This method is based on the construction of a correlation matrix among the measured degrees of freedom with accelerometers or strain-gages. It allows for deciding how many wet modes may be required to perform simulations in certain conditions (e.g. forward speed and sea-state).

Iijima *et al.* (2009) developed a scaled model design technique to tune the natural frequencies in torsional mode as well as vertical and horizontal bending modes. A backbone beam approach with several cut-outs was shown to be effective in giving an appropriate torsional stiffness as well as vertical and horizontal bending stiffness by selecting the configuration of the cut-outs. The natural frequency was measured in wet conditions. Vertical and horizontal bending and torsion moments were also measured by using longitudinal and shear strains calibrated prior to the tank tests. By using this scaled model, the hydroelastic vibrations in torsion as well as vertical bending in head/oblique seas were measured. Springing response to linear/nonlinear loads and whipping response to slamming impacts in both vertical bending and torsion were reported.

Oka *et al.* (2009) carried out a series of tank tests in regular and irregular waves using a segmented model for a large container ship, with backbone. It was verified that estimated torsional moment by means of FEA was strongly consistent with measured torsional moments. Ship motions, accelerations, wave-induced bending moments and torsional moments were measured in various seakeeping conditions. The relation of wave loads of a large container ship with respect to waves and ship speed was examined. Derbanne *et al.* (2010) reported on the springing measurements of a flexible large container ship. The model was made of 12 segments attached to a squared section steel rod with total length of $4.42\,m$. The steel rod was located just under the baseline of the ship in order to have the centre of torsion as low as possible. The tests were run without forward speed, in regular head and oblique conditions. Linear springing response in torsional mode and coupled resonance of the horizontal bending were found to be strongly coupled.

Stenius *et al.* (2011) considered the hydroelastic interaction involved in panel-water impacts for a high speed craft. Hydroelastic panel-water impacts were simulated by using the FEM code LS DYNA and a simplified in-house developed method. It was shown that hydroelastic effects can both increase and reduce the panel responses

18th International Ship and Offshore Structures Congress (ISSC 2012) - W. Fricke, R. Bronsart (Eds.)

depending on the impact envelope considered. Thomas *et al.* (2011) studied the slam events experienced by high-speed catamarans with a segmented model capable to measure the whipping induced load responses in way of the centre bow. Wet-deck slamming events were identified by analysing the load time-history provided by strain-gages and their intensity was related to the relative vertical motion (immersion and velocity) at the same section. As expected, the slam intensity showed a tendency to increase as long as the deck impact velocity became higher. The experiments also highlighted an evident dependency of the slam location on the forward speed.

2.5.3 Full Scale Measurements

Within the reporting period the work published on full-scale measurements of ocean going ships has clearly shown that wave induced stress components may vary in way of the two node hull girder frequency e.g. Okada *et al.* (2006), Miyahara *et al.* (2006), Heggelund *et al.* (2010), Ito *et al.* (2010), Hirdaris *et al.* (2009). These stress components show both transient (whipping) and more continuous (springing) variations.

For example, Hirdaris *et al.* (2009) presented a summary of an investigation into the effects of hull flexibility when deriving an equivalent service factor for a single passage of a Great Lakes Bulk Carrier from the Canadian Great Lakes to China. It was shown that the long term wave induced bending moment predicted using traditional 3D rigid body hydrodynamic methods is augmented due to the effects of springing and whipping by including allowances based on two-dimensional hydroelasticity predictions across a range of headings and sea states. The analysis results were correlated with full scale measurements that are available for this ship. The combined effects of springing and whipping responses on the wave-induced VBM results were predicted to enhance the design VBM and the service factors by up to 37.7 %. This prediction, although conservative, was considered necessary to ensure a suitable design margin for the possible sea states that might be expected. Comparisons against full-scale measurement data also showed that achieving good agreement between predictions and measurements, both for ship-wave matching and springing, depend on the parameters of the wave spectra as well as the estimation of structural damping for the latter and any uncertainties involved in measuring such data.

Miyake *et al.* (2010) presented the whipping measurement results of an ultra large 12,000 TEU container ship both in regular and irregular seas. The authors reported on the relationship between the maximum vertical bending moment amidships and the wave amplitude for various combinations of wave/ship length ratio in regular head seas. The non-dimensionalised hogging moments were almost constant and equivalent to the first harmonics of the hogging moments in small wave amplitude. However, the non-dimensionalised sagging moments increased with the increase of the wave amplitude. Discrepancies in sagging and hogging moments were also observed in irregular seas with differences more prominent for the values whose exceedance probability is lower.

Drummen *et al.* (2009) demonstrated that hull flexibility can increase the vertical bending moment by up to 35 % in sea states relevant for design. They also compared measurements and calculations of high frequency induced stress components and have shown that their developed hydroelastic model slightly over-predicts the increase of the bending moments due to hull flexibility.

Jensen *et al.* (2009) and Pedersen and Jensen (2009) have described a simplified calculation procedure for the probability distribution of the combined wave and whipping induced stresses. Reasonable agreements with full-scale measurements have been achievable provided that the pertinent parameters related to the estimation of the

18th International Ship and Offshore Structures Congress (ISSC 2012) - W. Fricke, R. Bronsart (Eds.)

impulse slamming loads are chosen with care. More detailed procedures based on the solution of nonlinear hydrodynamic strip theory formulations coupled with a Timoshenko beam model of the hull girder have been presented in Iijima *et al.* (2008), Drummen *et al.* (2009), Wang *et al.* (2009) and Vidic-Perunovic (2010).

2.5.4 Specialist Structures

Santos *et al.* (2009a,b) studied the symmetric response of a fast patrol boat using unified hydroelasticity analysis. 2D and 3D idealisations were adopted to predict the structural response behavior. The fluid-structure interaction effects were calculated using 3D potential flow analysis in a variety of seakeeping conditions. This work demonstrated the inherent limitations of the applicability of beam idealisations to vessels with a small length/beam ratio using either the Prohl-Myklestad methodology or an FEA model. It was concluded that structural discontinuities (e.g. deck openings) and the long superstructure that is not aligned with the ship's sides are additional factors affecting the applicability of 2D hydroelastic models.

Ikoma *et al.* (2009), and Van Kessel and Huijsmans (2009) studied the hydroelastic response behavior of aircushion supported structures in waves. In the former study, the motion reduction effect of aircushion was confirmed from theoretical calculations with zero draft assumption. In the latter one, a new method that takes into account the fluid-air-structure interaction of aircushion supported structures in waves was derived.

Damaren (2010) examined the hydroelastic properties of the vibration modes of a thin plate floating on the surface of an incompressible, inviscid, irrotational ocean of infinite extent. The results demonstrated that the modes of the plate of optimised shape exhibit large damping coefficients. Van Kessel (2010) presented the results for validation of a new hydroelastic code for flexible floating structures moored in waves. Numerical results were validated by model experiments of a flexible barge in waves from different headings. In addition, the obtained results were compared with results from other existing hydroelastic programs. In general it is shown that numerical results show good agreement with experimental values.

Milgram (2007) addressed the importance of evaluating the unsteady forces and moments on an underwater vehicle in finite-depth water, at small enough submergences for it to be influenced by sea waves. This study has employed strip theory, including the effects of finite depth and lift forces on fins to predict the unsteady seakeeping forces on streamlined underwater vehicles close to the surface. Comparisons with experiments have shown errors within the range of application of strip theory to ships.

Can and Ergin (2010) presented experimental data and theoretical calculations on the dynamic response behavior of a flexible submarine pressure hull model vibrating in air and water. Different representative to submarine hull aspect ratios were selected. Jagadeesh *et al.* (2011) presented a towing tank-based experimental study on forces and moments on Autonomous Underwater Vehicle (AUV) hull forms in the vertical plane. A five component force balance was used to measure the variation of axial, normal, drag, lift and pitching moment coefficients. The obtained results point out a relevant sensitivity on the parameters, especially for axial and normal force coefficients. As in a previous paper by Sulin *et al.* (2009) the authors used CFD tools (ANSYS-Fluent) to estimate the hydrodynamic coefficients of AUVs. However, the complex shape of the body under investigation provided a more challenging case. Because of the block-like structure of this underwater vehicle, the relationships between the hydrodynamic loads and the translational and rotational velocity of the vehicle are nonlinear. Although comparison against experiments appeared encouraging, the simplifying assumptions

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employed to carry out the simulation and the successive interpretation of the results, were not as straightforward as in the case of streamlined bodies. Saout and Ananthakrishnan (2011) proposed a theoretical methodology to determine the open-loop directional stability of a near-surface AUV. They used an approach similar to that carried out for surface ships that is based on solving the coupled sway and yaw equations of motion. The stability derivatives were obtained numerically through simulation of motions corresponding to planar motion mechanism model tests. For the numerical simulation, a boundary-integral method based on the mixed Lagrangian–Eulerian formulation was developed. The presence of the free surface, through radiation damping, was found to suppress unsteady oscillations and thereby to enhance the directional stability of the vehicle. The shape optimisation of an AUV required to operate at snorkelling condition close to the free surface, where torpedo-like shapes present some drawbacks, was studied by Alvarez *et al.* (2009). They dealt with this problem using a first-order Rankine panel method to compute the wave resistance on different axial-symmetric bodies moving close to the free surface, constrained to have the same overall volume. The optimised shape exhibited experimentally a smaller resistance than the reference one.

3 SHIP STRUCTURES – SPECIALIST TOPICS

3.1 Loads Versus Operational Guidance

Many new-build ships have extensive data collection systems that are used for continuous monitoring of engine and hull performance, for voyage performance and evaluation, etc. Often, such systems are, or could be, expanded to include also procedures for stress monitoring and for operational guidance, where statistics of the most critical wave-induced ship extreme responses and fatigue damage accumulation can be estimated for hypothetical changes in ship course and speed. The focus on goal-based standards (Papanikolaou *et al.*, 2010, Papanikolaou (Ed.), 2009, Skjong and Guedes Soares, 2008) implies that future developments of operator guidance systems should be based on numerical models that introduce probabilistic and risk-based approaches. Further remarks and discussions about risk-based methods for operational guidance have also been outlined by Shigunov *et al.* (2010), Bitner-Gregersen and Skjong (2009) and Nielsen *et al.* (2009).

The current state of the art in operational guidance typically relies upon mathematical models in which the on-site wave environment is automatically estimated. Ongoing developments in EU FP7 WATERBORNE project Handling Waves (2011) are driven by the development of systems that could be used for monitoring in real time the actual ship responses and associated structural loads due to weather changes and to possible changes in course or speed. The research programme supports the notion that the calibration of load predictions and the development of simplified numerical models that are accurate and fast is necessary in order to ensure that information and guidance are given with sufficient time to the ship's master. This is, for example, in further investigated and demonstrated in the work by Nielsen *et al.* (2009) and Nielsen (2010). In these investigations the horizontal acceleration and the racking failure mode of containers stowed on ships in heavy weather are studied. A procedure which can be used to obtain up-crossing rates for an inherent nonlinear ship response, such as the racking force in containers, is derived. It is also shown that first and second order reliability based formulations (FORM/SORM) and associated procedures may be significantly faster than more crude simulations (e.g. Monte Carlo). The motion simulation of container stacks on deck is considered also by Wolf and Rathje (2009).

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The authors deal with a (refined) numerical model from which knowledge about the dynamic forces acting on container stacks can be attained. The numerical findings and results of this work could be useful for establishing decision support criteria with respect to container and lashing loads. Considerations of computational efficiency in relation to calculation of fatigue damage rates in the ship hull girder and operator guidance have been presented by Ito *et al.* (2010) and Nielsen *et al.* (2011).

Typically, the underlying approach for operational guidance builds on a pure mathematical model, where the seakeeping characteristics of a ship, often given in terms of response amplitude operators (RAOs), are combined with information about the on-site sea state using linear spectral analysis to make statistical predictions of future responses to be expected. However, the on-site estimation of sea state parameters at the location of an advancing ship forms a crucial and fundamental problem to which a perfect solution has not been established. For this reason, concepts of a novel procedure for operational guidance have been proposed by Nielsen and Stredulinsky (2010) and Nielsen and Jensen (2011). The purpose of the procedure presented is to increase the reliability of the given guidance. Thus, predictions of future response levels are based on an integrated model using a mathematical model that has as input the estimated sea state parameters, and using also past measurements of the considered response(s). Both works include an analysis of full-scale motion measurements and the approach shows promising results.

3.2 Ice Loads

Environmental changes, harsher winters in the area of Baltic Sea and climate changes in other Arctic and Sub-arctic zones create new challenges for further exploration of Northern Regions including demands for more and environmentally safer ice-strengthened vessels. The following discussion reviews some key publications in the area of ice loading on ships and offshore structures that have been presented over the reporting period.

Bekker *et al.* (2009) described some of the characteristics of the drifting of ice cover and the associated scenarios of ice loads. Their study looks into the mathematical simulation of the physical process of interaction between the ice cover and the offshore engineering objects at Sakhalin offshore zone in terms of simulation and statistical methods. By taking into account the dynamics of an ice cover in the Sea of Okhotsk, the authors simulate various design cases of combined effects on marine structures from drifting ice features and ice fields. In a more recent study, Bekker *et al.* (2011) explored the results derived from a statistical modelling of ice loads on the ice-resistant platforms in Piltun-Astohsky and Lunsky oil and gas fields. The authors made a comparative analysis of ice loads on various types of gravity-based concrete structures according to the standards, procedures and guidelines imposed by different design codes. Comparative analysis of ice loads from level ice fields and from ridges show a wide range of load prediction variations. It is suggested that this scatter is caused by the various approaches and models for load estimation. Comparisons of the existing codes demonstrated that it is necessary to carry out long-term experimental and theoretical investigations including full-scale measurements on existing offshore structures.

Bjerkås *et al.* (2009) presented a case study employing direct simulation and empirical methods on the lighthouse Norströmsgrund in the Gulf of Bothnia. In this study design ice loads have been compared to existing code recommendations. It was concluded that the lighthouse was designed for a load level of 110 % higher than what is proposed

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by the recently issued ISO 19906 (2011) design code. Hence, it was suggested that separate dynamic analyses should be performed instead of simply adding amplification factors which is common practice in the prediction of static loads. On the other hand, Gürtner *et al.* (2009) simulated ice actions by means of a finite element model. In their approach fracture of the ice sheet was accounted for by the cohesive elements placed at internal FEA mesh boundaries in order to track traction versus separation forces. The simulation results indicated that the proposed numerical method derives comparable global ice loads to the lighthouse to those of the selected ice event.

Comparisons against the ISO 19906 (2011) standard for offshore installations are also provided by Masterson and Tibbo (2011). Their work looks into the determination of ice loads due to crushing on vertical structures and for bending loads on sloping structures. It is concluded that load calculations based on large scale measurements are preferable and more reliable than those made using small scale data which are then factored for full scale applications. It is also recommended that ISO 19906 could be the preferred guideline for determining loads on offshore structures placed in ice covered waters. Jordaan *et al.* (2011) presented a probabilistic load prediction model of the ice environment in the northeast Caspian Sea. Once again the methodology is consistent with approaches outlined in ISO 19906. The software used for the analysis included modules for season length, ice thickness and movement events, as well as ice crushing strength for vertical structures and models for flexural failure including rubble formation on sloping structures. A Monte Carlo approach has been used to simulate ice-structure interaction events on an annual basis. As a result a distribution of annual maximum forces from which n-year design loads can be extracted has been arrived.

Murray *et al.* (2009) reported the results from 1:30 and 1:50 model scale ice tests for the prediction of loads of an ice resistant spar design. They compared mooring and ice loads measured in fixed and compliant conditions. A limited number of tests were carried out at the two model scales in the same ice conditions to investigate scaling effects. The study indicated that the model scale testing methodologies employed, assuming the structure is fixed, provide good estimates.

Frederking (2010) described field data from operations of the CCGS Louis S. St-Laurent during a period of icebreaking escort operations in the Gulf of St. Lawrence in March 1985. The bow of the ship was strain gauged to measure ice impact loads. Forces, operational conditions (ship speed and power), and ice conditions (ice concentration, ice thickness and floe size) were recorded. From these data, time series of measured loads were used to obtain the maximum force of each measured impact, as well as the impulse associated with it.

Su *et al.* (2010) introduced a numerical method to simulate ship maneuvers and associated loads in level ice. The coupling between continuous ice forces and ship motions has been considered and the three degree-of-freedom rigid body equations of surge, sway and yaw have been solved by numerical integration. The numerical analysis results have been validated via comparison with the ship performance data from the ice trails of icebreaker AHTS/IB Tor Viking II. More recently, Su *et al.* (2011) derived an ice loading prediction process that has a clear stochastic nature due to the variations in the ice conditions and in the ice breaking processes of ships. The statistical characteristics of local ice loads were studied by field measurements. A numerical method was applied to simulate a ship moving forward in either uniform or randomly varying ice conditions where the thickness and strength properties of the ice encountered by the ship were assumed to be constant or randomly generated using the Monte Carlo

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method. To validate the numerical results, an icebreaking tanker, MT Uikku, has been modelled and the ice loading process was stochastically reproduced. The calculated amplitude values of the ice-induced frame loads were compared against the field measurements.

Haase *et al.* (2010) reported on the interaction between a conical structure and unconsolidated ice rubble that was simulated by a 3D discrete element simulation method. The failure process of the simulated ridge keels was studied by observing the rubble displacement during the simulation run. The simulation results were compared to full scale data and to results from an analytical ridge load model for cones.

Wang *et al.* (2011) described the development of a procedure for determining design ice loads on Arctic offshore structures using a first order reliability method (FORM) incorporating the uncertainties in the underlying ice floe and environmental parameters. In this work level ice and ice ridges were considered as major load sources interacting with the offshore structure in the ice regime. The geometric parameters of ice floes were assumed as random variables in the probabilistic approach. Specific site data were then used to demonstrate the results which are comparable to Monte Carlo simulations. It is concluded that the FORM approach is computationally economic and becomes increasingly accurate for rarer events.

Määttänen *et al.* (2011) reported on near full-scale ice crushing tests that were conducted in Aker Arctic test basin. An 1:3 scale ratio test rig was designed to allow ice to be crushed in controlled conditions against a stiffened plate presenting a typical full size ship or offshore structure plating. It was shown that contrary to expectations the plate compliance played no role in crushing pressure distribution. This differs from what is assumed in some ice rules, where the highest pressure is idealised at the location of stiffeners. The results also indicated that the ice crushing pressure in the design of plating thickness should be constant regardless of stiffeners.

Wille *et al.* (2011) presented a numerical model for drifting level ice interacting with a moored downward conical structure. The goal of this development has been to get better insight into the key processes that are important for the interaction process between moving ice and a floating structure. The level ice was modelled as a moving Euler-Bernoulli beam, whereas the moored offshore structure was modelled as a damped mass-spring system. It was concluded that the motions of the moored floating structure do not significantly influence the bending failure process of level ice. Also the influence of the in-plane deformation and the heterogeneity of ice on the bending failure process were found to be negligible. As a consequence, the dynamic response of the structure has been for the biggest part, determined by the ice failure process. Although the response of the structure can be dynamically amplified due to resonance for some particular ice velocities, no frequency locking of the ice failure onto one of the natural frequencies of the structure was observed. The model output showed qualitative agreement with model test results. It was however concluded that beamlike models of level ice sheets cannot accurately predict loading frequencies on downward conical moored floating structures because the ice blocks that break off are too long. Modelling level ice in two dimensions using plate may give better results, since it takes into account the curvature of a structure and both radial and circumferential ice failure.

3.3 Loads on Damaged Ship Structures

The principal difference between wave load effects employed for intact and damaged ships is driven by environmental conditions and exposure times after damage. While

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for intact ships the North Atlantic wave environment is usually adopted, local scatter diagrams are proposed, as applicable, for the reliability assessment of damaged ships (e.g. Luis *et al.,* 2009). Reduced exposure time to environmental conditions after damage should also be considered before salvage to a safe location. For example, Teixeira and Guedes Soares (2010) proposed a time period of one week as the voyage duration of a damaged ship to the dry-dock. They concluded that the mean extreme VBM of a Suezmax tanker is about 15 % lower when the exposure time is reduced from one year in the North Atlantic to one week in European coastal areas.

The magnitude of the loads on damaged ships is also subject to the extend and overall location of the damage. For example, Folso *et al.* (2008) and Rizzuto *et al.* (2010) have performed seakeeping computations on a damaged ship by the 3D linear hydrodynamic code PRECAL. For the case of the flooded ballast tank amidships, they obtained RAOs of the VBM worse than those evaluated in intact conditions. The correlation between sea states and occurrence of the accident is partly addressed in accordance to the IACS North Atlantic scatter diagram ($H_S \geq 7.5\,m$). The authors concluded that the VBM of the damaged ship reduces by 19 % of its mean extreme value when the vessel is exposed for one day in a truncated North Atlantic wave environment.

Hearn *et al.* (2008) also presented a study on the hydrodynamic and dynamic motion analysis of a damaged ship. In this work damaged ship statistics were used to provide the likely damage scenarios and particular emphasis was attributed on modelling the effects of water ingress when hydrodynamic and hydrostatic influences of the internal free surfaces as well as the aerostatic influences of the air contained within the damaged hold are accounted for. The change of the mean position of the internal surface as a consequence of the relative phasing of the motions of the ship and the internal free surfaces was also modelled.

Zaraphonitis and Samuelides (2009) addressed the loading induced on grounded hulls of bulk carriers. The determination of the loading included the influence of dynamic effects and the interaction of the hull with the sea bed in the grounding area.

An experiment on forced oscillation of a damaged ship section was presented by Drake *et al.* (2009). The authors simulated a damage of the keel by a longitudinal orifice. Various widths of orifice were investigated, with the damaged hull form in two configurations, open and airtight (to investigate the effect of trapped air stiffness). The hull was forced to oscillate for a range of amplitudes and frequencies and measurements of hydrodynamic force and internal free surface elevation are discussed.

Recently, Lee and Chan *et al.* (2011) developed a computational tool for the prediction of hydrodynamic loads of damaged ships. The results of the theoretical method and experimental tests were compared over a variety of design conditions. Whereas for the loads in intact condition, the prediction with a duration of 20 years at sea state 5 was used, for loads in damaged conditions, the prediction with 96 hours of exposure time at sea state 3 was employed. It was concluded that the maximum values of the most probable extreme amplitudes of dynamic wave-induced loads in damaged conditions are much less than those in intact condition because of the reduced time. An opening could change the distribution of not only still-water bending moment but also wave-induced bending moment. It is also observed that although some cross-sections are not structurally damaged, the total loads acting on these cross-sections after damage may be dramatically increased compared with the original design load in the intact condition.

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3.3.1 Still Water Loads of Damaged Ships

A review of stochastic models of still water bending moments applicable for damaged ships has been presented by Teixeira and Guedes Soares (2010). The simplest way to take into account consequences of the damage is to modify the still water load combination coefficient. Luis *et al.* (2009) proposed values of 1.1 and 1.5 to analyse the impact of the increased still water loads on the reliability of a grounded oil tanker. In most cases, flooding of ballast compartments in midship area is critical for double hull tankers, as this causes increase of sagging moments. Hussein and Guedes Soares (2009) calculated the effect of the flooding of ballast compartments of a double hull tanker and found increases of 30 % and 46 % for one side and both side damages respectively. Rizzuto *et al.* (2010) calculated asymmetrical flooding of the midship ballast tank on one side only of the Suezmax tanker. The still water bending moment corresponds to 152 % of the intact value for the same loading condition. They proposed to use coefficient of variation in reliability assessment of damaged ship slightly higher than for the intact ship. This is explained by additional effect in damaged conditions seen in water inflow and outflow through the damaged hull that is not accounted either in static or wave load analysis.

Santos and Guedes Soares (2008b) presented a time-domain theoretical model capable of predicting the behaviour of a damaged ship subject to progressive flooding in still water conditions. Their approach provides information in each stage of flooding, concerning the ship motions, the amount of water in each flooded compartment and shear forces and bending moments acting along the ship's length. Applications on a passenger Ro-Ro ship and a tanker led to the conclusions on the time required to reach the most critical conditions and the increase in global loads in damage condition. They also demonstrated that during the intermediate stages of flooding, floodwater distributions can be generated. Those may cause significantly higher shear forces or bending moments than the ones present in the final equilibrium damage condition.

3.3.2 Structural Integrity and Stability of Ships

Whereas computational methodologies and regulatory developments provide improved means for the assessment of the damage stability of ships in waves, there is still a long way to go before a variety of open issues, including combined loading and dynamic response matters, are fully satisfactorily addressed.

Papanikolaou (2007) reviewed the recent scientific and regulatory developments on the damage stability of ships and identified trends on the way ahead. Developments of numerical simulation methods for the prediction of damaged ship motions and associated loads in waves were discussed on the basis of related ITTC benchmark studies and the most significant open issues for further research were briefly addressed. In a more recent paper Papanikolaou *et al.* (2010) discussed the new probabilistic damaged stability regulations for dry cargo and passenger ships (SOLAS 2009), which entered into force on 1st of January 2009. Whereas these regulations represent a major step forward in achieving an improved safety standard through the rationalisation and harmonisation of damaged stability requirements there are serious concerns regarding the adopted formulation for the calculation of the survival probability of passenger ships, particularly for ROPAX and large cruise vessels. In Papanikolaou *et al.* (2011), the most recent progress of the work under the EU FP7 project GOALDS (Goal Based Damaged Stability, 2009-2012) is outlined. A thorough analysis and review of collected data of most recent grounding statistics of damages resulted to important new knowledge regarding the location and extent of grounding damages, both for passenger and

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cargo ships. A review of updated data of collisions damages, in which most recent ship damages were included, led to a confirmation of the validity of the currently used probabilistic modelling of collision damages for passenger ships, as considered in SOLAS 2009. Following the 1st international benchmark study of the 24th ITTC Specialist Committee on Stability in Waves (Spanos and Papanikolaou 2004), a 2nd international benchmark study on the performance of computer codes for the assessment of the stability of the damaged ships in waves was presented by Papanikolaou *et al.* (2008) under the work of the EU funded project SAFEDOR. Comparison of benchmark codes led to the conclusion that whereas the performance of standard computer codes remains unchanged the divergence of the numerical predictions for the damaged survivability of ships in waves is notable.

Santos and Guedes Soares (2008a) presented an application of shallow water theory to describe the motion of floodwater inside a damaged rolling ship in waves. A time domain hydrodynamic approach was applied to study the behaviour of a passenger Ro–Ro ship in regular beam seas and the characteristics of the floodwater motion were studied for a number of different wave frequencies. The dynamic floodwater roll moment was also compared against the static roll moment. The effects of parametric variations of different factors in the ship's survivability were addressed in a consecutive publication by Santos and Guedes Soares (2009). Numerical results were presented for a passenger Ro–Ro ship under a damage condition involving the main engine room. The permeability of this compartment was taken in consideration by modelling the engines as intact blocks. The ship's survivability in irregular waves has been assessed with respect to: the vertical location of the centre of gravity, the spectral description of the seaway, the roll damping factor and discharge coefficients, the depth to main deck, the double-hull in the main deck and the initial heel angle.

A **H**olistic **A**ssessment of Ship **S**urvivability **a**nd **R**isk after **D**amage was studied in the project EU project HASARD (SURSHIP, 2011). A comprehensive calculation procedure useful for quantitative assessment of damaged ships survivability (incorporating structural collision resistance, structural stability and collapse, time simulation of ship flooding and stability in waves) was developed. Results from systematic simulations through this calculation procedure (risk assessment/FSA) could be used in recommendations for future IMO rule making. Results of this project were published by Schreuder *et al.* (2010), following an interdisciplinary calculation procedure encapsulating the chain of events of ship collision, flooding, and loss of stability within given time. The presented method concerned the interaction between structural and damage stability computations and has been used to study the influence of various parameters such as the significant wave height and size of damage opening on a RoPax-ferry damaged in a collision with a ship of similar size.

The time dependent survivability of Ro-Pax vessels was also investigated by Spanos *et al.* (2010) by use of numerical simulations of ship motion and of flooding in waves. The study re-confirmed that a Ro-Pax ship may capsize fast when sustaining damages. The time dependent survivability may be estimated by applying a Monte Carlo probability simulation but may be limited within short times after the damage event.

Simonsen *et al.* (2009) presented the analyses and results of a study aiming at developing damage stability requirements which take into account the structural vulnerability to grounding damage, i.e. the kinetic energy available to generate damage and the structural resistance. The paper presents the analysis of new damage statistics in order to determine impact scenarios, in particular in terms of impact speed, impact location, and width and height of damage. A new empirical damage prediction formula

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was developed based on a combination of full-scale testing and extensive non-linear finite element analyses. This deterministic prediction method was validated against grounding experiments and then used in a probabilistic (Monte Carlo) simulation framework. It was concluded that the grounding damage statistics for all ships can be characterised by a single parameter namely the Grounding Damage Index (GDI) which includes the ship kinetic energy and its structural resistance to grounding damage. Simple, closed-form expressions were developed for the GDI and it was shown how the probability of exceeding a box-shaped damage is a simple function of the GDI and the size of the box. The paper therefore gives the background and the results for a new generation of damage stability rules where the structural crashworthiness is taken into account and where the passive safety level is explicitly expressed. It furthermore gives simplified prediction tools and data for actual ships, i.e. a toolbox that is readily available for risk analysis regarding grounding damage.

Kvon *et al.* (2010) addressed the coupled problem of loss of stability and structural integrity due to progressive flooding and structural failure by linear elastic fracture mechanics and the 'Paris Law' (Paris and Erdogan, 1963) crack propagation assessment methods. The authors considered the impact of wave induced loads on the deterioration of damaged ship strength. They applied adopted methods to the analysis of a sample ship mid-ship section sustaining collision or grounding damages and found both methods promising for concluding on the deterioration and the ultimate ship's strength after damage.

3.4 Green water

Shipping of green water occurs when the deck of the ship or a floating structure is immersed in the water. The green water constitutes in a certain sense a counterpart of the slamming problem provided that the water column impinges the structure from above. However, since the green water problem shares with sloshing similar flow features the computational approaches are in closer relationship with those applied to sloshing than to slamming phenomena. Within the reporting period research efforts concentrated on defining new methods that combine the straightforward calculation of pressure and loads of the techniques based on mesh definition (like FEM or BEM) with the interesting property of mesh-less methods, like SPH, that do not suffer large domain deformations or fragmentation.

Le Touzé *et al.* (2010) applied the SPH method to predict the fluid behaviour for two different dynamic flooding scenarios. The first is the interaction between a vessel and travelling waves. The second is the transient flooding behaviour that occurs during and immediately after a side collision between two vessels. Water heights were measured close to the point of impact within the vessel. Shibata *et al.* (2009) have proposed an incompressible variant of the SPH method known as moving particle semi-implicit method (MPS). In this paper, they compared the estimated pressure with the experiments of Tanizawa *et al.*, where the ship is towed in head waves. The investigation has shown that there is still some lack of agreement in terms of both pressure and forces acting on the deck due to relevant oscillations in time.

Chen and Kai (2009) developed a level set numerical method for the simulation of violent flows. In their approach Navier-Stokes equations were coupled with an interface preserving technique for the simulation of green water effects. Accordingly, the free surface flows were modelled as two phase (air/water) flows and represented by the zero level set function. Large eddy simulation (LES) and Smagorinsky models were employed to account for the effects of turbulence introduced by the violent free surface

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motions. The technique was employed for the simulation of slamming on a hemisphere and wet deck slamming of an X-Craft. Numerical results indicated that such an approach is able to deal with violent flows involving breaking waves, water droplets, trapped air bubbles and wave current interactions.

Zhu *et al.* (2009) developed a numerical program to model green water occurrence on floating structures based on a commercial CFD code. In their work a combination of numerical programmes is presented in which the motions of an FPSO are calculated by potential theory and CFD tools are used to investigate the details of green water impacts. A technique of dynamic mesh has been introduced in a numerical wave tank to simulate the green water occurrence on the oscillating vessels in waves.

Colicchio *et al.* (2010) proposed a 3D domain-decomposition strategy where a linear potential-flow seakeeping analysis of the vessel was coupled with a local nonlinear rotational-flow investigation. The Navier-Stokes solver was applied in the region close to the ship bow.

Lu and Yang *et al.* (2010) developed a numerical time domain simulation model to study green water phenomena and the impact loading on structures. A Volume of Fluid (VOF) technique was used to capture the violent free surface motion. The incompressible Euler Navier Stokes equations, written in an Arbitrary Lagrangian-Eulerian (ALE) frame, were solved using projection schemes and a finite element method on unstructured grids.

Lee and Lim *et al.* (2010) analysed and compared experimental results of green water on the deck of three different FPSO bow shapes in regular head waves. They established a database for CFD code validation and proposed some design considerations. The so called marker density method has been applied to capture the extremely complicate free-surface, including breaking, associated with the differentiated nonlinear governing equations.

Kendon *et al.* (2010) considered results from a 2D model test setup and compared the measured vertical loading on the deck against two simple potential theory based methods and against results from a commercial CFD code. The results demonstrated that a second impact event closely following a first impact event can have a much flatter free-surface profile (and stronger water entry force) as a result of its interaction with deck diffracted waves. They concluded that for isolated impact events the simple potential flow based models, which do not consider the influence of one impact event on another, are adequate to predict vertical loading. Extending the same strategy Colicchio *et al.* (2011) worked on the modelling of green water loads within seakeeping codes. They used a domain decomposition method and a potential flow analysis solver so as to determine the Navier Stoke inflow conditions. A similar problem was considered by Hu and Kashiwagi (2009) who studied the 2D water on deck problem with a constrained interpolation profile (CIP) based method. For the validation of the simulation, a new experiment involving a floating body of rectangular section in a wavy channel was designed. Reasonably good agreement was obtained with regards to body motions and the amount of water shipping, whereas still minor indications were given about local loads acting on the deck or the superstructure. The Natural Element Method (NEM) developed by Afansiev *et al.* (2011) employs both these features to solve the dam-break problem promising to be a valid alternative to other approaches for green water simulation.

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3.5 Sloshing

Sloshing is a phenomenon of fluid movement in a partially filled containment system that may be subject to nonlinear and possibly extreme external excitation. Over the course of the reporting period numerical solutions and model tests have been developed extensively with the aim to reliably capture aspects of sloshing behaviour on modern LNG vessels. In this particular case, due to the motion of the ship in waves, the LNG sloshes around the tank generating very high impact pressures on the containment system and the supporting hull structure. Recent advances concentrate on aspects of hull flexibility, model scale validation, use of advanced fluid dynamic methods for sloshing modelling or coupling with overall hull girder loads.

3.5.1 Model Experiments

Kuo *et al.* (2009) reviewed the relevant Exxon Mobil's sloshing assessment methods. In this work it is also highlighted that among the most significant developments is the introduction of a probabilistic based framework that facilitates modelling of the high variability of sloshing impact pressures due to sloshing physics and insulation materials.

Marès *et al.* (2009) described the main features into GTT's methodology for sloshing assessment. In an accompanying paper Pillon *et al.* (2009) presented how GTT developed and validated its numerical models to obtain a proper representation of the complex and nonlinear motions of the containment system. The authors explain that for the validation of numerical results model tests are necessary in order to analyse the behaviour of critical response components under different conditions related with the tank statics, dynamics or ambient and cryogenic temperatures. Gervaise *et al.* (2009) described recent GTT state of the art knowledge and developments on hardware improvements, assumptions for sea-keeping calculations, loads and strength evaluations.

Hirdaris *et al.* (2010) discussed some of the recent advances in model test tank investigations and reviewed the relevance of allowing unrestricted fill levels in LNG membrane tank ships. The assessment presented in this work allowed for a reduction in the barred fill range from 80 % to 70 % of the internal height of the tank. Model tests reviewing the loads on pump towers revealed that there are several issues related to the application of loads derived from model tests, namely (a) scaling issues due to the use of water and air (or some other ullage gas); and (b) suitable representation of the near boiling LNG liquid and vapour in the ullage space.

Brosset *et al.* (2009) provided an overview of the SLOSHEL Joint Industry Project along with information on experimental set ups, the parameters tested and numerical approaches employed. In furthering this work Bogaert *et al.* (2010a) and Zheng *et al.* (2010) highlighted aspects on scaling issues and summarised the key findings from model and full scale tests. Bogaert *et al.* (2010b) utilised a database of large scale impact tests and discussed in detail the behaviour of Mark III corrugated primary membrane systems under breaking wave impacts.

Bunnik and Huijsmans (2009) described a study of model test experiments on a large scale 2D section (scale 1:10) of an LNG carrier in various loading conditions without depressurisation. Using high speed video observations the wave front formed by the bore of the LNG in resonance was related to measured impacts on the tank hull. The loading on a hydroelastic hull panel with correctly scaled structural properties was also examined and the influence of the stiffness on the pressure pulse was found to be significant. Panigrahy *et al.* (2009) developed a liquid sloshing experimental setup to

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estimate the pressure developed on the tank walls and the free surface displacement of water from the mean static level. The pressure and displacements were measured on the basis of changing excitation frequency of the shaking table and fill level in the tank. The experiments were carried out without and with baffles.

Tabri *et al.* (2009) employed the numerical models developed by Godderidge *et al.* (2009) to study the sloshing induced liquid oscillation initiated by ship collision. Data about the dependence of accelerations, strain energy and tank water elevation on mass ratios and collision velocity were collected. Though only linear sloshing has been modelled comparisons between experimental trends and simulation analyses were reasonable.

Lugni *et al.* (2010a, 2010b) focused on the air cavity evolution during a depressurised wave impact, an event likely to occur not only in partially filled tanks but also in other violent flow phenomena like green water. Their underlying idea was to represent experimentally a repeatable impact event so as to distinguish its different stages and the main physical variables. It was concluded that air cavities may lead to the formation of highly localised pressures.

Xu *et al.* (2012) carried out sloshing model tests with 1:55 scale membrane-type LNG tank oscillating in regular harmonic motions. The purpose of this study has been to investigate the characteristics of free surface motions, impact pressures and structural responses. The structural features of the insulation layer were simulated by a plywood box equivalent to a $1.1\,m \times 1.1\,m$ simply supported panel and then scaled to a $20\,mm \times 20\,mm$ bronze sheet of $0.3\,mm$ thickness. A bidirectional strain gauge was disposed at the centre of each bronze sheet to measure dynamic stress responses. Impulsive spikes were presented in the temporal curves of structural strain records due to the sloshing impact pressures.

3.5.2 Hull Flexibility

Lee and Tan *et al.* (2010) investigated the coupling effect between a flexible ship and sloshing in beam regular waves by evaluating the added mass contributions due to liquid motions in partially filled tanks. Recently, Malenica *et al.* (2011) developed a modal (hydroelastic) method for assessing the influence of the dynamic motion of the liquid cargo in containment systems. Maguire *et al.* (2009) and Hirdaris *et al.* (2010) considered numerical simulations of fluid loading by CFD and structural response by FEA. The simulations described demonstrate that two different philosophies, namely the decoupled (or one way coupled) and coupled (or two way coupled) approaches are achievable. Accordingly, the effects of the transfer of pressures from the fluid code to dynamic FEA and the resulting instantaneous deformation response of the containment system boundary being transferred back to the CFD solver have been investigated. The later, although it may be computationally expensive, it allows for the use of the instantaneous deformed tank shape to evaluate the pressure at the each time step. However, it is computationally expensive.

Lee and Park *et al.* (2010) investigated the influence of hull flexibility on the hydrodynamic forces and moments associated with liquid sloshing and vice versa, as well as the dynamic characteristics (e.g. resonance frequencies) of the whole system. The method was validated by comparing hydrodynamic forces from sloshing obtained using rigid and flexible body approaches. The coupling effect between flexible ship and sloshing in partially filled tanks was investigated for an idealised LNG Carrier in beam regular waves, considering different partial filling scenarios.

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3.5.3 Advanced Numerical Methods

Gavory and de Seze (2009) reviewed the current status of the numerical methodologies used for sloshing assessment. Their work concluded that inviscid methods are still broadly used as an intermediate benchmark of validity against other available nonlinear computations. Cao *et al.* (2010) presented the range of validity of potential flow models by comparing the predictions with those by other CFD simulations and experimental measurements of the liquid motion in an oscillating tank.

Peric *et al.* (2009) demonstrated the application of a procedure to predict internal sloshing loads on partially filled tank walls of LNG ships subject to realistic wave excitations. A moving grid approach was employed and a finite volume solution method was designed to allow for arbitrary ship motions. An interface capturing scheme that accounts for overturning and breaking waves was used to compute the motion of liquid inside the tanks. Liu and Lin (2009) developed a Navier-Stokes numerical model to study the 3D liquid sloshing in a tank with a baffle. The numerical results were validated against available analytical solutions and experimental data. Another experimental study was performed by Wu and Chen (2009) who developed a 3D time independent finite difference method to study the sloshing waves and resonant modes of a fluid in a 3D tank. In this work, five distinct types of sloshing waves were observed and they were closely related to the excitation frequency.

Delorm *et al.* (2009) investigated experimentally the 2D shallow water sloshing phenomenon under forced rolling motion conditions by the SPH method. The numerical model depicted reasonably well the free surface shape obtained from tests and assisted in reproducing the pressure trends during a water impact, though overestimating the maxima. Lee *et al.* (2010) described an efficient and robust moving particle semi-implicit method to predict violent free-surface and floating-body motions as well as impact pressures. The floating-body-motions and the impact pressures induced by violent liquid sloshing motions were verified by comparing numerical results against conventional methods. It was concluded that the roll amplitudes could be significantly reduced for excitation frequencies away from the lowest sloshing natural frequencies.

Thiagarajan *et al.* (2011) applied a CFD method accounting for air/water interaction to the problem of sloshing in a rectangular tank. The fill levels varied from 10 % to 95 % of tank height, corresponding to a 1:30 scaled model of a prototype tank. The study employed the $k - \epsilon$ turbulence model to capture the features of the flow and a volume-of-fluid (VOF) model to track the sloshing free surface.

3.5.4 Coupling Sloshing with Motions

Faltinsen and Timokha (2009a, 2009b, 2011) presented an overview of sloshing in the tanks of ships with swash bulkheads. The authors highlighted that whereas nonlinearities are important for the assessment of sloshing excitations, ship hydrodynamics may be handled well by linear theory except for the motions and loads associated with viscous roll damping.

The use of simplified modelling of sloshing is also perceived as a mandatory approach when the interaction between global ship motion and partially filled tanks are investigated. This guideline was followed for instance by Lin *et al.* (2011) and Hirdaris *et al.* (2010) using a potential model for global ship motion coupled with a sloshing model for the prediction of LNG tank loads, the last one based on a RANS code with VOF surface tracking that exploits the open source CFD code OpenFOAM libraries.

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Hashimoto *et al.* (2010) reported on the use of nonlinear potential theory and particle based hydrodynamics for the coupled formulation of the sloshing/seakeeping problem. Bunnik and Veldman (2010) compared the results on RAOs of roll motions obtained linear and particle based hydrodynamics approaches against the experimental results reported by Molin (2008). They concluded that whereas linear potential theory shows a reasonable agreement there is a slight difference with the experiments near the sloshing peak frequency in terms of the spread of the peak as well as the shift of the peak frequency. The use of nonlinear potential flow hydrodynamics may allow for good agreement in all frequency ranges for both low and high sea states.

Huang *et al.* (2009) discussed the global force acting on the tank under coupled internal liquid and LNG carrier sway motions based on numerical and experimental results. They showed that the coupling between the tank sloshing and ship motions can be predicted by a linear potential theory as the global forces induced by the liquid sloshing are relatively periodic and deterministic whereas the local sloshing pressures are highly nonlinear and do not affect the ship motions.

Lee and Kim (2010) investigated the coupling and interactions between ship motions and inner-tank sloshing by a potential-viscous hybrid method in the time domain. For the time-domain simulation of vessel motions, the hydrodynamic coefficients and wave forces were obtained by a potential theory based 3D diffraction/radiation panel program in the frequency domain. The corresponding simulations of motions in the time domain were carried out using the convolution integral method. The liquid sloshing in a tank was simulated in the time domain by a Navier-Stokes solver. A finite difference method with SURF scheme assuming the single-valued free-surface profile was applied for the direct simulation of liquid sloshing. The computed sloshing forces and moments were applied as external excitations to the ship motion.

Nam *et al.* (2009) considered the motion responses of floating bodies in waves coupled with sloshing-induced internal forces and their effects on sloshing-induced impact loads. The linear ship motion was solved by using an impulse-response-function method. The nonlinear sloshing flow was simulated using a finite difference method. Two models were considered namely (a) a liquid natural gas floating production, storage, and off-loading unit with two partially filled tanks and (b) a modified S175 hull with an anti-rolling tank.

Tabri *et al.* (2009) studied the sloshing interaction in ship collisions both experimentally and numerically. Sloshing affects the collision dynamics and reduces the amount of energy available for structural deformations. An understanding of the interaction phenomenon was obtained by a series of model-scale experiments, in which a striking ship, with two partially filled tanks, collided with an initially motionless struck ship without any liquid on board. The simulation model was validated with experimental results and good agreement was achieved in the case of medium filling levels in the tanks. Tan *et al.* (2010) on the other hand investigated the influence of hull flexibility on the hydrodynamic forces and moments associated with liquid sloshing and the effects of sloshing on wave induced responses. It was observed that the liquid sloshing has an influence on the response of distortional as well as rigid modes, i.e. wave-induced motions and loads.

Bunnik and Veldman (2010) employed the following two different models to take into account the effect of sloshing on ship motions: (a) a linear diffraction method in which both the liquid motions in the containment system and the liquid motions outside the vessel are described by linear potential flow in the frequency domain; (b) a time-domain coupling method in which the sloshing liquid in the containment system is

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computed by CFD (Volume of Fluid method) and the ship hydrodynamics by means of linear diffraction theory. Both methods were applied to model tests described by Molin (2008), in which he measured the motion response of a barge with a partially filled water container on deck.

3.5.5 Design Assessment Procedures

Over the reporting period, procedures to predict sloshing loads and evaluate structural strength have been introduced by most Classification Societies. For example, Lloyd's Register (2009) developed a comprehensive sloshing assessment guidance document with recommendations on the procedures that can be applied for the assessment of sloshing loads on LNG tanks. The procedure comprises of three parts namely (a) ship motions analysis and determination of the design sloshing loads (b) structural analysis and (c) assessment criteria.

Wang and Han (2009) and Wang and Arai (2010) conducted a dynamic structural analysis, considering fluid-structure interaction, to determine the design strength capacity for the No. 96 containment system using sloshing model tests in terms of selected environmental conditions, vessel configurations and loading conditions. In these studies spatial, temporal and statistical characteristics of the measured sloshing loads were investigated. Linear transient FEA of the No. 96 containment system including both the structure and the LNG was performed to obtain structural responses at predefined critical locations under short duration triangular pulse which is referred to as Triangular Impulse Response Function (TIRF). In the FEA model orthotropic material properties for plywood and acoustic medium for LNG were considered. Statistical analysis results of peak stress values in each component of the containment system were used as the basis for determining design sloshing loads or strength assessment of the No. 96 containment system.

4 OFFSHORE STRUCTURES – SPECIALIST TOPICS

4.1 Offshore Lifting and Installation

Understanding of the loads imposed upon operating offshore floating cranes has been of interest for many years (e.g. Schellin *et al.*, 1989). The analysis of offshore crane vessels can be largely divided in two main categories namely structural analysis and hydrodynamic analysis.

In recent publications, Al-Sweiti *et al.* (2007), Ren *et al.* (2007) and Cha *et al.* (2010) reviewed the literature and reported on the effects of undesired crane load motions. The common approach applied assumes that the excitation is simply a prescribed motion of the pivot point of a hoisting rope. This assumption leads to a dynamical model with parametric excitation while the motion of the vessel is neglected. Although such an approach may be justified for vessels in sheltered basins and if the load to vessel ratio is very small, it is certainly not appropriate for large moored floating cranes operating offshore. The dynamics of such vessels is affected by strong coupling between vessel and load motions and depend on the characteristics of the mooring system. Along these lines, Al-Sweiti and Soffker (2007) developed mathematical tools for modelling and control of elastic ship cranes which have the Maryland Rigging system. Their study was extended by Ren *et al.* (2007) who demonstrated the effects of lifting cable length, reeling and unreeling speed of cable and wave frequency on cargo dynamic response. Cha *et al.* (2010) performed a more rigorous numerical analysis to identify the effects of nonlinear static and dynamic response of a floating crane and a heavy block that are connected using elastic booms and wire ropes. In

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their work two mathematical models of different levels of complexity have been used to systematically determine the responses of the vessel payload systems to periodic forcing of waves. One technique is the multiple scales method which allows for the investigation of the nonlinear dynamical system in frequency domain and results in an analytical solution. The other technique applies numerical path following methods to trace bifurcations (parameter values for which a qualitative change in the dynamics can be observed) of periodic solutions.

4.2 Cables, Risers and Moored Structures

The publications concerning cables risers and mooring systems during the reporting period deal primarily with the coupled floater mooring global response. It is also evident that there is still a great deal of interest for issues that influence the nonlinear dynamic behaviour of mooring lines and the slow drift motion of the moored floaters. Recent developments on the later were highlighted in section 2.1.3 (e.g. Hansen *et al.*, 2009; Clauss and Sprenger *et al.*, 2009; Brake *et al.*, 2009).

The purpose of coupled analysis is to accurately predict the loads on mooring lines and risers at extreme design conditions. Chan and Ha (2008) used a fast domain coupled analysis along with a frequency domain mooring analysis to predict the first order slowly varying drift motions of an FPSO in design conditions. The line tensions predicted in the time domain were compared with the frequency domain solutions. Chen *et al.* (2008) used the coupled analysis to assess the effect of two different top tensioned riser configurations, one with buoyancy cans and one with tensioners on the motion responses of a truss spar in ultra deepwater. Nonlinear spring properties of tensioners and hydrodynamic loadings on the risers and the mooring lines were calculated.

The coupled analysis requires extensive computational efforts. Hence there is a need for the development of more simplified methods for use in practical design applications. Within the reporting period efforts concentrated on developing a highly efficient frequency domain approach in which the drag forces are linearised. For example Low and Grime (2011) have shown that the geometric nonlinearity of the mooring lines/risers may be insignificant. This was demonstrated by applying statistical techniques in conjunction with frequency domain analysis to predict the extreme responses of the coupled system. The crossing rates for surge, sway and yaw obtained were found to agree well with those extracted from the time domain simulation, whereas the result for yaw is less favourable.

4.3 Vortex Induced Vibrations (VIVs) and Wake Induced Oscillations (WIOs)

VIVs are highly nonlinear motions induced by flow periodical irregularities. Over the last few decades, significant progress has been made in understanding the VIVs of long circular cylinders by means of numerical simulations and physical experiments. The following discussion highlights some recent operational considerations as well as theoretical developments in the area of VIVs and Wake Induced Oscillations (WIO).

From an operators' perspective it is today far more desirable to eliminate or reduce VIVs than it is to amplify their effects. For example, Tongarelli and Taggard (2008) reported on the hydrodynamic performance of various offshore units and production platforms. The measured data presented in this work shed some light on the physical details of full scale riser response omitted from predictive riser design tools. They were also used to establish performance indicators for some VIV suppression devices that are currently in use.

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A comprehensive review of VIV prediction methods was presented by Williamson and Govardhan (2008). The authors summarised fundamental research results presented over the last two decades. Many of those are related with the push to understand and, as applicable, implement very low mass and damping mechanisms in existing and forthcoming experimental and computational techniques. The authors focused on vortex induced dynamics and energy transfer phenomena that may give rise to dynamic loads. More recently, Kevlahan (2011) employed potential flow and 2D Navier Stokes calculations to investigate the role of vortex shedding in the non resonant flow induced vibration of periodic tube arrays. This dual approach untangles the effects of potential and vertical flow. The negative damping theory is shown to be inconsistent with the Navier Stokes simulations allowing only a single degree of freedom in tube motion. Whereas the later is thought to significantly overestimate the simulation of critical velocities, the results presented assist to untangle the role of vortex shedding and potential flow in way of the non resonant fluid elastic instability of tube arrays.

Investigations on flow interaction with moving circular cylinders have always been carried out in 2D because of the unaffordable computational effort that 3D simulations may demand. There are a number of publications in this topic. For example, Prasanth (2006) studied the laminar flow induced vibration of a circular cylinder at low Reynolds numbers. On the other hand Wanderley *et al.* (2008), and Al Jamal and Dalton (2004) adopted RANS and LES turbulence models to simulate the VIV response at moderate Reynolds numbers. Such studies have also been extended to cases of two circular cylinders. For example, Prasanth and Mittal (2009) built upon the work of Schulz and Kallinderis (1998) and Papaioannou *et al.* (2008) and reported on the shielding effect of upstream cylinders in laminar flow induced conditions.

In contrast to VIV problems understanding of the downstream effects in WIO is relatively lagging behind. This is probably because of the technical difficulties to approximate the large amplitude motions that mooring and riser cylinder like structures suffer from. Recent studies mainly focus on model measurements. For example, Okajima *et al.* (2007) studied the stream-wise oscillation of two tandem circular cylinders in different arrangements. On the computational developments front Meneghini *et al.* (2001), Jester and Kallinderis (2003) reported on 2D laminar flow interactions between two fixed circular cylinders. Carmo and Meneghini (2006), Deng *et al.* (2006), Kitagawa and Ohta (2008), Palau-Salvador *et al.* (2008) performed 3D numerical simulations at different Reynolds numbers using approximation models (e.g. LES methods) that are able to simulate turbulence effects.

4.4 Spars and TLPs

The successful design and operation of floating production units requires appropriate evaluation of the environmental loads that prevail during transportation installation and operation. To this end recent research also concentrated on spars and Tension Leg Platforms (TLPs).

A numerical prediction of the spar motions in waves, wind and current was carried out by Liapis *et al.* (2010). The predictions were based on the COSMO/WAMIT commercial software and compared well with model test results. Special line members were included to take the viscous loads and damping into account. Koo *et al.* (2010) studied the motions and loads for the float-over installation of spar topsides. The numerical analysis involved multi-body hydrodynamic interaction, simulation of impact forces and validation studies. In the transportation analysis it was found that the predicted

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catamaran barge global motion statistics were slightly conservative in comparison with those of the model tests.

In the past three years research on TLPs concentrated on experimental and numerical studies. The aim has been to improve their design by damper mechanisms that may reduce the loads on the tendons. For example, Heidari *et al.* (2008) presented a study on the design of a dry-tree FourStar TLP operating in a 4300 ft water depth. Bian *et al.* (2010) presented the design of an integrated ultra-deepwater TLP with an air spring type vibration absorber to suppress the vertical resonance motions. Jayalekshmi *et al.* (2010) investigated the effect of tether-riser dynamics on the response characteristics of deepwater TLPs in water depths of 900 m and 1800 m and in random waves. The nonlinear dynamic analysis of deep water TLPs was carried out by using FEA and results were reported in the form of statistical responses. These values increase with water depth and a significant increase was observed when risers were included in the analysis. Taflanidis *et al.* (2008) also explored the idea of using mass dampers for the reduction of dynamic loadings and hence the protection of offshore platforms. To achieve greater vibration suppression appropriate tuning of the parameters of the dampers was necessary. The later was achieved by a stochastic design approach.

Srinivasan (2010) addressed the use of TLP in ultra deepwater to support dry-tree in oil and gas production. To reduce the effects of the wave loading, truss-pontoons were used. A technically feasible and cost-effective artificial sea-bed was used to ease the tendon design in deepwater and harsh environment. As a result a simple and slim hull, which is easy to design, fabricate, transport and install, was obtained. Lee and Lim (2008) studied the fatigue induced loads on a TLP by using a frequency domain analysis coupling the effects of first order wave, mean drift and linearised viscous forces. Survivability analysis was then carried out in the time domain where the second order wave and nonlinear viscous forces were considered. The optimisation process led to a hull form with improved dynamic performance and minimised top tension of the tendon.

4.5 Semi-submersibles

The study on loads of submerged bodies has received considerable attraction for many years. The interaction between gravity monochromatic waves and a fixed submerged horizontal circular cylinder with its axis parallel to the crests of the incident wave was first studied by Dean (1948) who used a linearised potential theory and a conformal mapping technique. The first experimental study related to this phenomenon was undertaken by Chaplin (1984) who calculated the nonlinear forces of the reflected and transmitted waves originated by a fixed submerged horizontal cylinder. His study revealed the nonlinear components of these forces with frequencies up to 3 times the fundamental wave frequency.

Over the last few years the analysis of hydrodynamic performances of submerged bodies has become increasingly important with the growing interest in offshore activities related with the generation of ocean wave energy via wave induced motion of oscillating submerged bodies. For example, numerical and experimental studies by Kent and Choi (2007) suggested a solution for the velocity potential imposed upon submerged bodies by a multi pole expansion. More recently, Conde (2009) studied the fully behaviour of a 2D horizontal cylinder by a nonlinear diffraction analysis theory. Guerber *et al.* (2010) extended a 2D fully nonlinear potential flow numerical wave model to include a submerged horizontal cylinder of arbitrary cross-section. The in-

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teraction between the free-surface flow and the surface tension for a circular horizontal cylinder has been investigated by Moreira and Peregrine (2010). Yan *et al.* (2010) has investigated the fully nonlinear interaction between freak waves and 2D submerged cylinders and Bai *et al.* (2010) has studied the 2D submerged dikes interaction with viscous free surface waves using the Cartesian cut cell approach.

Matsumoto *et al.* (2010) carried out wave basin tests for a large semi-submersible. They observed relatively large low-frequency motions in heave, roll and pitch, which affected the dynamic air gap measurements and loads. Hussain *et al.* (2009) discussed the requirements for a floating vessel designed to support top tensioned risers. Mansour (2009) introduced the performance of a new conceptual semi submersible design that provides motion response similar to a Spar. It was concluded that the use of a free-hanging Solid Ballast Tank (SBT) may significantly increase the heave natural period while controlling the heave response in the wave frequency range.

Current loads on stationary submerged vessels have been investigated by Vaz *et al.* (2009). Model-tests, semi-empirical models and CFD methods were used to predict these loads. Two key issues affecting the modelling accuracy, the location of the transition to turbulent flow and the control of the numerical errors were identified and discussed. Their field measurements indicated that the design guidance derived from model tests, as presented by Rijken and Leverette (2008), result in very conservative estimates motions. It was also observed that the flow field around the columns may cause oscillations along one of the vessel's main diagonals under particular conditions.

Simos *et al.* (2009) showed that semi-submersible hulls may be subjected to second order slow motions in heave, pitch and roll. These resonant motions are directly related to the large dimensions and relatively low natural frequencies of the floating systems. Their paper discussed the evaluation of the 2nd order wave induced motions of a large-volume semi-submersible platform using the WAMIT second order module. It was shown that the hydrodynamic forces induced by the 2nd order potential affects significantly the resonant response. Matos *et al.* (2010) studied the scale effect of the slow drift motions in vertical plane of a large volume semi-submersible platform. The importance of considering the resonant roll and pitch motions in the seakeeping analysis of large-volume semi-submersible platforms was demonstrated.

5 UNCERTAINTIES IN WAVE LOAD PREDICTIONS

Specification and quantification of uncertainties related to environmental models, load predictions and response calculations is important part of the risk-based assessment, design and operation of marine structures. To date, load uncertainties have been specified by reliability based code formats (e.g. Bitner-Gregersen *et al.*, 2002) and for development of decision support systems that may be useful for navigation guidance (e.g. Spanos *et al.*, 2008; Bitner-Gregersen and Skjong, 2009). Bitner-Gregersen and Skjong (2009) suggested to divide uncertainties into two groups namely (a) aleatory (natural and physical) and (b) epistemic (knowledge based). According to the authors the information about uncertainties should be introduced in the reliability analyses in the form of random variables. Aleatory uncertainties represent a natural randomness of a quantity, also known as intrinsic or inherent uncertainty, e.g. the variability in wave intensity over time and cannot be reduced or eliminated. Epistemic uncertainties represent errors which can be reduced by collecting more information about a considered quantity and by improving the methods of measuring it. These uncertainties may be classified into: (a) data related (b) statistics related and (c) model related.

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Data uncertainties appear due to the imperfection of an instrument used to measure a quantity, and/or a model generating data. If a considered quantity is not obtained directly from the measurements, but some estimation process is interposed (e.g. the significant wave height), then the measurement of uncertainty must be combined with the estimation of model uncertainty by appropriate means. Statistical uncertainty, often also referred to as estimation uncertainty, is due to limited information such as a limited number of observations of a quantity and also due to an estimation technique applied for the evaluation of the distribution parameters. Model uncertainty is due to imperfections, simplifications and idealisations made in physical model formulations for an event as well as in choices of probability distribution types used in the representation of uncertainties. The accuracy of a quantity characterises the extent to which a measured quantity agrees with the true value. To characterise the later it is necessary to indicate a systematic error (also known as bias) and a precision (or random) error. The systematic error, or bias, of an estimator for a quantity considered refers to a systematic deviation from the true value of the quantity. The precision of the quantity considered refers to random variations, and is usually summarised by the standard deviation. A normal distribution is commonly adopted to describe the precision.

Significant efforts have been made by ISSC in recent years to explain uncertainty in predicted extreme wave loads on ships (e.g. ISSC, 1997, 2000). Roughly, uncertainty in wave loads may be divided into uncertainty of wave loads calculated under linear assumptions and uncertainty of nonlinear effects. Uncertainties of linear wave load predictions refer to the shape of wave spectra, the choice of wave scatter diagram, transfer functions, methods for prediction of long-term extreme values and human actions. Uncertainty of nonlinear effects in wave loads may comprise different sagging and hogging bending moments mainly due to non vertical ship sides and influence of slamming and whipping on extreme vertical bending moments.

The traditional approach for assessing the wave induced loads in intact ships structures assumes that the sea states are dominated by wave systems generated by local winds. However, in many situations marine structures are subjected to the combination of more than one wave system and in this case the frequency spectrum exhibits two peaks. Double-peaked wave spectra can be observed when a swell system combines with wind-generated waves. For example, Teixeira and Guedes Soares (2009) have demonstrated that, for a trading ship of non-restricted operation, the long-term distributions of the wave induced vertical bending moment for combined sea states do not change significantly when compared with the ones obtained from sea states of a simple component. In their work it is recognised that double peaked wave spectra can have a significant impact on the design and operability of fixed and offshore platforms. They suggest that it would be important to assess damaged ships since collisions and groundings may occur in sea areas with swell dominated sea states and the manoeuvrability may be affected as a consequence of the accident.

Ivanov (2009) proposed a method for calculating the hull girder bending stresses following the procedure in the class rules but in probabilistic terms. In this work the still water and wave-induced hull girder hogging and sagging loads are presented in probabilistic format as one phenomenon, i.e. using bi-modal probability density functions. The probabilistic distribution of the total hull girder load is calculated using the rules of the composition of the distribution laws of the constituent variables. Parunov and Ćorak (2010) investigated the influence of environmental and operational uncertainties on the long term extreme vertical wave bending moment of a container ship assuming rigid hull. As the long term distributions of vertical wave bending moments

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are highly dependent on the assumed environmental and operational parameters, their different combinations are considered. Results are compared among themselves as well as with the IACS rule vertical wave bending moments. Statistical parameters which may be useful for reliability-based design of container ships are quantified. Shu and Moan (2009) studied the effect of the heavy weather avoidance on the long-term wave-induced pressure along the midship transverse section of a VLCC and a bulk carrier. They proposed a practical model to consider the effect of heavy weather avoidance on the wave pressure along a mid-ship transverse section. Mohhamed *et al.* (2009) discussed the basis of a cross-spectral formulation that could be used to assess the combined effects of wave loads on hull girder strength. The methodology accounts for long term probability distributions and considers phase relationships between narrow banded load processes.

Jensen (2009) discussed useful stochastic procedures for wave load problems covering the range from slightly linear to strongly non-linear (bifurcation) problems. The methods employed were (a) Hermite transformation, (b) Critical wave episodes and (c) First Order Reliability Method (FORM). The procedures are illustrated by results for the extreme vertical wave bending moment in ships. Another simplified procedure for determining the long term distribution of wave hull girder loads acting on container ships including transient loads such as slamming and green water effects has been presented by Jensen *et al.* (2009). The authors combined high frequency transient loads with lower frequency wave induced loads and the entire simplified solution is presented in closed-form solution. For non-linear processes a good estimate for the mean out-crossing rate was found using FORM. An interesting – but not general – property with the FORM analysis for the specific problem of the extreme bending moment is that the associated reliability index is inversely proportional to the significant wave height for fixed values of other operational parameters. As pointed out by Jensen (2010) this means that the computational efficiency of Monte Carlo simulations for the specific problem can be increased drastically by introducing a scaling of the significant wave height; a phenomenon previously investigated by Söding (1986). Gaidai *et al.* (2010) described a method for the prediction of extreme whipping stresses measured in deck amidships a container vessel during operation in harsh weather. Whipping response time series were analysed for two different voyages of the same ship, similar route and similar season month. Two different statistical methods were applied and compared with respect to the extreme response estimate. Parunov *et al.* (2011) investigated long-term distribution of slamming loads of container ships accounting for different types of environmental and operational uncertainties. In this work the uncertainties studied were (a) the choice of the wave scatter diagram, (b) the effect of the avoidance of heavy weather, (c) the effect of the manoeuvring in heavy weather and (d) the method for predicting the long-term extreme slamming pressures.

6 FATIGUE LOADS FOR SHIPS AND OFFSHORE STRUCTURES

6.1 Fatigue Analysis of Ships

In recent publications the contribution of high frequency whipping and springing vibrations to the fatigue damage in the hull girder is extensively studied by Storhaug (2007) and Storhaug and Moan (2007). It was concluded that the high frequency components could be as important as the contributions from the wave frequency range. Similar observations have been found from full-scale measurements in container ships and LNG vessels, e.g. Storhaug and Moan (2007), Heggelund *et al.* (2010) and Nielsen *et al.* (2011). As noted by Storhaug (2007) it is difficult to distinguish be-

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tween springing and whipping vibration components in full-scale measurements and their individual contribution to the fatigue damage cannot be assessed easily from such measurements. In total they might, however, typically increase the expected fatigue damage by 20 – 50 % depending on the sea state, loading condition, speed and heading. Based on both full-scale measurements and model tests, the following general conclusions can be made with respect to fatigue damage accumulation in the hull girder of ships:

- The correlation between significant wave height and fatigue rate is strong, and most fatigue damage is accumulated in head or following sea (Heggelund *et al.*, 2010);
- It is necessary to further study the effect of safety margin between hull girder capacity and loading by a more refined approach (Storhaug *et al.*, 2010a);
- Whipping and springing-induced fatigue accumulation is a complex phenomenon, which is not properly included in design rules yet (Storhaug *et al.*, 2010b; Boutillier *et al.*, 2010);
- The only way to progress in the understanding of fatigue phenomena is to combine all the available tools including model tests, full-scale measurements and numerical models/simulations (Storhaug *et al.*, 2010b).

In a slightly different line of work, Garbatov *et al.* (2010) studied the combined effects of vibration and wave induced loads on fatigue. Their analysis considered local and global loads due to wave actions and cargo effects by means of the hot spot fatigue analysis approach. Detailed FEA was used to determine the critical hotspots and the stress distributions on the hull structural joints. As a result of the performed analysis the stress concentration factors have been defined and used for fatigue damage calculation by taking into account the combination of low-frequency wave induced loads and transient loads. It was concluded that the calculated local stresses around the structural singularities depends on the structural idealisation, the element types used and the mesh subdivision. In a subsequent publication Garbatov and Guedes Soares (2010) reported on the importance of assessing fatigue life prediction related uncertainties by discrete, closed form and spectral approaches. This work analysed the influence of various factors (e.g. ship main characteristics, operational profile, wave climatic data, heading distributions) and considered the random origin of structure born deviations (e.g. mean stress effect, imperfection, weld shape improvement, hot spot calculation and resulting notch stress concentration factor) to the fatigue life of a butt welded ship structural component. It has been observed that there is significant difference between the mean fatigue damage pairs of the heading direction and distribution. Also, different fatigue damage calculation approaches may introduce different level of uncertainties resulting in different means and standard deviations of fatigue damage.

A number of studies have recently been dedicated particularly towards onboard monitoring of fatigue damage rates. Models and procedures have been developed to evaluate fatigue damage accumulation in the hull girder both for short-term (30 minutes to 3 hours) decision support, (e.g. Nielsen *et al.*, 2011) and for long-term voyage planning (e.g. Mao *et al.*, 2010a and Mao *et al.*, 2009). These studies present comparisons between measurements and predictions of fatigue damage rates and promising results are obtained. As uncertainties related to fatigue damage analysis can be profound independently of the prediction period, it should be considered to use risk-based approaches for the evaluation of fatigue damage rates. This has not been attempted until now, but ideas may be gained from the studies by Mao *et al.* (2010b) and Choung *et al.* (2010).

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6.2 Fatigue Analysis of Offshore Structures

Fatigue is one of the most significant failure modes for offshore platforms which are mostly made of metals (Bengtsson and Rychlik 2009, Cui *et al.* 2011). Metal fatigue has been studied for more than 170 years. However, the fact that fatigue life prediction methods are not based on Fatigue Crack Propagation (FCP) theories remains a concern. Cui *et al.* (2011) outline their idea to develop a unified fatigue life prediction (UFLP) method for marine structures. The key issue for this development is to establish a correct crack growth rate relation. Hence, a new crack growth rate model based on the concept of partial crack closure is presented. It is concluded that their improved model shows strong capability in simulating the crack growth curves under different load ratio of various metal materials. Moreover, the model has been successfully applied for simulating some special fatigue phenomena such as compressive to compressive loading effect and overload retardation effect.

The importance of uncertainty in fatigue life prediction of marine structures subjected to Gaussian loads has been discussed by Bengtsson and Rychlik (2009). In particular, they discussed how general types of environmental loads (that often vary with time) can be included in a stochastic by computing a measure of risk for the fatigue of a structural components during a specific time period. In their model, the combination of different types of uncertainties was facilitated by use of a calculated safety index. Another study which deals with uncertainty related to the analysis of fatigue data has been presented by Guida and Penta (2010) who introduced the concept of Bayesian inference. In their study a Bayesian analysis of SN fatigue data is outlined for estimating material properties and for establishing fatigue design curves from small size samples.

Recently, two practical approaches for fatigue life assessment have been presented. The former by Low (2010, 2011) presents an approach for calculating the fatigue damage from a stochastic bimodal process, in which the High Frequency (HF) and Low Frequency (LF) components are of narrow band Gaussian format. The novelty of this method is claimed to be its ability to incorporate two critical effects, which have been unrecognised in prior studies; the reduction of the small-cycle amplitudes caused by the LF process, and the offset between the HF and LF peaks. The approach is found to produce highly precise damage estimates ($\sim 1\,\%$ error) when benchmarked against simulations made as a number of case studies of theoretical multimodal processes (with no particular attention to where the process may derive from). On the other hand the approach by Jia (2011) looks at the calculation of wind induced fatigue of tubular structures by taking into account the effects of the wind direction, across wind and wind grid size. It is argued that calculation procedure has the merit of reducing uncertainties without degrading a required safety level, which may lead to a positive economic impact with regard to construction and maintenance costs.

7 CONCLUSIONS

7.1 Wave Induced Loads on Offshore Structures

Traditionally, the prediction of wave loading of zero speed body wave interactions has been based on potential flow solutions for the prediction of global loads imposed upon FOIs. Research results have also been presented in the area of bottom founded structures. There is clearly a trend towards the use of CFD based methods and nonlinear hydrodynamic diffraction approaches. However, these models require further experimental verification.

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When shallow water operation is considered, the influence of the seabed bathymetry variation on the loads needs to be examined. Current research is directed towards understanding the effects of varying water depths and associated high frequency responses of FOIs in waves by using nonlinear diffraction models, Langragean – Eulerian methods and hybrid methods for the assessment of sloshing motions in the time domain. Once more these approaches require further experimental verification.

Side by side configurations that are used in offloading operations drive developments in the area of multi body interactions. Within the reporting period the calculation of loads is performed mostly by linear and partly non linear boundary element methods with the aim to assess operability of the coupled systems and assess the loads on the structure, the mooring lines as well as lines connecting the bodies and articulations. Accordingly, the publications concerning cables, risers and mooring systems deal primarily with the so called coupled floater mooring global response. Time and frequency domain mooring methods are employed to predict the first order responses in extreme weather conditions. Considering that coupled analysis requires extensive computational efforts more efficient computation schemes are needed for use in practical design.

Whereas significant progress has been achieved in the area of VIVs investigations of wave induced oscillations on downstream circular cylinders are relatively lagging behind probably due to the technical difficulties to approximate large amplitude motions. It would be useful to expand research efforts in this area.

7.2 Wave Induced Loads on Ships

A large variety of nonlinear methods for the forward speed problem was reported. One may distinguish between methods based on potential theory and CFD based methods. Between those extremes there are various methods such as partly nonlinear or blended methods in which different modelling assumptions are used to approach selectively nonlinear effects. Further verification of available techniques against experimental measurements is necessary.

Understanding hydroelastic responses of ships is recognised as an important design verification tool. Whereas linear hydroelastic theories have reached a degree of maturity 3D nonlinear theories are still under development. The primary difficulty in applying CFD is related with the computational efficiency as well as the implementation of free surface flows particularly for large scale free surface effects around ships. In any case the use of CFD based methods (e.g. CIP or RANS) looks promising and should be investigated in further.

The need for quality benchmark data is as great as ever, particularly relating to the measurement of global loads from model tests. Within the reporting period experiments on elastically scaled models have been broadened and it would be useful to see this trend continued and expanded. Whereas full scale measurements provide the most robust form of validation in terms of realism of the data collected the number of investigations is limited and worthwhile to be expanded.

Evaluation of rogue wave induced loads continues to be dealt using partly non linear methods and comparing prediction against model tests. It will be interesting to apply fully nonlinear methods, including CFD based methods, to this type of approach. The potential flow formulation of slamming problems has continued to raise interest. Recent research studies focused on the evaluation of slamming loads on symmetric and asymmetric sections using the Wagner approach. There is some rise in the use of

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hybrid CFD based methods (e.g. RANS or SPH) using commercially available solvers. However, it would be interesting to carry out further validation studies.

7.3 Specialist Topics

Typically the underlying approach for operational guidance builds on combined theoretical seakeeping models and linear spectral analysis used for statistical predictions. Recently, concepts of novel procedures for operational guidance have been proposed to increase the reliability. The approach shows promising results. Specification and quantification of uncertainties related with environmental models, load predictions and response calculations is important part of risk based assessment for design and operation of marine structures. Load uncertainties have been specified for the improvement of reliability based code formats and for the development of decision support systems for onboard navigation. It is recognised that both model experiments and sea trials are providing the most reliable data for the validation of numerical codes. In the future it is hoped that more data will be publicly available.

Whereas there is currently some focus on developing fluid structure interaction models that simulate flooded damaged ship dynamics, the use of reliability methods and the broader implementation of available methods within the context of risk based design and assessment are strong trends that will be impacting on future research and development. With reference to sloshing loads recent advances concentrate on aspects of hull flexibility, model scale validations and implementation of advances CFD methods and tools to study the effects on the hull girder response. Perhaps, amongst the most important developments is the introduction of a probabilistic based framework that facilitates modelling the high variability of sloshing impact pressures due to sloshing physics.

The issues of fatigue analysis of offshore structures are by and large similar to those for ships. Within the reporting period efforts were focused on including nonlinear effects in fatigue predictions. Important properties are the non-Gaussian broad band width of the nonlinear response and the sequence of loads. Further investigations are necessary in order to clarify to what extend transient and hydroelastic effects need to be considered in fatigue analysis and structural design of ships.

Whereas a number of models and procedures have been developed to evaluate fatigue damage accumulation in the hull girder for decision support, probably the best way to proceed in understanding the phenomenon is to combine all available tools including full scale measurements and numerical simulations.

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COMMITTEE II.1

QUASI-STATIC RESPONSE

COMMITTEE MANDATE

Concern for the quasi-static response of ship and offshore structures, as required for safety and serviceability assessments. Attention shall be given to uncertainty of calculation models for use in reliability methods, and to consider both exact and approximate methods for the determination of stresses appropriate for different acceptance criteria.

COMMITTEE MEMBERS

Chairman: Seref Aksu
Stephen Boyd
Stuart Cannon
Ionel Chirica
Owen Hughes
Satoshi Miyazaki
Jani Romanoff
Jörg Rörup
Ivo Senjanovic
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KEYWORDS

Quasi-static response, strength assessment, ship structural analysis, finite element modelling, fatigue, corrosion, ice loads, steel sandwich panels, green shipping, energy efficient ships, alternative propulsion, passenger ships, container vessels, offshore structures.

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CONTENTS

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1 INTRODUCTION

A ship is a highly complex structure designed and built to withstand a variety of loads, namely, wave and wind loads which are ever changing, deadweight loads as a result of ballast, fuel and cargo distributions, and accidental loads such as collisions and groundings. Recently Finite Element Modelling (FEM) and Analysis (FEA) techniques have been developed to a level where these can be applied to analyse complex ship structures during the design process. Moreover, when design innovations are pursued, useful information can be obtained from direct load, response, and strength analyses. In such cases, it is essential to identify the relationship between the limit states and the corresponding loading conditions in a more precise manner. A comprehensive review of various strength assessment approaches was carried out by the previous ISSC Technical Committee II.1 (Aksu *et al.*, 2009). In the previous committee report, the developments on the determination of ice loads and responses and collision analysis were discussed. A comprehensive review of calculation procedures was presented. Load application methods, the compatibility between product models and models for numerical tools used for load and response assessment, the issue of inter-model data exchange were discussed. The interaction between CFD and FEA was covered. Recent studies on steel sandwich panels were reviewed and deformation limits for steel sandwich panels with elastomer core are discussed. With regard to safety, discussion on harmonization of IACS common structural rules and IMO's Goal Based Standards were presented. Also, included in the previous committee report was a case study where differences in scantlings based on the fatigue assessment using IACS common structural rules for tankers and bulk carriers were presented.

The present committee report is organised in the following manner:

In Section 2, strength assessment approaches for quasi-static response of ship and offshore structures are reviewed. The review is focused on the quasi-static modelling of dynamic problems. In particular, recent developments on the determination of ice loads and responses, slamming loads and responses on high speed vessels and collision analysis are discussed.

Section 3 forms a significant part of this report where a comprehensive review of calculation procedures has been presented. First, load application methods are discussed. This includes still water, wave-induced and extreme design loads both in intact and damaged conditions. Second, fluid-structure interaction is discussed. Third, recent studies covering response calculations of ship and offshore structural problems are reviewed with reference to reliability models, limit state analysis, etc. Finally, a review of recent research in relation to new and improved techniques for finite element modelling and analysis is presented.

The review on the uncertainties associated with reliability based quasi-static response assessment is presented in Section 4. Uncertainties associated with still water and wave loads, load combination factors both in intact and damage conditions are discussed. Similarly, uncertainties associated with capacity, especially the effect of corrosion is reviewed. Recent examples of reliability based structural assessment together with the inspection and maintenance applications are presented.

Section 5 was dedicated to composite structures, especially steel sandwich panels. Recent studies on steel sandwich panels have been reviewed. Also, a review of composites, in general, has been provided.

In Section 6, as part of design trends, developments and challenges, a comprehensive review is provided on the topics of green shipping, IMO's introduction of energy effi-

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ciency design and operation indexes, cleaner alternative propulsion, safer ships, North Pole passage and Panama Canal expansion. The structural responses of specific ship structures, such as passenger ships, container vessels are reviewed.

In Section 7 offshore structures are reviewed. Owing to the small representation from the offshore field on the present committee, the review was limited.

The conclusions drawn from the study formed Section 8.

2 STRENGTH ASSESSMENT APPROACHES

Significant advances have been made in relation to complex and sophisticated analysis techniques for ship and offshore structures, thus application of direct calculation methods involving dynamic analyses has increased. Nonetheless, simplified analysis procedures for the quasi-static response calculations are still commonly used and are of significant importance since they provide initial guidance during the early design stage.

2.1 Quasi-Static Modelling of a Dynamic Problem

2.1.1 Loads

In order to optimise the scantlings of a ship structure, a detailed knowledge of the loads acting on the structure is needed. Thus, for instance, in determining the loads acting on a vessel arising from hydrodynamic actions, numerous efforts are made by various specialists around the world to better evaluate extreme values through numerical computations, measurements on scaled models and/or from full scale trials.

When evaluating finite element analysis as a predictive tool for sea loads, Amin *et al.* (2008) noted that there is no clear definition of the term 'quasi-static analysis'. Usually the analysis type quasi-static involves a system where only equivalent static pressure forces and inertia forces are considered. In their model of a wave piercing catamaran, Amin *et al.* (2008, 2009) discussed the simulation of slamming loads. The slam load was assumed to act statically, that is, an instance of slamming was defined and used to establish a quasi-static load case. The results of finite element analysis (FEA) were directly compared with trials data with respect to time and showed discrepancies.

Impact-pressure actions are often categorised in the quasi-static domain when the ratio of the peak pressure duration to the fundamental period of vibration of a structures is equal to or greater than three. Quasi-static loads and the associated responses tend to be related to large actions that result in buckling, plastic collapse and stress concentrations resulting in fatigue cracking (Paik, 2010; NORSOK, 1999).

Lewis *et al.* (2010) examined the pressures caused by impact of a free falling wedge. High-speed video, local pressure measurements and body accelerations were gathered. The aim of this research was to provide quality experimental data for validation of CFD models of this and other impact problems commonly found in high-speed craft. This paper is mainly focused on the experimental aspects and a detailed uncertainty analysis was conducted and demonstrated experimental repeatability. The pressure results were found to compare well with those found in the literature. Good quality experimental studies such as this are vital for validation and can be used either in the time domain or to provide quasi-static scenarios.

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2.1.2 Response

Quasi-static response analysis of ship and offshore structures deals with failures resulting in yielding, buckling, plastic collapse and determining stress concentrations together with the associated fatigue failure. In the context of ISSC committee structure, it, therefore, naturally interacts with other committees since all the abovementioned failure mechanisms are specifically dealt with in dedicated committee work.

Therefore, the committee has concentrated on the determination of quasi-static loads and the variety of ship responses that are resulting in application of these quasi-static loads. However, the readers are encouraged to refer to the other committees' work if they are interested in the comprehensive review of specific responses and failure modes.

2.2 Linearization / Simplification of Nonlinearities

2.2.1 Ice Loads

In the previous ISSC II-1 Committee report (Aksu *et al.*, 2009), it has been highlighted the increased interest in determining ice loads in parallel with the increasing demand for ice strengthened tankers and other ice-going vessels. Also, there have been initiatives by regulatory agencies to rationalize ice strengthening design standards. As a result, the 2012 ISSC Secretariat has decided to form a specialist committee in this field. As such, a very brief review will be provided here.

In order to model ice loads by simulation of the actual pile up process against structure discrete element method (DEM) extended with FEM has been utilized in a number of papers. Polojärvi and Tuhkuri (2009) simulated a ridge keel punch through test using DEM-FEM in 3D. Rigid discrete elements were used to represent each ice block. The failure process of rubble pile was simulated and the shear strength was estimated. The simulated results were compared with those derived experimentally at model and full scale and the agreement was found to be good. The same methodology was applied by Paavilainen *et al.* (2011) to simulate ice sheet failure and rubble formation process against inclined structure in 2D. Emphasis was placed on the formation process and prediction of extreme ice loads. The applicability of DEM in modelling ice-related problems was demonstrated using the results from the National Research Council's Institute for Ocean Technology (NRC-IOT) and commercially available DECICE software by Lau *et al.* (2011). The study considered a wide range of ice-structure and ice-ship interaction problems such as ice loads on conical structures, jamming of floes at bridge piers, modelling of the mechanical behaviour of ice rubble, pack ice stability and associated forces on offshore structures, rubble loads exerted on an inclined retaining wall, ridge keel resistance during seabed scouring, response of a moored conical drill-ship in ice and ship manoeuvring performance in ice.

Appolonov *et al.* (2011) considered the main dynamic fracture models for local contortion of ice. For the two design models, failure under local ice crushing loads has been studied. Sawamura *et al.* (2009) developed a numerical method for calculating the repetitive ice breaking pattern and load when a ship advances into a level ice field. The authors focused on the ice bending failure in an ice breaking process in level ice. A circle contact detection technique was adopted in determining the contact point between a ship bow and level ice. The dynamic effect of an ice plate bending is included by using results from fluid-ice interaction FE analysis. The crushing effect is estimated by the simplified formula which considers the geometrical location between the ice edge and ship. Sawamura *et al.* (2010) extended their research to investigate the ship manoeuvring problem in level ice. In the simulations, the ship was

18th International Ship and Offshore Structures Congress (ISSC 2012) - W. Fricke, R. Bronsart (Eds.)

manoeuvred with constant turning radii and constant ship velocity. The 3 degrees of freedom (3DOF) rigid body equation was applied to describe the surge, sway and yaw of the ship motion. The contact position between the ship-hull and the ice-edge was determined by the circle contact detection algorithm.

Likhomanov *et al.* (2009) presented results of in situ experiments for the determination of applied ice loads to the ship during interaction with various types of ice formations. The experiments were conducted on board of an icebreaker in the North-East part of the Barents Sea. Experiments with ten various objects, e.g. level ice, different types of hummocks and bergy bits were performed. The reliability of the results is confirmed from the comparisons between the calculated values and the results based on independent measurements for the same parameters. The study also gives comparisons between the vertical force applied to the bow part of the ship calculated in compliance with data of inertial measuring system and the tensometry data. In general, good agreement between these values during all stages of ship-ice interaction was achieved.

Based on the design ice load that corresponds to a certain return period, Jia *et al.* (2009) proposed a practical approach for designing the frames behind the side-shell or the bow of a ship subject to ice. The authors employed FE modelling and analysis with consideration of four typical types of section profiles. Both the geometric and material non-linearity was considered. From the analyses, the relationships between the loads and the beam's cross-section properties were obtained for different permanent set requirements.

2.2.2 Slam Loads on High Speed Catamarans

Reliable computation of loads is critical in FE analysis. Amin *et al.* (2009) discussed modelling wave loads in their FE analysis of a high-speed wave-piercing catamaran. To apply loads, the force per frame was calculated then distributed evenly over three locations at each frame of the vessel's lower structure. An instance from trials strain data (wave height, relative bow motion, bow vertical acceleration, vertical acceleration at the longitudinal centre of gravity, and trim angle) was chosen and the ship was 'balanced' on the corresponding wave profile. The authors concluded that this procedure offers a reliable design wave load for a given sea state. Davis *et al.* (2010) tested a scaled hydroelastic model of a wave-piercing catamaran to replicate slamming loads. Equivalent slam loads on a $96\,m$ catamaran, which were ascertained using a combination of FE analysis and strain gauge readings from sea trails, were measured on the scaled model.

Veen and Gourlay (2011) described a method for calculation of slamming pressures on hull-section shapes. The method employs two-dimensional Smoothed Particle Hydrodynamics (SPH) to improve the constant-velocity wedge method to assess slamming. The varying impact velocity of a hull as it enters the water and the effect of slamming loads on global motions are calculated over the entire hull section. Calculated slamming pressures on a wedge model showed favourable agreement with experimental results.

2.2.3 Accidental Loads Arising from Collisions and Grounding

Accidental loads arising from situations such as collisions and groundings require structural crashworthiness assessments involving crushing, yielding, and fracture of the vessels involved. In this section, recent research in the area of grounding and collision loads is presented.

Zaraphonitis and Samuelides (2009) addressed the strength of the damaged structure and the loading induced on damaged hulls of bulk carriers. The determination of the

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loading included the influence of dynamic effects and the interaction of the hull with the sea bed in the grounding area. Samuelides *et al.* (2009) presented the probability of occurrence of grounding, which is based on a database of accidents involving Greek ships from 1992 to 2005. The authors identified the parameters influencing the occurrence of groundings and investigated using statistical significant tests.

Simonsen *et al.* (2009) developed damage stability requirements which take into account the structural vulnerability to grounding damage, i.e. the kinetic energy available to generate damage and the structural resistance. The authors presented analysis of new damage statistics in order to determine impact scenarios, in particular in terms of impact speed, impact location, and width and height of damage for high speed craft. Furthermore a new empirical damage prediction formula was developed based on a combination of full scale testing and extensive non-linear finite element analyses. The simulation method was calibrated and validated against real statistical damage data for conventional ships and then it was used to generate damage statistics for high-speed craft. The study suggested that the grounding damage statistics for all ships can be characterized by a single parameter; the Grounding Damage Index, which is a function of the ship's kinetic energy and its structural resistance to grounding damage.

During ship collisions part of the kinetic energy of the involved vessels, immediately prior to contact, is absorbed as energy dissipated by crushing of the hull structures, by friction and by elastic energy. Pedersen and Li (2009) presented an estimate of the elastic energy that can be stored in elastic hull vibrations during a ship collision. In normal ship–ship collision analyses both the striking and struck ship are usually considered as rigid bodies where structural crushing is confined to the impact location and where local and global bending vibration modes are neglected. That is, the structural deformation problem is considered quasi-static. Pedersen and Li (2009) considered a simple uniform free–free beam model for estimating the energy transported into the global bending vibrations of the struck ship hull during ship–ship collisions. The striking ship is still considered as a rigid body. The local interaction between the two ships is modelled by a linear load–deflection relation. The analysis results for a simplified model of a struck coaster and of a large tanker show that the elastic energy absorbed by the struck ship normally is small and varies from 1 % to 6 % of the energy released for crushing.

A formulation for the analysis of the impact mechanics of ship collisions that can be applied to both 2D and 3D cases was proposed by Liu and Amdahl (2010). The equations of motion are solved in a local coordinate system, and a transformation matrix between the global and the local coordinate system is proposed. It is stated that the derived closed form solution of the external mechanics of ship collisions gave excellent agreement with an alternative 2D formulation for ship–ship collisions. The method has been extended to estimate the required energy dissipation in ship–iceberg collisions. Tabri *et al.* (2009) presented a theoretical model to predict the consequences of ship–ship collisions. The model considers the inertia forces of the moving bodies, the effects of the surrounding water, the elastic bending of the hull girder of the struck ship, the elasticity of the deformed ship structures and the sloshing effects in partially filled ballast tanks. The study focused on external dynamics and internal mechanics (the collision force as a function of penetration) using data obtained from experiments. The model was validated with two full-scale collision experiments, one with a significant sloshing effect and the other without it.

SEA-Arrow (sharp entrance angle bow like an arrow) has no protrusion of the bulbous bow to reduce bow waves and has a transverse stiffening system in the narrow bow

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space to apply the buffer bow concept. Comparative collision studies between SEA-Arrow and the conventional bulbous bow using elasto-plastic finite element analysis are conducted by several researchers (Yagi *et al.*, 2009; Takaoka *et al.*, 2010). It was shown that the buffer bow characteristic of SEA-Arrow is superior to that of the conventional bulbous bow, since much more energy is dissipated by the plastic deformation of the striking and struck ships until the inner shell of struck ship ruptures. For further improvements, Takaoka, *et al.* (2010) proposed replacing the longitudinal stiffened steel panels of outer shells with hybrid structures composed of polyurethane elastomer cores and steel face plates to optimise the energy absorption of the SEA-Arrow structure.

Impact load estimation of drift-wood hitting the bow structure of high-speed vessels was investigated by Toyama (2009). The study included the estimation of impact loads for drift-wood of different sizes and craft speed by considering the whipping motion and local crushing of the wood at the impact region. In a study by Cho and Lee (2009), the results of lateral collision tests on 33 stiffened plates are reported. A simplified analytical method was developed for the prediction of the extent of damage to stiffened plates due to lateral collisions.

Klanac *et al.* (2009) presented a study on the coupled optimisation and collision analyses. Through the coupling of multi-objective structural optimisation and crashworthiness analysis, a conventional tanker structure was optimised for higher collision tolerance, accounting for the change in hull mass, so that the increase in safety is efficient. The authors proposed two new concepts, a 'two-stage' optimisation approach, reducing the number of needed collision simulations, and a rapid collision simulation approach that utilizes coarse FE mesh and reduces calculation time.

3 CALCULATION PROCEDURES

3.1 Load Application Methods

In line with the previous International Ship and Offshore Structures (ISSC) Congress Technical Committee II.1: Quasi-Static Response Report (Aksu *et al.*, 2009), application of loads relevant to quasi-static response analysis is discussed here.

For physically realistic global structural finite element analysis of ship hulls, the designer needs to apply a set of design loads obtained from either a seakeeping analysis or experiments. For a manageable analysis process, the number of load cases must be kept small. Eisen *et al.* (2009) describes the design load selection method as supported by the GL ShipLoad software, which was extended by special functionality to aid the designer in determining design load sets by an automated algorithm. Dupau and Leguen (2009) reported the numerical methods performed by the French ministry of defence in determining extreme ship responses and fatigue damage induced by global wave loadings. Amin *et al.* (2009) developed a 'reverse engineering' procedure to model slamming events on large high-speed wave piercers using quasi-static analysis. Rather than using calibration factors from a generic load case to apply loads in an FE model, data from sea trials was utilised to develop a quasi-static load case for the FE model. From an actual slam, a set of start and end times, force, and location was assumed and the quasi-static slam impulse was calculated.

Flockhart *et al.* (2010) presented a method to predict lifetime fatigue pressure loading acting on bilge keel appendages on typical warships. The method involves modification of an existing linear panel method seakeeping code to calculate viscous roll damping pressures acting on bilge keel surfaces. The viscous roll damping pressures are combined with incident, diffracted and radiated wave pressures and oscillating hydrostatic

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pressures to give total fatigue pressure loading on the bilge keel. Bilge keel fatigue pressure load spectra are derived in the form of a lifetime probability of exceedance function of pressure peaks. The results of the technique are compared to measured loads obtained during a dedicated sea trial carried out in limited seaway conditions. A comparison is also made with the fatigue design pressures determined according to the Germanischer Lloyd classification rules.

Thomas *et al.* (2011) presented an experimental study into determination of wave-induced design loads for a new concept design of a large catamaran, Gas Cat, as a floating natural gas processing, storage and offloading facility, capable of processing and storage of 1 million bbls of condensate and approximately 240,000 m^3 of liquid natural gas. One important area of the investigation was the estimation of the wave-induced cross-demi-hull loads experienced by the catamaran in a variety of operational scenarios. The experimental results showed that changes in demi-hull separation were found to have little influence on the measured cross-demi-hull loads. Forces and moments were the least for the head sea condition; which suggest loads will be reduced if the vessel weathervanes with the prevailing swell direction. The forces and moments which may be expected in the Timor Sea 10,000-year return storm conditions have been estimated based on the model results.

3.2 Global Wave Loads

3.2.1 Intact Ship

Jensen (2009) presented a paper where procedures for the estimation of extreme wave loads and load responses for marine structures are provided taking due account of the non-linearities in the load process. A range of problems from slightly linear to strongly non-linear are considered. The methods are: Hermite transformation, Critical wave episodes and the First Order Reliability Method (FORM). The procedures were illustrated by results for the extreme vertical wave bending moment in ships. The paper makes the following statements:

- The Hermite transformation is the obvious choice if the load or response process can be modelled by a second order stationary process.
- The use of critical wave episodes based on linear models is more effective if the memory in the system is low and the non-linearities large.
- The FORM approach can be a very versatile approach, able to cover even bifurcation problems such as parametric rolling and problems with large dynamic responses.

Jensen (2009) concluded that the extreme values for wave load responses can be predicted by the available statistical procedures using reasonable computer resources, but conditional on the hydrodynamic analyses being able to correctly model effects like impact slamming loads and green water on deck.

Ivanov (2009a, 2009b and 2009c) proposed a method for calculating the hull girder bending stresses using a similar procedure to that adopted in the class rules but resulting in probabilistic terms. The still water and wave-induced hull girder hogging and sagging loads are presented in probabilistic format as one phenomenon, i.e. using bi-modal probability density functions. The probabilistic distribution of the total hull girder load is calculated using the rules of the composition of the distribution laws of the constituent variables.

The wave-induced load effects that occur during long-term operation of a chemical tanker in the North Atlantic were investigated by Parunov *et al.* (2009). The ratio

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between the wave bending moment determined from direct analysis and that of the rule wave bending moment is determined to be 1.22, 1.11 and 1.13 for full, ballast and partial loading conditions, respectively. Parunov and Ćorak (2010) investigated the influence of environmental and operational uncertainties on the long-term extreme vertical wave bending moment of a container ship assuming a rigid hull. Since the long-term distributions of vertical wave bending moments are highly dependent on the assumed environmental and operational parameters, the authors considered different combinations. Results are compared among themselves as well as with the IACS rule vertical wave bending moments. Statistical parameters of uncertainties are quantified, that may be useful for reliability-based design of container ships. Mohamad *et al.* (2009) presented an optimisation framework for the design of planing craft where design evaluation assessment for competing hull forms was carried out for combination of wave-induced design loads.

Large waves generated by large ships can travel long distances, possibly damaging offshore structures and adversely affecting the stability of smaller ships. Dong *et al.* (2009) presented an analysis method, which is a combination of the thin strip theory and the boundary element method, to evaluate the waves generated by a moving ship and the action of the waves on a marine structure, which was idealised as a cylinder. It was discussed that such repeated forces, though not quasi-static, can contribute to fatigue damage.

3.2.2 Damaged Ship

For a damaged ship, a model of wave loads similar to the intact case has been proposed by Luis *et al.* (2009), Hussein and Guedes Soares (2009a) and Teixeira and Guedes Soares (2010). Principal difference between the wave loads applied to intact and damaged ships is that different environmental conditions and exposure times are to be taken into account. While for intact ships North Atlantic wave environment is usually adopted, less severe environmental conditions and reduced exposure time to environmental conditions after damage should be considered before the ships is taken to safe location. For example, ocean wave statistics covering the European coastal areas is proposed for reliability assessment of damaged oil tanker by Luis *et al.* (2009); Teixeira and Guedes Soares (2010) considered a time period of one week as the voyage duration of the damaged ship to the dry-dock. Consequently, Teixeira and Guedes Soares (2010) found that the mean extreme vertical wave bending moment of Suezmax tanker was reduced by about 15 % when reducing exposure time from one year in the North Atlantic to one week in European coastal areas. Hussein and Guedes Soares (2009b) investigated the ultimate strength capacity of a damaged bulk carrier.

Differences between wave loads for reliability assessment of intact and damaged oil tankers are taken into account by Rizzuto *et al.* (2010). Seakeeping calculations for a damaged ship using a seakeeping code capable of dealing with non-symmetric hulls are reported by Folso *et al.* (2008). For the case of the flooded ballast tank in midship area, the authors obtained RAOs of vertical wave bending moments greater than those for intact ship.

3.3 Fluid-Structure Interaction

As stated by the previous ISSC Technical Committee report II.1 (Aksu *et al.* 2009), understanding of fluid-structure interactions is gaining increased attention in ship design. Engineering problems involving the interaction of structures and fluids with large motions of the free fluid surface are common in ship hydrodynamics and offshore structures. Sloshing in a ship tank is a good example of the fluid structure interaction

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problem. The study on liquid sloshing is supported and motivated by an increasing demand for LNG and LPG carriers, double-hull tankers and VLCCs, which may not be able to avoid rough sea conditions and may consequently experience severe sloshing induced loads. Sloshing may cause damage to wall structures of the containment system in tankships. Coupled with ship motions, liquid sloshing can also cause violent motions and even capsize ships carrying liquid cargoes in rare extreme conditions.

A general overview of sloshing problems in ship tanks and possible solution strategies are discussed by Faltinsen and Timokh (2009). Zhu *et al.* (2010a) considered viscous flow theories to investigate the tank sloshing flow behaviour and its induced impact loads. The coupling effects of ship motion and sloshing is considered, in which the linear ship motion is solved using an impulse response function method. The simulations of ship global motion and tank sloshing for a LNG carrier with cargo hold have been carried out numerically and experimentally. The comparisons between numerical and experimental results show good agreement. Zhu *et al.* (2010b) presented a numerical technique to simulate liquid sloshing in tanks induced by multi-degree excitations. The motion of incompressible fluid is described by Navier-Stokes equations and continuum equation. The governing equations are discretized by finite volume method and solved by simple schemes. The profile of liquid surface is reconstructed by the volume of fluid (VOF) technique. The numerical method is checked by experimental results of liquid sloshing induced by one-degree excitation, showing a good agreement. Godderidge *et al.* (2010) investigated the implications of using an inhomogeneous multi-phase CFD simulation of sway induced sloshing in a rectangular tank. The results are compared this with less computationally expensive homogeneous (averaged) approach as found in the majority of literature on the subject. Both methods were compared to experimental data. The inhomogeneous approach demonstrated a marked difference in the peak pressures which were under predicted by the homogeneous approach. This research clearly demonstrated that for violent sloshing problems a multiphase approach should be used.

As an initial step to improve understanding of the whipping response due to severe slamming, Amin *et al.* (2009) conducted a quasi-static FE analysis of a catamaran. The authors investigated different modelling configurations, mesh density at strain gauge locations, the effect of geometry simplifications and subsequent adjustments to the longitudinal centre of gravity. Two approaches used to compare quasi-static analysis with trials data.

Coupled hydrodynamic-structural analyses over a range of operating conditions were performed to investigate the efficiency of design of adaptive propellers (Mulcahy *et al.*, 2010a). The finite volume computational fluid dynamics code CFD-ACE+ was used for hydrodynamic calculations and the finite element code for composites SYSPLY for structural calculations. Mulcahy *et al.* (2010b) conducted steady coupled hydrodynamic-structural analyses of a propeller blade. As part of a proposed scheme to design a shape-adaptive propeller, a baseline rigid foil was determined and corresponding static blade loads computed for the design environment. Merz *et al.* (2009) modelled the low frequency structural and acoustic responses of a simplified submarine to propeller forces. For the structural part of the problem, the FE method was coupled to the boundary element (BE) method to model the interaction with the surrounding fluid. The authors investigated whether the submarine's tailcone should be modelled as a rigid or flexible body. It was found that for low frequencies, the tailcone did not have a significant impact on the structural response of the submarine under excitation. As such, a rigid cone was used which reduced computational costs. Liu

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and Young (2010) conducted fluid-structure interactions modelling of a composite propeller using a coupled finite element analysis - blade element momentum (FEA-BEM) numerical tool. This was used as a performance evaluator for the evolutionary optimisation of the geometry to determine the unknown unloaded geometry of the blade. Both steady and unsteady analyses were conducted, the latter using a four-cycle wake pattern to create a spatially varying (non-uniform) wake.

Nicholls-Lee *et al.* (2011) examined the fluid structure interactions associated with underwater tidal turbines. The method employed a surface panel code with a frozen wake methodology to provide hydrodynamic loading. The structural response was evaluated using FEA. The two numerical methods were coupled via a MATLAB routine, commonly referred to as loosely coupled fluid structure interactions. The case study examined was a composite three-bladed tidal turbine with a diameter of $20\,m$. The composite architecture included bend-twist coupling and the results demonstrated that the coupled response of the blade resulted in an improvement in energy capture from a steady state flow.

Pitman and Lucey (2009) presented a new method to model the interaction of a uniform incompressible flow with a flexible panel fixed at both ends. The method combines theory and computational modelling, whereby coupled equations for the flow-structure system were utilised to derive a single matrix equation for panel displacement. For the flexible panel example, this is realised by using both boundary element and finite element methods. Although the research was focused on determining the eigenmodes of finite fluid-structure systems, the developed method was used to perform a linear stability analysis of a flexible panel with inhomogeneous wall properties and complex boundary conditions. Tan *et al.* (2011) extended this work by investigating how hydroelasticity of hull panels could be controlled by localised spring supports. The authors' results show that the added spring stiffness can be effective in controlling the critical flow speed at which static buckling-type instability occurs.

Rafiee and Thiagarajan (2009) studied viscous fluid flow past structures that can undergo large deformations. A Smoothed Particle Hydrodynamics (SPH) method was proposed. To reduce the risk of numerical difficulties and unrealistic fractures in the deformable structure, an artificial stress term was added into the momentum equation. A coupled FE and SPH can be used to compute the structural response of ships to waves. Groenenboom *et al.* (2009) completed a FE-SPH simulation of a generic frigate in high seas to show the interaction between waves and deformable structures.

3.4 Modelling

Varela *et al.* (2011) discussed the development of a computer system for the fast parametric generation of a 3D model of ship hull structure. The model covers not only the geometry of the hull and the main structural systems but also data describing the arrangement of plates and stiffeners of the component panels, including scantlings, spacing and materials. Since the objective of the system is to generate and help to evaluate alternative structural configurations, with information on total or partial weights and centres of gravity, the ease and speed of generation of a model is quite relevant. Therefore a simplified geometric modelling, representing curved shapes with polygonal approximations, is adopted.

Ojeda *et al.* (2008) reviewed the different approaches and idealisations used in nonlinear modelling of stiffened structures. Stiffened structures are relevant to the efficient design of high-performance craft as weight reduction can be realised by using relatively stiff materials and optimised structures. The authors concluded that design level

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accuracy of non-linear analyses of stiffened structures is achievable by utilising the finite-strip method, which has a smaller computational overhead when compared to full finite element analyses. However, the orientation of the stiffener within the strips is limited. For arbitrary stiffener orientations, finite elements with stiffened shell formulations can be employed.

Man *et al.* (2009) proposed an energy-based implicit modelling method to obtain the non-linear behaviour of composite materials. The method allows full field strain and boundary forces to be employed in the model. A numerical model created to validate the method involved training a neural network to capture the relationship for non-linear shear stress-strain of a typical carbon fibre reinforced polymer. Statistical analysis showed that the developed neural network was robust in terms of reproducing accurate structural responses. The advantage of the proposed method over other techniques is non-reliance on stress data obtained from experiment.

Domnisoru and Chirica (2011) focused on numerical methods for ship hull structure strengths and fatigue analyses, in order to estimate the initial design ship service life. The numerical analyses were divided into three-interlinked parts. The first part includes the hull strength analysis method, based on 3D/1D-FEM models, under equivalent quasi-static head wave loads. The second part presents the ship hull dynamic response analysis method, based on non-linear hydroelasticity theory with second order wave spectrum. The third part includes the fatigue analysis method for the initial ship hull structure, based on the long-term prediction ship dynamic response, the cumulative damage ratio and the design S-N material curves. The numerical analyses are carried out for a large double hull tanker. The full and ballast loading cases are analysed. The numerical results outline the extreme hydroelastic wave loads and the ships initial service life evaluation.

3.5 Response Calculations

3.5.1 Buckling and Ultimate Strength

Plates are widely used in marine and offshore industries. Quantifying their structural behaviour is important for reliable design and safety. Shufrin *et al.* (2009) presented an elastic non-linear stability formulation for the structural response of rectangular plates subjected to both out-of-plane and in-plane loads. Shufrin *et al.* (2010) extended the approach for trapezoidal plates subjected to out-of-plane loads. The method was derived from thin plate theory with non-linear von Kármán strains. The authors investigated various boundary conditions of rectangular plates when determining the relationship between applied loads and the resulting response in the post-buckling range. The applicability of the model for trapezoidal plates was revealed by showing the impact of complex geometry and load cases on deflection. Zhang and Khan (2009) investigated the buckling and ultimate capability of plates and stiffened panels in axial compression. The authors proposed a semi-analytical formula for ultimate compressive strength assessments of stiffened panels based on verified results of non-linear FE analyses for a series of 61 stiffened panels. The developed method was also applied to the deck and bottom structures for a range of various size oil tankers and bulk carriers. Chaithanya *et al.* (2010) investigated the behaviour of stiffened plates with different distortion levels as pre-existing fabrication-related (like weld-induced) imperfections are of great importance from a structural design point of view. The range of scantlings, the distortion types and levels were chosen based on panels used in the construction of the UK's Type 45 destroyers. A new strength parameter is proposed to represent

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buckling strength, which takes into account the inelastic post-buckling behaviour of the structure.

A plate with an opening behaves in a complex manner when subjected to compressive or shear stresses. The failure mechanisms that can take place include yielding, buckling and cracking. Wang *et al.* (2009) performed a total of 954 linear and non-linear FEM analyses to check the buckling and ultimate strength of plates with openings. They introduced strength reduction factors as a ratio between the results those for plates with openings and those without openings.

It has been recognised that the current shipbuilding industry design practice for perforated plates is not robust and it is believed that this problem has caused structural damage accidents in actual ship structures with openings. Kim *el al.* (2009) carried out numerical and experimental studies to introduce a new design formulation of the critical buckling strength for perforated plates. For this purpose, the authors have conducted tests on a total of 90 perforated plates and also a total of 9 stiffened panels with an opening. Existing and newly derived design-formula solutions of buckling and ultimate strength of the test plate panels are compared with experimental results and non-linear finite element computations.

Lopatin and Morozov (2009; 2010) studied buckling of plates with different supports under in-plane bending. For the case of a plate with two parallel simply supported edges and two parallel free edges (SSFF), the buckling equation was reduced to an ordinary differential equation. For the case of a plate with two parallel clamped edges and two parallel free edges (CCFF), the solution method was reduced to the calculation of a dimensionless buckling coefficient which is dependant on the stiffness and dimensions of the plate. The analyses were extended to isotropic and laminated carbon fibre reinforced plastic (CFRP) plates. The influence of various aspect ratios and carbon fibre orientations on the critical buckling coefficients was studied.

A method to analyse the ultimate strength capacity of ship hull girder subjected to combined torsion and bending is developed by Ogawa *et al.* (2010). Ship hull girder is idealized as a thin-walled section beam using FEM with consideration of the warping in torsion. For progressive collapse analysis, Smith's approach is applied by dividing cross section into the plate and stiffened panel elements. The proposed method is applied to the progressive collapse analysis of 1/13-scale three-hold models referring to a Post-Panamax container ship.

A design methodology for a scaled model for post-ultimate strength behaviour of a ship's hull girder in waves is investigated by Wada *et al.* (2010). For the collapse behaviour, the scaled model must follow the law of similitude in terms of appropriate simulation of the strength as well as geometry and stiffness. Thus, a segmented model with a bending collapse mechanism amidship using sacrificial steel bar specimen in bending was adopted as a solution. The final design is confirmed by FE-analysis as well as a series of tests including a four-point bending test under static loads. It is confirmed that the scaled model possesses a moment-rotational relationship as intended. Kimura *et al.* (2010) investigated the post-ultimate strength behaviour by developing a method where the whole ship is modelled by two rigid body systems connected each other via a nonlinear rotational spring. The results of this study were compared with scale model results described in Wada *et al.* (2010).

For the ultimate strength assessment of large high-speed craft operating in deep ocean environments, representative plate load-shortening curves may form part of simplified hull girder ultimate strength methodologies; for the case of a high-speed aluminium

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vessel, the curves need to account for the effects of parameters including alloy type, geometric imperfection, softening in the heat-affected zone, residual stresses, lateral pressure and biaxial load. Benson *et al.* (2011) examines the strength of a series of unstiffened aluminium plates with material and geometric parameters typical of the midship scantlings of a high-speed vessel, using a non-linear finite element approach.

Corak *et al.* (2009) calculated elastic, fully plastic and ultimate bending moments for five tankers and three bulk carriers. The study demonstrated how the working and ultimate conditions are mutually related and recommended ranges of values for relations among elastic, plastic and ultimate bending moments. The experimental results of the collapse of three hull box girders which are made of high tensile steel of $690\,MPa$ of nominal yield stress subjected to pure bending moment were presented (Gordo and Guedes Soares, 2009). It is suggested that the concept is very useful in identifying the governing parameters affecting the ultimate strength of 3D structures under predominant bending moment.

3.5.2 Combined Global and Local Loads and Responses

Amlashi and Moan (2009) presented a study on the development of simplified methods applicable to practical design of ship hulls under combined global and local loads. An important issue is the significant double bottom bending in the empty hold in alternate hold loading (AHL) due to combined global hull girder bending moment and local loads. Therefore, the stress distributions in the double bottom area at different load levels i.e. rule load level and ultimate failure load level, are presented in detail. The implication of different design pressures obtained by different rules (CSR-BC rules and DNV rules) on the stress distribution is investigated. Both (partially) heavy cargo AHL and fully loaded cargo AHL are considered. Effects of initial imperfections, local loads, stress distribution and failure modes on the hull girder strength are discussed.

Sireta *et al.* (2010) presented a study dealing with the methods for evaluation of the quasi-static ship structural response under the action of the sea waves. Coupling between the seakeeping code based on potential flow theory (Hydrostar) and the general 3-D FEM structural code (Nastran) is discussed. Several types of application are considered namely: linear, nonlinear, frequency domain, time domain, partial and complete structural models, internal tank. Parunov *et al.* (2010) investigated structural behaviour of a General Cargo Vessel of 2,240 dwt. Complete Ship Model (CSM) analysis procedure and calculation results are presented. The main concern of the study was to analyse the torsional behaviour of the ship with a large deck opening and corresponding stress concentration at hatch corners. The study demonstrated how 3-D FE analysis may be employed as a tool for improving structural safety of general cargo ships. Boote and Cecchini (2009) systematically investigated the stress distribution close to hatch corners of bulk carriers in order to determine and quantify the influence of the selected parameters on this phenomenon.

3.5.3 Fatigue Strength

Different approaches exist for the fatigue strength assessment of ships in particularly those that are prone to fatigue cracking due to high cyclic loads. Fricke and Paetzold (2010) presented results from an industry-wide joint research project in Germany, aiming at the harmonization of fatigue approaches. The study included extensive numerical analysis as well as full scale testing. As far as full scale tests are concerned, two joint types were selected. The first concerned web frame corners being typical for ro-ro ships. The second type was the intersection between longitudinals and trans-

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verse web frames, which recently showed fatigue failures in container ships. The study draws following conclusions from the investigations:

- The initiation of the first cracks in the tests was followed by a long crack propagation phase. A reasonable failure criterion was considered to be a crack length of 20 mm.
- The numerical analysis of the structural hot-spot stress requires special considerations in some cases, such as for attachments on the bulb of Holland profiles.
- The computation of the effective notch stress in large structures is possible with the help of the submodel technique, requiring more effort than the other techniques.
- The fatigue assessment with the different approaches, including the Palmgren–Miner Rule for variable amplitude loading, generally gives results on the conservative side.
- The failure behaviour of complex structures determined in numerical analyses may differ from the actual failure behaviour due to varying residual stresses.

The Thermographic Method (TM), based on thermographic analyses, has been applied to predict the fatigue behaviour of butt welded joints, made of AH36 steel, largely used in shipbuilding (Crupi *et al.*, 2009). Experimental tests have been carried out to assess the fatigue capacity in terms of S–N curves and fatigue limits. The predictions of the fatigue capacity obtained using the Thermographic Method show a good agreement with those derived from the traditional procedure.

Full stochastic fatigue analysis based on wave loads analysis is a recommended approach due to its high accuracy but requires a large computing effort. Jang *et al.* (2009) proposed an adaptive approximation in multi-objective optimisation for a full stochastic fatigue design problem. Two conflicting objectives are taken into consideration; to minimize steel weight and to minimize total weld toe grinding length. Whether to employ weld toe grinding or not for a hot spot can be seen as a selection variable. In order to treat such selection variables along with continuous variables in the multi-objective optimisation, Multi-objective Genetic Algorithm (MOGA) was introduced. Also, a convergence criterion of the adaptive approximation framework is proposed considering the feature of discrete objective function attributed to the introduction of selection variables. Sekulski (2009) investigated a possibility of simultaneous optimisation of both topology and scantlings of structural elements of large spatial sections of ships using Genetic Algorithm (GA). Based on the study results, the author suggested that GA can be an efficient optimisation tool for simultaneous design of topology and sizing high speed craft structures. Das and Jones (2009) proposed a method for shape optimisation for improved fatigue life. Fatigue optimised shapes are based on the stress pattern in areas where cracks propagate; whereas stress optimisation considers only the boundary stress distribution. It was also shown that an acceptable design range, rather than a single optimal solution, allows lower computational effort during design and flexibility to alter other design parameters. Domnisoru *et al.* (2009) described numerical structural strength and fatigue assessment methodology for a large LNG carrier with membrane type cargo tanks under extreme hydroelastic wave loads.

Huang *et al.* (2009) proposed a crack growth rate curve method, which is based on the equivalent stress intensity factor range (ESIFR) as the driving force. By expressing the crack growth rate data with ESIFR instead of stress intensity factor range (SIFR), the authors argued that it is possible to establish a concise model for crack growth data under different R-ratios from the curve corresponding to $R = 0$ both for base metals and welded joints.

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For fatigue design it is necessary to provide guidelines on how to calculate fatigue damage at weld toes based on S-N data when the principal stress direction is different from that of the normal direction to the weld toe. Such stress conditions are found in details in different types of plated structures. Lotsberg (2009) proposed an alternative equation for calculation of an equivalent or effective stress range for fatigue cracking from weld toes subjected to proportional loading.

Grenier *et al.* (2010) studied the effect of fatigue strain range on properties of high-strength structural steel. The authors presented two test series that were conducted to determine the effect of two different strain ranges (2000 and 3000 micro strains) of fatigue cycles on the mechanical properties of high-strength structural steel. The study concluded that the cycle-dependent behaviours of the material can cause a slight increase or a significant decrease in the yield strength when compared to its virgin state. However, the ductility of the steel does not change much as the strain cycle increases.

The rainflow cycle count method is one of most commonly used method for fatigue analysis of welded structures. Bengtsson *et al.* (2009) presented a simplified method to estimate the coefficient of variation for the accumulated rainflow damage for random loads.

Zhao *et al.* (2009) performed an analysis to determine the stress concentrations of the moon-pool openings in a rescue ship. In a rescue ship system, a moon-pool is designed in the vicinity of amidships and this results in high stress concentrations in the structure near the hole. The authors predicted external loads of hull by combining theoretical analysis and rule calculation. Finite element method and photo-elastic model tests are used to study the stress distribution and stress concentration factor of main-deck plating and bottom plating near the moon-pool hole.

Xie *et al.* (2010) presented a fatigue strength analysis of the connection between the side frame and hopper sloping plating of a large bulk carrier. The study is based on the S-N curve method and the assumption of linear cumulative damage of Palmgren-Miner's rule, using the hot spot stress method. The initial connection design failed to comply with the criteria of fatigue life based on rules. Analysis on the effect of different type of local structure on the fatigue strength of frame is carried out by varying connection details of side frame ends and the thickness of plating around the frame.

3.5.4 Welding Distortions

The effect of welding sequence on residual stress and distortion in flat-bar stiffened plates was investigated by Gannon *et al.* (2010). The simulation consisted of sequentially coupled thermal and structural analyses using an element birth and death technique to model the addition of weld metal to the work piece. The temperature field during welding and the welding induced residual stress and distortion fields were predicted and the results were compared with experimental measurements and analytical predictions. The authors drew the following conclusions from the study. In the case of longitudinal residual stresses, welding sequence did not have a significant influence on the distribution pattern of the stress; however it did affect the peak values showing as much variation as 3.5 times between one sequence to another. The distribution and peak values of residual stress were similar to measured values and to those available in open literature. Maximum tensile residual stresses equal to the material yield strength were predicted in the vicinity of the weld and maximum compressive residual stresses from 97 MPa to 58 MPa in the plate and stiffener respectively. In the

18th International Ship and Offshore Structures Congress (ISSC 2012) - W. Fricke, R. Bronsart (Eds.)

case of welding-induced distortion, the predicted distortions were of lower magnitude than typical values suggested in the literature.

The influence of welding-induced geometric distortions and residual stresses on the compressive ultimate strength in the longitudinal direction of plates and stiffened panels were investigated using finite element analyses considering a range of plate thicknesses with various levels of residual stresses (Khan and Zhang, 2011).

A submarine is essentially a cylindrical shell stiffened by ribs. A new method AEM (Analytical Element Method) is discussed by Wang *et al.* (2010b) to analyse cylindrical shell structure stiffened by ribs representing a submarine hull. Based on cylindrical shell theory, rigid matrix and loading matrix of the cylindrical shell and rib are constructed. The results obtained by AEM showed good agreement with FEM analysis results for a cylinder model having outer ribs or inner ribs.

Wang and Wan (2009) studied the strength and deformation limits of a cone shell structure that is commonly used in pressure vessels and submarine pressure hulls. The general solution of differential equation is expressed as power series solution and the particular solution is obtained by Galerkin method. He *et al.* (2009) extended the study to determine the effects of various parameters such as radius and thickness of pressure hull shell and tank shell, the space between solid frames and the space between stringers on the strength and stability of pressure hull shell. Wang *et al.* (2010a) presented a theoretical method to analyse the strength and deformation of a ring-domed shell. The results obtained with this method are in good agreement with FEM results. The study concluded that large deflection effect is important and should be considered for ring-domed structures under external static pressure.

3.5.5 Service Life Assessments

Sloan (2008) discussed the optimal design of warships, and how modern navies require a balance of acquisition and through-life costs. The impact of fabrication and through-life costs on the structural design of warships was explored. Furthermore, Glanville (2010) considered the advantages and risks involved in the modular design of a multi-role naval vessel. In the context of the Australian Navy, an analysis of the design drivers of a multi-role vessel is required, which affect the choice of hull-form and materials. A partnership between ABS and the United States Navy (USN) was introduced to create a "Service Life Assessment Program" (Eccles *et al.*, 2010). The intent of the program is to identify areas of ship health in which ABS can assist the USN and in which there is common knowledge. The steps of the program include the creation of an FE model of an as-built ship, and application of expected operational loads to the model. This will identify the as-built structural strength margins, corrosion allowances, areas of high stress to receive attention during inspection, and fatigue resistance in primary structural elements. Over the life of a ship, the FE model is modified to represent the current condition of the structure based on surveys. In addition, a hull maintenance model provides a structural history of a ship in terms of condition, damage events, and repairs. Lehrer (2010) discusses development of a comprehensive software-based Hull Inspection Program (HIP) for owners by ABS. The inspection criteria are graded with a rating from 0 to 6. A traffic light status, red (5 to 6), yellow (3 to 4), and green (0 to 2), is assigned to each zone for each criterion. These scores are then added for each zone and combined to get a normalized score for the compartment. Specific critical areas are defined by the hull structural analysis that identifies those areas with a particularly high risk of failure.

A paper by Lin *et al.* (2009) examines the vibration characteristics and vibration

18th International Ship and Offshore Structures Congress (ISSC 2012) - W. Fricke, R. Bronsart (Eds.)

control of complex ship structures. It is shown that input mobilities of a ship structure at engine supports, due to out-of-plane force or bending moment excitations, are governed by the flexural stiffness of the engine supports. The frequency averaged input mobilities of the ship structure, due to such excitations, can be represented by those of the corresponding infinite beam. The torsional moment input mobility at the engine support can be estimated from the torsional response of the engine bed section under direct excitation. It is found that the inclusion of ship hull and deck plates in the ship structure model has little effect on the frequency-averaged response of the ship structure. Also, it is shown that the vibration propagation in a complex ship structure at low frequencies can be attenuated by imposing irregularities to the ring frame locations in ships. Vibration responses of ship structures due to machinery excitations at higher frequencies can be controlled by structural modifications of the local supporting structures such as engine beds in ships.

A paper by Li *et al.* (2011b) is concerned with the elastic, axisymmetric, stress analysis of saddle-shaped end closure which consists of the inverted domed shell, the domed shell and the stiffening ring which connects the former two shell components together under axisymmetric external hydrostatic pressure. The moment theory of the revolutionary shell is utilized to obtain the flexural internal forces of the inverted domed shell and the domed shell at junctions with the stiffening ring using the force method according to the deformation compatibility at junctions. The closed-form solutions to elastic stress distributions for the saddle-shaped end closure are obtained. To demonstrate the applicability of the proposed analytical method, efforts were made to analyse a typical saddle-shaped end closure using both the analytical method and the finite element software ANSYS and to compare the results obtained from different methods. Verification results reveal that the analytical stresses agree well with those calculated using the finite element method. The analytical method can be employed to analyse various stresses of the saddle-shaped end closure accurately which is certainly helpful to the optimal design of such structure.

The difficulty of human occupied sphere design is the large openings such as human access openings and view window openings. Liu *et al.* (2010) investigated the effects of view window openings of deep sea Human Occupied Vehicle (HOV) on the stress and boundary condition influences by theoretical analysis and tests.

The structure and equipment for small and medium LNG carriers are quite different from large-scale LNG carriers. At sea, the static and dynamic loads acting on the bearings can be quite significant and act simultaneously, giving rise to a complicated stress distribution in the nearby hull structure. Thus, reliability and safety of a LNG carrier is influenced by the reliability of the bearings and the surrounding structure. The types and the functions of the C-shape independent liquid tank's bearing of the small and medium LNG carrier are described in detail by Yang *et al.* (2011). From the rules of the China classification society for the construction and equipment of ships carrying liquefied gases in bulk, the radial force distribution function of the bearing-load area is deduced under various working conditions, including still water, heave only, rolling only, and heave and rolling simultaneously.

3.6 Finite Element Modelling and Analysis

Finite element (FE) analysis is used both for verification and as an investigative tool.

In order to investigate variations in material properties of sandwich plates on transverse deflections, Pandit *et al.* (2008, 2009) developed a stochastic finite element type. The quadratic element has nine nodes and eleven degrees of freedom per node. The

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element was purposely created to model a laminated sandwich plate with transverse normal deformation of the core and to be computationally efficient. Raju *et al.* (2010a) used FE modelling and analysis extensively to predict the failure load and the interlaminar stress distribution of top hat stiffeners subjected to tensile load. Curved composites under tension fail due to delamination around the bend. The FEA results indicated that the numerical model matched the initial failure observed in experiments. Similarly, in a study of short fibre composites used in the construction of curved shapes, Raju *et al.* (2010b) used FE analysis to verify the displacement and failure of experimental results. The analysis investigated the effect of different lay-ups on the behaviour of curved laminated composites under bending. Dong (2010) calculated the process-induced deformation of composite T-stiffener structures. Deformation of composites during processing is attributed to the spring-in of angled parts. The effect of design parameters on the spring-in of the T-stiffener skin was investigated.

As part of a procedure for fatigue-life optimised shapes, Das and Jones (2009) used FE to analyse the stress field of a block with a cut-out under biaxial loading. NE-NASTRAN was integrated into an optimisation procedure, which also included geometry creation and automated meshing. Chirica *et al.* (2010) developed an approach utilising FEM for a fatigue assessment of ship structures in the early design stage. To overcome the challenges due to limited information in the early design stage, generic structural elements and predefined fatigue-critical details were chosen.

To verify the ability of a Structural Health Monitoring (SHM) system to detect delamination, Kesavan *et al.* (2008) created FE models of T-joints embedded with various damage configurations as a training set. The models were fitted with sensors, so that when the structure was loaded, the strain response was obtained and saved in a database. The database was then used in the SHM system to predict delamination locations and sizes of a T-joint with new damages.

Xu and Wan (2010) investigated the effect of pitting corrosion of a shell plating using FE modelling and analysis. A two layer shell element model consisting of the corrosive layer and the intact layer for a corroding shell was set up. The equivalent material constants such as equivalent Young's modulus and equivalent Poisson's ratio of the corrosive layer were proposed. The stress concentration of the corroding shell element so called pitting corrosive shell element (PCSE) was deduced based on super parameter shell element and the FE formulation of stiffness matrix and equivalent node vector. Xu and Wan (2011) extended their study to analyse a deep-sea sphere shell with pitting corrosion under pressure. The ultimate strength and buckling analyses of a spherical shell with pitting corrosion were carried out using an FE model comprised of PCSE shell-solid assemble based on multipoint constraint and solid elements.

Luo *et al.* (2009) conducted an elastic-plastic buckling analysis of a deep-sea pressure vessel by using the general FEM software. The critical load obtained from elastic buckling analysis showed that structural plastic buckling due to the high external hydrostatic pressure is the dominant failure mode for deep-sea pressure vessel. The study recommended using three-dimensional 8-node iso-parametric elements in the FE modelling for realistic prediction of plastic buckling.

FE analysis was used in the design of the T-foils used in a trimaran ferry designed by Austal (Clarke *et al.*, 2011). The thickness and webbing of the foil are varied to achieve a lightweight and reliable design for the given operating conditions.

Ship hull deformation influences the propulsion shafting alignment significantly.

18th International Ship and Offshore Structures Congress (ISSC 2012) - W. Fricke, R. Bronsart (Eds.)

Shi *et al.* (2010) proposed a new method for shafting alignment considering ship hull deformations. The method takes into consideration various loading conditions of the ship, wave loads and environment temperature differences in extreme conditions, as well as elastic constraints. The method calculates the deformations of the double bottom and converts them to bearing offsets, which behave as boundary constraints for shafting alignment calculations. As expected, shafting alignment is influenced most significantly by ship loading conditions, especially by the loadings of the aft part of ship. Wave loads impact shafting alignment to some extent. However, the effect of temperature variation was found to be quite significant.

4 UNCERTAINTIES ASSOCIATED WITH RELIABILITY BASED QUASI-STATIC RESPONSE ASSESSMENT

4.1 Uncertainties Associated with Loads

Uncertainty assessment of loads is performed for ship structural reliability studies. For reliability assessment of ship hull girder capacity, basic load variables considered are vertical still water bending moments and vertical wave bending moments. Combination factors are also important to account for the fact that maximum values of both do not occur simultaneously. Besides traditional structural reliability analyses of intact ships, a number of studies dealing with damaged ships have appeared in the literature recently. This section will review probabilistic models for variations in loads used in ship structural reliability studies.

4.1.1 Uncertainties Associated with Still Water Loads

4.1.1.1 Intact Ship

Parunov *et al.* (2009b) performed a statistical investigation of still water bending moments from loading manuals of double hull tankers of different sizes that may be of interest in ship structural reliability studies. Loading conditions are grouped according to three characteristic modes of operation of tankers: full load, partial load and ballast. Statistical properties for these modes are compared and their dependency on ship size is investigated. Loading conditions giving maximum bending moments in hogging and sagging are identified and these values are compared to minimum design requirements of still water bending moments from CSR. Statistics of differences between still water bending moments at departure and arrival are also analysed and presented.

Garre and Rizzuto (2009) adopted a predictive model for quantifying the stochastic variability of the global static bending load acting on a tanker ship in sagging. Their investigation was aimed at providing quantitative information on the uncertainties associated with the prediction of the still water loads. This information was then used in a reliability evaluation of the hull girder strength. The various sources of variability in bending loads are reviewed. Attention is focussed on the influence of the uncertainties affecting the cargo weight distribution on board.

4.1.1.2 Damaged Ship

A review of stochastic models of still water bending moments applicable for damaged ships is presented by Teixeira and Guedes Soares (2010). The simplest way to take into account consequences of the damage is to modify the still water load combination coefficient K_{us} appearing in Equation 1:

$$M_{SD} = K_{us} M_{SI} \tag{1}$$

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where M_{SI} and M_{SD} are the still water bending moments for intact and damaged conditions respectively. Luis *et al.* (2009) proposed values of 1.1 and 1.5 to analyse impact of the increased still-water loads on the reliability of the grounded oil tanker. In most cases, flooding of ballast compartments in the midship area is critical for double hull tankers, as this causes an increase in sagging moments. Hussein and Guedes Soares (2009a) have calculated the effect of the flooding of ballast compartments of a double hull tanker and found increases of 30 % and 46 % for one side and both side damages respectively.

Rizzuto *et al.* (2010) calculated asymmetrical flooding of the midship ballast tank on one side only of a Suezmax tanker. The still water bending moment in damaged condition corresponds to 152 % of the intact value for the same loading condition. For a reliability assessment of a damaged ship they proposed to use a coefficient of variation (CoV) which is slightly higher than the intact ship. This is justified by the additional effect in damaged conditions observed for water inflow and outflow through the damage opening that is not accounted for either in static or wave load analysis.

4.1.2 Uncertainties Associated with Wave Loads

A method for calculating the hull girder bending stresses following the general procedure in the class rules with a modification to account for probabilistic terms was proposed by Ivanov (2009a, 2009b). The still water and wave-induced hull girder hogging and sagging loads are presented in probabilistic format as one phenomenon, i.e. using bi-modal probability density functions. The probabilistic distribution of the total hull girder load is calculated using the rules of the composition of the distribution laws of the constituent variables. Ivanov *et al.* (2011) presented a study into the probabilistic distribution of the total bending moments of FPSOs. It was advocated to use extreme value statistics for the ultimate strength calculations and individual amplitude statistics for fatigue assessment.

Hull girder torsion of a recent design, 8,000 TEU container ship was investigated to assess a variety of analysis methods regarding rule development (Rörup *et al.*, 2010). The study included comparisons amongst the strip theory based software tool GL-ShipLoad, a panel method GL_PANEL and a Reynold-averaged Navier-Stokes solver COMET. Generally, the simulated COMET tool predicted torsional moments lower than those obtained from the GL-ShipLoad and the GL-PANEL codes. The authors stated that simulated wave formations surrounding the ship appeared to be realistic and indicated that COMET predictions were possibly more accurate.

4.1.3 Combination Factors

Huang and Moan (2008) presented a review of numerical models for combining still water and wave loads of ocean-going ships. They derived an analytical formula for combined characteristic value of still-water and wave loads. For container ships, the wave-load combination factors of $0.77 - 0.80$ and $0.67 - 0.70$ are recommended for the return periods of one year and 20 years respectively. For tankers, the still water load combination factors of $0.80 - 0.85$ and $0.70 - 0.80$ are recommended for the return periods of one year and 20 years respectively.

Mohammed *et al.* (2010) presented the basis of a cross-spectral formulation that could be used to assess the combined effects of wave loads and still water loads on hull girder strength. The methodology accounts for long term probability distributions and considers phase relationships between narrow banded load processes.

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4.2 Uncertainties Associated with Capacity

Corrosion is one of the most important parameters affecting the capacity of a marine structure and as such strongly affects the structural integrity of ageing marine structures. In their overview of recent advances in corrosion analysis and management for steel ships and offshore structures, Paik *et al.* (2008) stated that industry stakeholders are becoming increasingly sensitive to significant losses of marine structures due to corrosion. Therefore, the authors concluded that it is essential that advanced technologies for age-related deterioration are developed. Melchers and Paik (2010) examined ship structural management strategies with regard to corrosion. In parts of a ship that are vulnerable to both corrosion and high stress, the loss of plate thickness may be significant. When strains approach the yield strain of steel, the rate of general corrosion increases. The authors recommend that further investigation into the long-term behaviour of corroded plating under large strains is required. Jurišic *et al.* (2011) presented the investigations of the global and local corrosion wastage of three single hull oil tankers. Analysis of data is based on existing thickness measurements from Croatian Register of Shipping. Hull girder section modulus and local corrosion wastage of main deck plates and longitudinals are determined as a function of time taking into account the lifetime of the protective coatings.

Melchers and Jeffrey (2008) discussed the impact of recent probabilistic corrosion modelling of marine structures for engineers. Rather than assuming a conventional corrosion rate, recent models take into account complexities and non-linearities in the corrosion process. In an overview of the approaches to modelling corrosion wastage of aged structures, Melchers (2008) discussed the need to understand the fundamentals of the in-situ corrosion. Furthermore, existing models of corrosion loss are founded on inadequate knowledge of the corrosion process or on aggregated data from a wide variety of sources which produces significant uncertainty in the prediction of corrosion and the influence of the composition of steel and environmental parameters (Melchers, 2010). Melchers (2010) developed a corrosion loss model based on the fundamental characteristics of corrosion in steel and including the influence of bacteria. The progress of corrosion is represented by a sequence of phases described by fundamental theory and mathematical equations. This model was applied in conjunction with an atmospheric model to predict the expected uniform corrosion loss in seawater ballast tanks of vessels with the view to establishing effective maintenance procedures for naval steel structures (Gudze and Melchers, 2008). The model accounts for the physical process of corrosion and the operational profile of the ship. The results of the corrosion model correlated well to experimental observations.

Melchers *et al.* (2010) presented results of the observed statistical character of the surfaces of 10 large ($1.2\,m \times 0.8\,m \times 3\,mm$ thick) steel plates exposed in temperate climate marine immersion, tidal and splash zones for 2.5 years. For the analysis the plates were cut into smaller segments, mechanically scanned, digitised surface topographies obtained and then analysed. Considerable differences in the mean corrosion loss between different exposure zones were observed. The authors inferred that the deepest corroded pits are not statistically independent as commonly assumed in extreme value statistical representations.

Sterjovski (2010) investigated the repair of plates damaged by pitting corrosion via pad-welding. Guidelines were developed to ensure the structural integrity of naval platform hulls was preserved after pad-weld repairs. Saad-Eldeen *et al.* (2011) analysed the ultimate strength of a slightly corroded box girder subjected to four points

18th International Ship and Offshore Structures Congress (ISSC 2012) - W. Fricke, R. Bronsart (Eds.)

loading resulting in a constant vertical bending moment along the box girder. Employing a non-linear finite element analysis, different elasto-plastic material modes have been developed accounting for the residual stress effect and post-buckling behaviour. Comparison between numerical and experimental results for the slightly corroded box showed good agreements.

4.3 Reliability Based Structural Assessment

Melchers and Guan (2007) noted that when using tools to estimate the probability of structural failure of complex structures, the results of analysis depend on the level of detail in modelling data. Models should sufficiently represent the actual structure and its individual behaviour, which can be facilitated by finite element analysis which adds complexity to structural reliability analysis. Shama (2009) discussed the factor of safety in probabilistic structural assessment of marine structures.

Yu *et al.* (2009a) introduced structural uncertainties into established fatigue design assessment process such as the Lloyd's Register's ShipRight FDA3 procedure. In their study, the authors randomised the key design parameters in a spectral fatigue model, where a pseudo-excitation method is used to reflect the non-linear effect of inertial loads and external wave pressure in the splash zone. A stepwise response surface method is used in tandem with fine mesh finite element analysis to obtain the probability of failure. Gayton and Lemaire (2009) presented a probabilistic methodology for the calibration of partial safety factors for the design of structures subjected to potential fatigue failure. The general calibration procedure is based on the solution of an optimisation problem that is based on finite elements.

The reliability analysis of ship structure was carried out both on the local structure elements and the structure system (Shang and Shi, 2009). The ship was treated as a three-dimensional spatial thin-walled structure composed of beams and stiffened plates. The element reliability analysis was performed using stochastic finite element method and advanced first order second moment method. The advanced branch-and-bound algorithm was used to find the main failure mode and the reliability index of ship structure was calculated by probabilistic network evaluation technique (PNET).

Joung *et al.* (2009) discussed the shortcomings associated with using commercially available structural assessment/reliability codes for accurate estimation of probability of failure. They then presented a design methodology and a software module, which is claimed to overcome the current deficiencies in these commercial packages. The methodology and the software module were applied to the design and manufacture of a stiffened pressure vessel, capable of deep diving up to 6,000 m.

Fujii, *et al.* (2008) reports on the evaluation of the ultimate hull girder strength and its sensitivities with respect to design parameters by series of progressive collapse analysis applying the Smith's Method. Employing a non-linear Strip method, time-dependent nonlinear ship motion analysis was performed to estimate wave-induced bending moments. Utilizing the calculated results, reliability index and failure probability were calculated using the First Order Reliability Method (FORM). Strength reliability analysis of ring-stiffened cylindrical shells was studied using response surface method and FORM (Yu *et al.*, 2009b). The analysis showed that the FORM together with the use of response surface importance sampling results in good accuracy.

Eamon and Rais-Rohani (2009) presented the application of probabilistic design modelling and reliability-based design optimisation (RBDO) methodology to the sizing

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optimisation of a composite advanced submarine sail structure under parametric uncertainty. Using probabilistic sensitivity analysis, the influence of individual random variables on each structural failure mode is examined, and the critical modes are treated as probabilistic design constraints under consistent lower bounds on the corresponding reliability indices. The study concluded that, in comparison to a deterministic-optimum design, the structural mass of the probabilistic optimum design is slightly higher when consistent probabilistic constraints are imposed, and the overall structural stiffness is found to be more critical than individual component laminate ply thicknesses in meeting the specified design constraints.

4.4 Reliability Based Inspection, Maintenance and Repair

Maintenance management in the maritime industry is continuously being improved in order to ensure that the hull structure and its systems are operated and maintained in accordance with the established rules and regulations. New maintenance strategies that combine new tools, such as reliability analysis and condition monitoring, with the traditional maintenance methods, have been introduced.

Real-time condition monitoring techniques are receiving more attention by the operators since they can be used as early warning systems of incipient failure and continuous assessment of probability of failure. Kesavan *et al.* (2008) demonstrated the usefulness of Structural Health Monitoring to detect the location and size of any delamination type failure in a composite structure. Gardiner *et al.* (2008, 2009) reported the development of a hull condition-monitoring network for the Armidale Class Patrol Boat. With the use of aluminium as hull material for a structure, a need has arisen to better understand the structural response of high-speed aluminium semi-planing hulls for naval applications. The data obtained from the sensor network will be used to establish a capability for structural management and life-assessment of the Royal Australian Navy's Armidale fleet.

A predictive reliability analysis of ship structures subjected to crack growth based on experimental data was presented by Garbatov and Guedes Soares (2009). Based on statistical analysis of experimental data using the Weibull model, the authors developed several practical scenarios for inspection and repair. Anastasopoulos *et al.* (2009) presented a study where the use of acoustic emission is considered as a global, real-time monitoring, non-destructive testing (NDT) method for the assessment of the structural integrity of large-scale structures. Ntroulias *et al.* (2010) presented a review of the modern maintenance methods in shipping, as well as a review of the reliability assessment tools, such as Fault Tree Analysis (FTA), Failure Modes, Effects and Criticality Analysis (FMECA) and Markov Analysis. Further on, Fault Trees with time-dependant dynamic gates are used to model the pipe-laying system of two vessels in order to examine their reliability performance through FTA. Analysis allows determination of the reliability behaviour of the systems and their subsystems, as well as their most critical failures. Based on the results, the improvement of the maintenance of the pipe-laying system is realised. The same methodology was applied to determine the reliability of the machinery systems of a cruise ship (Lazakis *et al.*, 2010).

A submarine may have to operate for a period of time with local corrosion damage in the pressure hull if a suitable repair method is unavailable or too expensive for implementation. A paper by MacKay *et al.* (2010) describes collapse tests on twenty ring-stiffened aluminium cylinders, which were conducted to study the effect of corrosion damage on hull strength and stability. The experimental data suggested that corrosion thinning of the shell reduced pressure hull overall collapse and yield pres-

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sures by up to 20 % and 40 %, respectively due to the depth of thinning. It was also found that the volume of material lost to corrosion seems to have less influence on overall collapse strength than the depth of thinning. The effect of shell thinning on inter-frame collapse was found to be less severe. Also, the effect of artificial corrosion of the ring-stiffeners on the collapse strength of cylinders was very small, possibly due to the predominance of direct rather than bending stresses.

5 SANDWICH PANELS AND DEFORMATION LIMITS

5.1 Recent Studies on Steel Sandwich Panels

Previous research has shown a good level of interest in the creation of hybrid metallic-composite structures. In Romanoff *et al.* (2009) the concept of improving shear characteristics of laser-welded steel sandwich panels by filling them with polymeric foams was introduced. With only slight weight increase the stiffness and strength of these panels in weak direction could be improved significantly.

Frank *et al.* (2010) presented an optimisation system for corrugated core steel sandwich panels which is based on the homogenisation and Reissner-Mindlin plate theory; the system utilises Ansys as structural solver. The system has been used with buckling and yielding constraints to design a funnel and deckhouse structure (Kniep *et al.*, 2010). Romanoff (2011) and Romanoff and Varsta (2009) comment on modelling issues related to the interaction between the periodic steel sandwich panels and the girder system when homogenized Reissner-Mindlin plate elements are used. It has been shown that these elements can be used together with offset beams to obtain good accuracy if the periodic structure is reconsidered in the post processing. The technique is capable of modelling the interaction including the effective breadth appropriately. Romanoff *et al.* (2010) investigated the interaction between the steel sandwich panels and the hull girder when different joint configurations were considered. The study shows that the primary, secondary and tertiary responses are coupled when the joints between the sandwich panels are non-symmetrical. The non-symmetry was selected due to ease of production. In the case of symmetrical joints, this coupling diminishes. Polic *et al.* (2011) present a finite element based shape optimisation tool for the non-symmetrical joints to decrease the mass and the stresses on the joint. The plate thicknesses in steel sandwich panels are below those used commonly in shipbuilding. This complicates the fatigue assessment since many of the standard approaches used in shipbuilding consider plate thicknesses above 5 mm. Frank *et al.* (2011) carry out stress analysis of laser-stake welded joints having thickness at this area using notch stress method having fictious radius of 1 mm and 0.05 mm and J-integral. The methods have been validated at this plate thickness and the aim is to move below the thicknesses that are normally used in shipbuilding. The problem however with 1.0 mm approach is that in plate thicknesses below 5 mm the weakening effect is unknown in complex structures; this might have an effect on the overall load-carrying mechanism. Therefore, 0.05 mm and J-integral approaches seem to be more attractive. Ehlers *et al.* (2011) presented principles of modelling laser-welded X-core structures in the case of ship collisions. They interpolated the quasi-static modelling of ship collisions. The conclusion was that the quasi-static simulation under-predicts the penetration for a given force.

Kolster and Wennhage (2009) investigated the possibilities for structural optimisation of laser-welded sandwich panels with an adhesively bonded core and uni-directional vertical webs. Closed-form expressions for the equivalent stiffness and elastic buckling strength of laser-welded sandwich panels are numerically evaluated to demonstrate the effect of parameter variations on stress and deflection. Due to the number of

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design variables and constraints, Kolster and Wennhage (2009) adopted a structural optimisation method based on the method of moving asymptotes (MMA) to minimise the structural weight for a typical accommodation deck configuration. It is concluded that, within the range of production parameters and rule requirements, substantial improvements can be made with or without an adhesively bonded core.

Leekitwattana *et al.* (2011) proposed an alternative steel sandwich panel and a method of determining the transverse shear stiffness analytically. The new topology consisted of inclined shear connectors in a bi-directional pattern. A braced frame analogy and its periodical unit cell, based on a force–distortion relationship concept, are used as the basis for deriving transverse shear stiffness relationships using the modified stiffness matrix approach. The approach was validated against other topologies from literature. The results indicate an improvement in transverse shear performance. Chomphan and Leekitwattana (2011) examined a reduced finite element method based on the unit cell to make 3D FEA more computationally efficient. The results compared well with the analytical solutions.

Zanic *et al.* (2009) presented a design of a Container- Ro/Ro where structural optimisation of ship's superstructure is achieved with deck sandwich modules embedded in the deck supporting structure. The study was conducted as part of EU FP6 project DeLight Transport in an effort to optimise the novel design in relation to reduced production cost and deadweight savings.

The requirement for an efficient joint between the two substrates of a hybrid metallic composite structure has been previously investigated by a number of authors. Boyd *et al.* (2008) extended their investigation into hybrid connections by conducting optimisation of the joint to minimise weight and maximise strength. Further investigations into the performance of metal-composite joints came out of the European Union FP6 MARSTRUCT network. A consortium of researchers investigated the manufacture, analysis and testing of adhesively bonded steel-composite double lap joints. Although the concept of hybrid joints appears to be advantageous there are two areas that may limit their implementation. Firstly it is confidence in the failure mode and secondly it is strength. Studies have been conducted to investigate the improvement of the strength of metal-composite joints. One approach was undertaken by Ucsnik *et al.* (2010) in which cold metal transfer (CMT) pins are attached to the metal substrate. These act as an anchor for the composite and also aid in improving the peel strength capability of the composite material by providing some through thickness reinforcement. The conclusion from this research was a substantial improvement of the strength of the joint.

Grafton and Weitzenböck (2011) discuss steel-concrete-steel structures and its application to ship and offshore engineering. The concept is based on new concrete type having 2.5 times lower density than traditional high strength concrete. It is claimed that the structure is competitive to steel structures on weight.

5.2 FRP-GRP Composites

The advanced composites are increasingly used in the marine industry because of their performance and efficiency attributes. In response to the need to accurately model the damage behaviour of composite structures, the Cooperative Research Centre for Advanced Composite Structures (CRC-ARS) in Australia is extending research on composite material systems (Orifici *et al.*, 2008).

Extensive research has been carried out in the area of fire structural response of polymer composites. Mouritz *et al.* (2009a) reviewed relevant progress towards analysing

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laminates and sandwich composites. Composites with high flammability and low fire resistance are being increasingly used in ship and offshore structures. As such, research in this field is integral part of assessing survivability and safety. Mouritz *et al.* (2009b) investigated the effect of heat and fire on the mechanical properties and failure of polymer composite materials used in ship structures. They developed coupled thermal-mechanical models which predict the loss in strength and time-to-failure of laminates. Mouritz *et al.* (2009a) noted that modelling of damage due to fire has advanced for individual types of damage but not for combined types of damage. There is a lack of research into the fire structural behaviour of laminates under shear, torsion and fatigue. Models featuring highly non-linear behaviour also need to have increased robustness. Keller and Bai (2010) reviewed modelling work concerning the fire behaviour of fibre-reinforced polymer composites. They noted that post-fire properties and behaviour of polymer composites are of interest in a reliable endurance design. Gu *et al.* (2009) studied the compressive load-bearing capacity of polymer matrix composite panels in naval structures and civil infrastructures under the combined thermal–mechanical condition. The thermal field under fire heating and the degradation of mechanical properties with elevated temperatures are investigated. Design diagrams to determine design loads for a given fire protection time, or alternatively to determine design fire protection time for given loads are constructed.

Blake *et al.* (2009) presented the use of a stochastic approach to the design of stiffened marine composite panels accounting for variations in material properties, geometric indices and processing techniques, from the component level to the full system level. Analogous to an analytical model for the solution of a stiffened isotropic plate, the authors considered the use of equivalent elastic properties for composite modelling. This methodology is applied in a reliability analysis of an isotropic (steel) stiffened plate before the final application for a reliability analysis for a FRP composite stiffened plate. Li *et al.* (2009) combined an elastic-theory-based approach and a classical laminated plate theory to obtain an expression for the through-thickness stresses in curved layered composite beams on an elastic foundation under flexural loading. With this expression, the authors derived the solution to through-thickness stresses in curved layered composite beams under pure bending.

Chirica *et al.* (2009 and 2011) presented a methodology based on numerical and experimental studies to analyse torsion response of a ship hull made of composite materials. The torsion analysis is performed on a scale model (1:50) of a container ship to determine the influence of the very large deck openings on the torsion behaviour of the ship hull. Raju *et al.* (2010a) used FEA and experimental data to predict the mechanical strength of marine-grade composite top hat stiffeners under transverse loading. It was noted that for curved laminates, the definition of the boundary conditions is particularly critical to the accuracy of the solution. The prediction of the failure load and the interlaminar stresses of the FE and experimental analyses were in good agreement. Beznea and Chirica (2010) studied the influence of elliptical delamination on the changes in the shear buckling behaviour of composite ship structure plates. An orthotropic delamination model, by using COSMOS/M software package, is applied. The damaged and the undamaged parts of the structure have been represented by well-known layered shell elements. The influence of the position within the thickness and the ellipse diameter ratio of delaminated zone on the critical shear buckling force were investigated. Chirica and Beznea (2011) have continued the development of a delamination model by using the surface-to-surface contact option. Tsouvalis and Gar-

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ganidis (2011) investigated the effect of elliptic delaminations (its shape, magnitude and location) on the buckling behaviour of a marine composite hull.

Holes induce the stress concentration on the structure and decrease the structural strength. In order to determine the stress concentrations factor for a composite plate with elliptical hole, Li *et al.* (2010) applied the theory of functions of complex variable. The stress function of complex variable which exactly describes the stress field is obtained by using conformal mapping. The stress analysis on the composite material plate with elliptical hole is carried out based on the established mathematical model.

Grabovac and Whittaker (2009) reviewed the success of carbon fibre composite patches used to eliminate fatigue cracking in the superstructure of a Royal Australian Navy frigate over 15 years. The repair was found to re-establish the strength and function of the structure.

A paper by Blasque *et al.* (2010) addresses the design and optimisation of a flexible composite marine propeller. The authors aimed to tailor the laminate to control the deformed shape of the blade and consequently the developed thrust. A hydro-elastic model of the propeller was developed, and the laminate lay-up which minimizes the fuel consumption for the cruising and maximum speed conditions was simultaneously determined. Results show a reduction of 1.25 % in fuel consumption for the combined case corresponding to a decrease of 4.7 % in the cruising speed condition. The authors concluded that it is possible to design a medium-size flexible composite marine propeller that will enable reduction in fuel consumption while withstanding the imposed loads.

Andrews and Moussa (2009) investigated the blast limitation of composite sandwich panels utilising failure mode maps. The work initially investigated the mode of failure for a variety of sandwich panel geometries and material property variation. This is all conducted assuming quasi-static loading. The second phase of the study was to couple the quasi-static failure mode maps with a theoretical model for blast loading. Although a nice approach the results obtained for the various case studies presented in the paper have not been validated, an issue raised by the authors. Tilbrook *et al.* (2009) examined underwater blast loading of composite sandwich beams. The paper provides a good overview of literature on the subject of shock response of sandwich structures. The authors present a sequence of 3 stages in which a sandwich beam responds to the blast loading: the fluid-structure interaction, core compression, and beam bending and stretching. The authors examined the coupling between these phases. A finite element model is presented to establish the response of the sandwich beams to blast and result is 4 response regimes. These are partial core densification at the supports before the mid-span of the back face decelerates; full core densification at the supports before the mid-span of the back face decelerates; partial core densification at the supports after the mid-span back face decelerates; full core densification at the supports after the mid-span of the back face decelerates. The conclusions show that for a given blast impulse and beam geometry there is an optimum transverse core strength that minimises the back face deflection. Chirica *et al.* (2012) investigated the protective capacity of ship hull structures made of composite materials subjected to a close proximity explosion of a spherical charge. The study employs a non-linear finite element analysis. The methodology for determination of the blast pressure load and the mechanism of the blast wave in propagating in free air are given. The spatial pressure variation is determined by using Friedlander exponential decay equation. A parametric study was conducted to determine the effects of explosive magnitude, distance from source of

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explosion, plate thickness on the behaviour of the ship structure laminated plate to blast loading.

Qin and Batra (2008) developed a hydroelastic model incorporating a {3,2}-order composite sandwich panel theory and Wagner's water impact theory to examine the slamming process of composite ship hulls. A numerical procedure was developed to solve, simultaneously, the fluid and structure deformation response. The governing equations are nonlinear because the a priori unknown wetted area is a function of the deformations which are to be found. It was found that the core of the sandwich panel acts as an effective absorber of impact loading through transverse shear deformation.

In the area of ship crashworthiness and impact protection, metallic foams are increasingly utilised as energy absorbers and weight savers. Metallic foams constitute the core of some sandwich structures. Zhu *et al.* (2009) investigated impulse loading of sandwich panels with aluminium foam core. An analytical method to predict the deflection of the panel was used to measure energy absorption during plastic deformation. The deformation process was divided into three phases; impulse at the front face, compression of the core, and deformation of the back face.

Pandit *et al.* (2009) investigated variations in material properties of sandwich plates on transverse deflections. In demonstrating the performance of a stochastic laminated sandwich model, the authors investigated the effects of boundary conditions and lay-ups on the deflections of square sandwich plates with scatter in material property.

6 SHIP STRUCTURES

6.1 Design Trends, Developments and Challenges

Stronger, safer and more durable structures are now recognised due to increased awareness by the authorities and the society in general in relation to safety of passenger and crew, environmental protection. At the same time, the increased competition demands for the increased productivity and the reduced costs in the ship building industry.

In this section, the recent developments in areas of green shipping, energy efficient designs, cleaner alternative propulsion, safer ships, Northern Sea route and Panama Canal expansion are discussed in relation to their potential impact to design and operation of ships.

6.1.1 Green Shipping

Ships are continuously travelling in world's oceans and have close interaction with the sea environment and atmosphere. Ships are the most energy efficient transport media in terms of transportation of goods per tonne-mile. Ships have been, and will continue to be used in global logistics. In recent years there have been pressures for energy efficiency and reduced emissions from the regulatory authorities as well as from society in general due mainly to the depletion of fossil fuels and global warming. Based on an article published in New Scientist (2011), if all the international shipping fleet were a single country, shipping would be the 7th largest emissions contributor in the world. This is larger than the whole aviation industry (see Figure 1). As with other modes of transportation, ships are required to be more energy efficient as well as compliant with global environmental protection. Therefore, it is very important for ship designers to design environmentally friendly ships, not just for regulatory compliance, but mainly for their performance and competitiveness.

A number of technologies are considered as green ship technologies for near future and long-term. Improvements in the area of hull hydrodynamic efficiency of ships, weather

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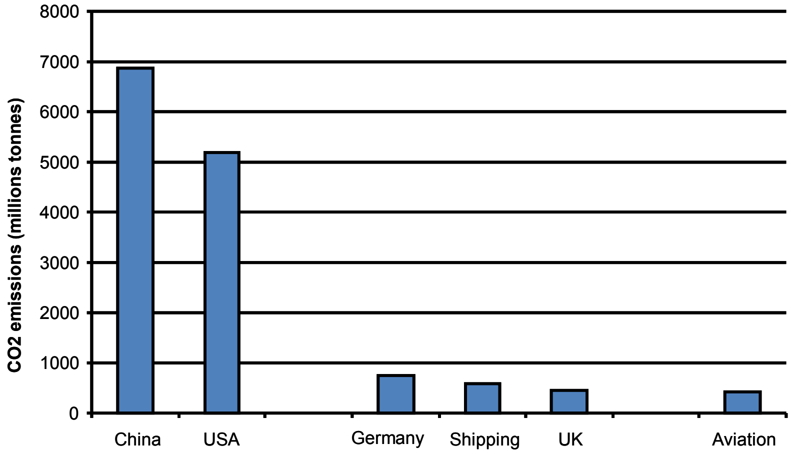

Figure 1: CO_2 emissions from any fossil fuels burned for energy generation, transportation, heating and other uses. All large shipping and aviation are considered as individual groups. (Figure adapted from New Scientist, 15/12/2011)

routing, and using LNG as fuel onboard are considered as the near future green ship technologies. For the longer term, future green ship technologies, hydrogen and fuel cell ships, renewable energy ships - using solar, wind and wave power, and nuclear powered ships are considered. In this section, the recent developments in these green technology areas are reviewed.

Energy efficiency and minimisation of emissions have recently become important topics to reduce global warming. A wide range of research topics on ship powering have been conducted to minimise resistance for this purpose. Ship hull form optimisation has been utilised commonly to reduce the wave resistance component of a ship. Air lubrication is one promising method to reduce the viscous resistance of a ship. It can be established by the utilisation of techniques such as air cavity, micro-bubbles, and air film formation. Insel *et al.* (2009) describes efforts to reduce the resistance for a tanker form by means of air lubrication, the work was carried out at Istanbul Technical University. The results indicate that resistance reduction can be obtained by using this technique even at low speeds. Mizokami *et al.* (2011), also developed frictional resistance reduction technology by means of air lubrication, carried out confirmation of the air blow condition with a mock-up examination and the numerical computation. It was stated that for a large shallow water ship, the air lubrication method provided an energy saving of 12 %.

Reduction of fuel consumption as a result of slow steaming or route optimisation has also received increased attention recently by the ship operators as a countermeasure to reduce green house gas (GHG) emissions. Selecting a proper route for a ship will not only reduce fuel consumption but also provide safe navigation. Habu *et al.* (2010) presented a study on the route optimisation in stormy weather. In this study, the selection of optimum route for ships running in stormy weather is established based on improved efficiency and navigation safety. For the calculation of navigation cost, an efficiency criterion function is used, which consists of the navigation time and fuel consumption. The navigation safety was evaluated by considering limiting values for wave height, wind speed and roll angle.

In order to increase ship performance in actual navigation conditions, a definitive

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evaluation method of the performance needs to be established. Tsujimoto *et al.* (2010) developed the 10 mode "Index for Ships". The index consists of ship speed in ten kinds of weather conditions as well as ship speed in calm seas. Verifications were carried out by numerical simulation, model tests, and full scale measurement and it is concluded that the hybrid calculation is robust to evaluate ship speed in actual scenarios.

Nelson (2010) discussed the increasing efforts made by LNG shipowners in employing enhanced operational techniques and new technologies to reduce the impact on the environment and, in some cases, also reducing the vessel's operating costs. The operational techniques and new technologies such as hull form, propeller design and interaction with the hull, main propulsion system design, underwater coating technologies, reliquefaction plants, and emissions control systems are considered and/or implemented by the LNG shipowners to meet the current and proposed future national/regional and international environmental regulations.

6.1.2 Energy Efficiency Design Index, Energy Efficiency Operation Index (SA)

In July of 2011, the IMO established two instruments to reduce marine CO_2 emissions. These instruments, the Energy Efficiency Design Index (EEDI) and the Ship Energy Efficiency Management Plan (SEEMP), will be mandatory and will come into force on January 1st, 2013.

The IMO adopted the Energy Efficiency Design Index (EEDI) as a newbuilding standard, assuring that ship designs achieve a minimum level of efficiency and decreased carbon emissions. Although EEDI certification will not be mandatory for newbuildings until the 1st of January 2013 (contract date), owners and managers at the vanguard of sustainable shipping are already voluntarily looking to the EEDI as a means of demonstrating the efficiency of their new ship designs.

While measures such as the EEDI focus on a ship's design, and thus on newbuildings, the SEEMP concentrates on energy savings potential during the operational life of a vessel. Every ship shall have an SEEMP, preferably tied into a company-wide energy management program. The SEEMP fosters structured and codified management processes to increase a vessel's energy efficiency - IMO specifically mentions the EEOI (Energy Efficiency Operational Indicator) as a well-established and industry-specific tool to quantify and monitor results, although other methods may be used as well.

From 2013 onward, the SEEMP will be mandatory for all vessel segments. The presence of an SEEMP on board each vessel will be checked at the intermediate or renewal survey (whichever comes first after Jan 1st, 2013) but so far there is no requirement for the SEEMP to be approved by the flag state or by a Recognized Organization (RO).

Devanney (2011) discussed the impact of the energy efficiency design index on very large crude carrier design and CO_2 emissions. The author argued that, over a market cycle, imposition of EEDI will result in a slight increase in VLCC CO_2 emissions, relative to no regulation at all. The following specific concerns were raised. First, for VLCCs, EEDI effectively limits installed power, which requires owners to use smaller bore, higher revolutions-per-minute engines resulting in higher specific fuel consumption and, more importantly, require a smaller and less efficient propeller. This means the EEDI-compliant VLCC consumes more fuel when the market is not in boom, which is 90 % of the time. Further, the author suggested that a $ 50 per tonne of CO_2 bunker tax might be more efficient and will reduce VLCC CO_2 emissions by more than 6 %.

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6.1.3 Cleaner Alternative Propulsion

Nishizawa *et al.* (2010) presented a feasibility study on an electric propulsion tanker without ballast water. The hull shape was developed to minimize the frictional resistance and the viscous pressure resistance for a tanker with 100,000 DWT. Because of a buttock-flow stern hull shape, the new tanker was designed as an electric propulsion ship with podded-propulsors. Based on the results of the present feasibility study, the authors concluded that the high initial cost for building can be balanced by lower operational costs achieved by reduced fuel, lubricant and maintenance costs, and by increased income as a result of increased deadweight capacity.

Using LNG as fuel is an efficient way to cut emissions. All SO_x emissions are eliminated and the NO_x and CO_2 emissions are reduced by about 80 % and 20 % respectively (Levander *et al.*, 2006). It is argued that natural gas is one of the largest sources of energy worldwide and at today's rate of consumption it is expected to last about 150 years. There are currently approximately 25 ships that are operating with LNG fuel in world waters. Viking line is building the world's first large LNG passenger ferry (Horizons, 2011). However, there are some storage, safety and operational concerns using LNG.

- The main problem with using LNG in ships is the large amount of space required for the LNG tanks. Compared with marine diesel oil (MDO), an equal energy content of LNG requires about 1.8 times more volume than MDO. After adding the tank insulation, which results in a maximum filling ratio of 95 %, the required volume is increased to about 2.3 times. The practical space required in the ship may become even larger if a cylindrical LNG tank and the surrounding space lost around is considered.
- Natural gas is perceived to be highly explosive and dangerous when used as a ship fuel. However, this is not necessarily true and it can be used safely as fuel if the right precautions are taken. In a liquid state, natural gas is not explosive, nor is it corrosive or toxic. However, there are material issues with low temperatures. On the other hand, the marine industry has significant experience in dealing with this problem by the operation of LNG vessels. In gaseous state, natural gas is lighter than air, which means that in case of leakage the gas will disperse upwards and not build up in the ship's bilge. The ignition temperature of natural gas is relatively high ($600^\circ C$) compared with diesel oil ($250^\circ C$) (Levander *et al.*, 2006).
- Availability of propulsion engines. Previously, a number of LNG ships had gas turbines as main propulsors. Although less fuel efficient compared with diesel engines, LNG operators were able to burn the boil-off gas with these. Recently, major engine manufacturers (Wärtsilä, MAN) introduced hybrid dual-fuel (H-DF) engines that can burn liquid or gas fuel at the same time. These engines use LNG as primary fuel and marine diesel oil as pilot and back-up fuel (Levander *et al.*, 2006).

Bernatik *et al.* (2011) discussed the safety and security aspects of storing of LNG as a potential alternative fuel. The contribution deals with possible scenarios of accidents associated with LNG storage facilities and with a methodology for the assessment of vulnerability of such facilities. The study presents the results of determination of hazardous zones around LNG facilities in the event of various sorts of release.

Although Brown (2011) agrees with very clear considerable local benefits in using LNG as a marine fuel, he cautions that LNG is just another fossil fuel and draws attention to concerns and claims that LNG does not reduce CO_2 emissions on a like-for-like

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basis with other fossil fuels when carbon foot print from well to flue emissions is considered. Much of the excitement around LNG's prospects devolves from the prospect of abundant, cheap, gas as a result of gas from new reserves of 'unconventional' gas exploited through technologies such as fracking of shale gas. However, a study by Howarth *et al.* (2011) raises concerns on methane escape to the atmosphere. Natural gas is composed largely of methane and the authors claimed that 3.6 % to 7.9 % of the methane from shale-gas production escapes to the atmosphere in venting and leaks over the lifetime of a well. Methane contributes substantially to the greenhouse gas footprint of shale gas on shorter time scales, dominating it on a 20-year time horizon. The footprint for shale gas is greater than that for conventional gas or oil when viewed on any time horizon, but particularly so over 20 years.

Utilizing the ocean wind power is considered as an option to reduce the fuel oil consumption of a large merchant vessel. Ouchi and Uzawa (2010) proposed a new eco-ship concept of "Motor Assisted Sailing Ship" to contribute to a low carbon society. The ship is fitted with huge hard sails (height: $50\,m$, Bredth: $20\,m$, Area: $1{,}000\,m^2$) made by CFRP composite having a high lift performance wing shape section and also having a vertically telescopic reefing mechanism. The nine pieces of hard sails (total sail area $9{,}000\,m^2$) generate enough forward thrust to drive $180{,}000\,DWT$ Bulk Carrier at $14\,kn$, in the case of wind velocity of $13\,m/s$ from a beam. A case study using real sea conditions was carried out and more than 50 % of propulsion energy is acquired from the ocean wind power on average.

6.1.4 Safer Ships

Onboard decision support systems (DSS) are used to increase the operational safety of ships. Ideally, DSS can estimate future ship responses within a time scale of the order of 1–3 hours taking into account speed and course changes, assuming stationary sea states. A paper by Nielsen *et al.* (2009) suggested a procedure which is based on parallel system analysis, to incorporate random variables and associated uncertainties in the calculations of the out-crossing rates that are the basis for risk-based DSS. Bitner-Gregersen and Skjong (2009) presented a concept for a risk based decision support system for navigation of ships that encounter deteriorating weather conditions and dangers of damages to a ship and its cargo. The authors advocated that it is possible to develop a system that is systematically built on risk assessment approaches with the intention of being applicable for a specific ship with a specific loading situation in a real-time environment. Bitner-Gregersen and Skjong (2009) based their concept on modern reliability methodology, state-of-the-art hydrodynamics software and information sources relating to the environment.

Tamura and Shinoda (2010) presented a paper on the application of FSA (Formal Safety Assessment) to collision accidents between fishing vessels and cargo vessels. Most marine accidents related to vessels are caused by human errors, such as misdetection, misjudgement and misoperation. The study claims that collision accidents between fishing and cargo vessels with consequences of loss of life occur frequently in the sea off Japan. In this context, the safety assessment for these types of marine accidents is carried out through the steps of Identification of hazards by Variation Tree Analysis, Construction of Marine Casualty Database, Collision Course Analysis, Risk Assessment by Event Tree Analysis, Estimation of probabilities of collision accidents based on ship traffic data and Evaluation of Risk Control Options using Contingent Valuation Method, which is in accordance with Formal Safety Assessment (FSA) approved by IMO in 2002.

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Yuzui *et al.* (2011) proposed Inclusive Impact Index by the IMPACT Research Committee in the Japanese Society of Naval Architects and Ocean Engineers. Inclusive Impact Index is defined and calculated based on the ecological footprint, ecological risk, human risk, cost, and benefit. Applicability of the index to the environmental risk assessment problems in the maritime field such as evaluating the risk of an oil tanker is discussed.

Det Norske Veritas in Australia have reported weaknesses in the applicability of the International Maritime Organisation (IMO) High Speed Craft (HSC) code to passenger and cargo craft used in crew transfer, patrol and service. In response to industry requirements to standardise certification and safety rules of craft operating in different countries and offshore installations, DNV have published new rules. The 'Tentative Rules for Domestic Service Craft' cover structures and equipment (Det Norske Veritas, 2011). The notation for hull structural design states that the bow and fendering system, intended to be pushed against hard foundations, must be strengthened to withstand the applied loads.

6.1.5 Northern Sea Route, Panama Canal Expansion

As intentions for use of large-size commercial ships as a part of arctic transportation systems are becoming reality, however it appears that these decisions are mostly based on the results of cost-effectiveness calculations. Pavlenko and Glukhareva (2010) discussed the issues connected with the usage of the Northern Sea Route and Northwest Passage. The authors suggested possible solutions that can be used for the development of international marine shipping infrastructure, safe navigation support and systems of response to emergency situations in Arctic Ocean. Somanathan *et al.* (2009) modelled shipping through the Northwest Passage in northern Canada and compared the economics of this route relative to the Panama Canal. Container shipping between Yokohama ad New York and St. Johns, Newfoundland, is simulated for the two routes using bluewater ships for the Panama Canal and identically sized Canadian Arctic Class 3 (CAC3) ships for the Northwest Passage. The required freight rate (RFR) to recover all costs including capital recovery is found to be similar for the two routes. Sazanov (2011) reviewed some main challenges related to large-size ships manoeuvrability and performance in ice as well as interaction of ships with icebreakers. From the limited review carried out here, it appears that not much research was conducted on the structural/design changes required for the commercial ships to operate in Northern Sea route.

An article in Oil and Gas journal (Oil and Gas, 2010) argued that Panama Canal expansion will permit more than 80 % of the global LNG fleet to move through the canal, compared with only 6 % of the fleet currently. However, no LNG vessels now traverse the waterway because that 6 % of the fleet is too small to engage in large, long-haul trade. Panama Canal expansion may have a significant effect on the LNG cargo movements. For example, producers such as Trinidad and Tobago, Algeria, Nigeria, and Angola will be able to move their cargoes to Asia. Similarly, Asian cargoes will be able to access Atlantic Basin markets. As the trade expands, there may be need for more LNG vessels.

6.2 Types of Analysis for Various Ship Types

6.2.1 Passenger Ships

On passenger ships, the committee considered two main aspects related to quasi-static response; the modelling of structural details such as openings and joints and the principles of assessing the global response of the hull girder.

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Mobasher-Amini *et al.* (2009a; 2009b) presented a domain decomposition method for passenger ship structures where structural heterogeneities exist for example due to window or balcony openings. The method utilizes linear elastic Finite Element Method. It also addresses the problems of subdomain interfaces arising from the presence of elastic joints or stiffeners. Bäckström and Kivimaa (2009) worked in detail on the topic of large openings in longitudinal bulkheads and simulate the crack propagation due to shear-induced deformation. Biot and Moro (2011) carried out similar analyses using both linear-elastic and elasto-plastic notch stress analyses. Andric and Zanic (2010) made detailed investigation how the openings should be modelled to achieve reasonable accuracy in the global finite element analyses. They concluded that with orthotropic equivalent plate elements reasonable accuracy can be obtained when stiffness is concerned. Romanoff *et al.* (2010) claimed that when using novel deck structures, such as steel sandwich panels, special attention needs to be paid on the interaction between the sandwich decks with non-symmetrical joints and the global hull girder analysis.

Remes *et al.* (2009) presented a new conceptual structural design platform, ConStruct, especially designed for passenger ships. It is based on the Coupled Beams theory presented by Naar *et al.* (2004). The work was continued in Remes *et al.* (2011) where they investigated the hull-superstructure interaction of optimised passenger ships. They concluded that for ship with equal volumes on the hull and superstructure, the global bending moment is carried out equally between the hull and the superstructure in weight optimal design. When vertical centre of gravity is set as design objective the superstructure starts to carry more of the bending moment due to the shift of neutral axis. It is also seen that the neutral axis varies across the length of the ship and therefore the entire length of the ship needs to be modelled; this happens even in case of prismatic ship. Andric and Zanic (2010) concluded that prismatic FE-model can be used to calculate the normal stresses at the midship and the deflections along the length of the ship. Thus, these two investigations propose that beam methods where deck efficiencies are assumed to correct the effects of non-linear normal strain distribution along the height direction of the ship are not sufficient for structural analysis other than at the midship location. In Caprece *et al.* (2010), the ship has been split into three representative short beam sections where the bending moment and the shear forces are applied. The paper, however, does not present a comparison of normal stresses to conclude how well the approach works. Having these aspects in mind, a proposal would be to complete a benchmarking study where different methods to assess passenger ship response would be compared. Davidson *et al.* (2011) considered the load cases and structural design of a multihull ferry. The authors conducted research to determine the most efficient roof-to-hull structure, where various roof-to-hull structures in terms of resistance to deflection and cargo and passenger carrying capability are considered.

The cruise ship, Costa Concordia, ran aground off the coast of the Isola del Giglio island on the night of 13th January 2012. She suffered serious damage on 3–4 watertight compartments, lost its stability and capsized. The 4,200 people aboard are evacuated to the nearby Isola del Giglio island (Associated Press). At the time of last update of this report, 17 people are known to have died and 15 people are still unaccounted for (BBC, 28th Jan 2012).

From the initial investigations, it appears that human factors caused navigational misconduct which then resulted in the grounding accident. The captain of the cruise vessel has been arrested for misconduct and man slaughter. It is too early to speculate, with certainty, either the account of events that led to the capsizing of the vessel or what possible implications that the accident will have on the design of passenger vessels. However, the committee is certain that the accident will have an influence on passenger vessel design.

6.2.2 Container Ships

In recent years container ships have seen dramatic change with respect to their size and it is an ongoing trend. In 2011, the first container ships carrying 18,000 TEU were ordered. The capacity of these vessels, at 400 m length and 59 m wide, were designed to capitalise the size effect. A larger ship will be more efficient in terms of fuel consumption per TEU transported; however, it presents challenges operationally and from a naval architectural point of view. The extreme size of the hull and its inherent flexibility may be limiting design factors. Extensive research is required to ensure an adequate structural capacity over the ships lifetime.

With more bow flare, more flexible hulls and higher speeds, larger vessels are more exposed to whipping. Storhaug *et al.* (2010) investigated the effect of springing and whipping on a 360 m ultra large twin island container ship design. Model tests with a new flexible design have been carried out to investigate how the wave-induced vibration affects the fatigue and extreme loading at different cross sections. The focus is given to the consequence of extreme loading with whipping based on long duration tests in realistic extreme weather, but also the effect of whipping (and springing) on fatigue is investigated. The tests are carried out in head seas, and all parameters are realistic such as loading condition, vibration modes, vibration frequencies, damping, wave spectra and speed.

To assess high-frequency ship response for rule development purposes of large modern container ships, Rathje *et al.* (2011) compared numerical predictions with experimental data. The numerical results were based on a technique that relied on superimposing rigid body motions on elastic hull girder deformations, whereby a finite element Timoshenko beam idealizing the hull was two-way coupled to a RANS solver for the fluid-structure interaction problem. The experimental data were obtained from model tests of a segmented 10,000 TEU container ship equipped with load cells, accelerometers, and pressure sensors. A long-term measurement campaign onboard a 4,600 TEU panamax container ship yielded full-scale measurements. For the investigated cases, data analysis confirmed that predictions accounting for high frequency response yielded higher section loads than those based on rigid body assumptions.

Senjanovic *et al.* (2011) pointed out that natural frequencies of Ultra Large Container Ships (ULCS) can fall into the range of encounter frequencies in an ordinary sea spectrum. Present Classification Rules for ship design and construction do not cover such conditions completely and hydroelastic analysis of ULCS seems to be the appropriate solution for analysis of their response in waves. Within the paper the importance of the hydroelastic approach and methodology of hydroelastic analysis are elaborated. Furthermore, structural model based on advanced beam theory is described in detail. The improvements include taking into account shear influence on torsion, contribution of bulkheads to hull stiffness as well as determination of effective stiffness of engine room structure. Hydrodynamic and hydrostatic models are presented in a condensed form.

Two aspects relevant for operation and structural design of wide-bodied container ships were addressed by Rathje *et al.* (2010). First, speed loss in waves was investigated to demonstrate the effect of waves on comparable calm water speeds. Second, wave-induced global hull girder torsional loads were determined to assess effects of the

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increased breadth on hull girder torsion, generally considered the most critical load component. An extended Reynolds-averaged Navier-Stokes equations solver simulated the ship advancing in calm water as well as in selected regular head and bow waves. Spectral techniques obtained long-term predictions of torsional moments, based on nonlinearly corrected transfer functions of ship response computed with a boundary element method. To assess the reliability of these torsional moments, additional simulations were carried out of this ship in two equivalent regular design waves that represent wave conditions considered critical for structural design.

Tanaka *et al.* (2009) presents the results of an experimental study to evaluate the effect of torsional moment on the ultimate strength of container ships in longitudinal bending. The progressive collapse tests are conducted using 1/13-scale three-hold models referring to a Post-Panamax container ship. The models are fixed to the rigid wall at the aft end (cantilever beam) and loads are applied to the fore end so as to generate both torsional and vertical bending moments. Several loading conditions which vary the ratio of torsional and bending moments are adopted for the progressive collapse tests and the nonlinear finite element analyses using LS-DYNA. From the results of collapse tests and numerical simulations, the progressive collapse behaviour including the warping-strain distribution and the ultimate strength interaction relationship is examined.

Along with the rapid increase in the size of container ships over the last few decades, it has become necessary to use thicker plates in way of the hatch coaming. The use of higher tensile steel with yield strength 460 N/mm^2 is also inevitable to avoid using excessively thick plates. The main area of application for the new higher tensile steel is the upper hull girder area. To investigate the effect of plate thickness and tensile strength on fatigue strength for the weld joints, Kwon *et al.* (2011) conducted a series of fatigue tests with specimens of butt weld joint and longitudinal fillet weld joint with the different plate thickness and tensile strength steel. From the test results of each series of specimens which were taking into account recent developments concerning material and welding techniques, the effect of plate thickness and material was investigated. Using the fatigue test data, fatigue strength was calculated on butt weld joints and longitudinal fillet weld joints in way of hatch coaming top plate for a large container ship.

The characteristic high tensile loads in this area in combination with large plate thicknesses and high strength steel raise the possibility of brittle fracture. In order to address these concerns, research has been carried out on brittle crack arrest ability from a number of different perspectives, including the use of both numerous large-scale crack arrest tests and numerical calculations. According to Yamaguchi *et al.* (2010) a back-up brittle crack arresting function has been included in the ship's construction in order to ensure structural reliability and hull integrity. The effect of joint design on crack arrestability of thick steel plate using shipbuilding steel without block joint shift was investigated by An *et al.* (2011). Several crack arrest tests were conducted by varying joint designs to prevent a catastrophic failure along the block joint of hatch side coaming structure. A brittle crack arrest technique was developed using an arrest weld, which located in end of hatch side coaming weld line. Steel plates with 80 mm thickness were used and two welding processes, which are flux cored arc welding (FCAW) process only and combined welding process (EGW+FCAW).

Kaneko *et al.* (2010) developed thick YP460 N/mm^2 class steel plates for the application of large heat-input welding. This report describes the development concept of YP460 MPa class steel plates and the material characteristics of the base metal and

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welded joints. A brittle fracture test (ESSO) was performed to determine the stress intensity factor K_{ca} as an index of arresting characteristics.

For the new material class with $460\,N/mm^2$ minimum yield strength Doerk and Rörup (2009) describe the development of a safety concept based on a brittle fracture prevention strategy using fracture mechanics methods. The safety concept results in toughness and quality requirements, which are practically applicable in shipbuilding industry. Effects of different influence parameters such as design temperature, fracture toughness, initial defect size, and shape of load spectra are discussed. Furthermore, prospective inspection and assessment strategies are presented.

Shin *et al.* (2011) established an alternative for the prevention of the unstable fracture of ultra-large container ships during design life of 20 years. In order to do it, primary and secondary stress levels and fatigue crack growth rate for the weldment were evaluated in accordance with classification rules and relevant test methods. From the test results, it was found that the fatigue crack growth rate increased with an increase in welding heat input. With those results, the allowable embedded defect size and crack tip opening displacement (CTOD) requirement for the weldment to prevent the unstable fracture at the hatch coaming were established by using a comprehensive fracture assessment.

Toyoda *et al.* (2008) conducted full scale measurement of deflections of a Post-Panamax container ship. Interferences between fittings such as hatch covers, lashing bridges and other container securing instruments need to be addressed when new size of ships is explored. The three components of the deflections were measured, i.e. torsional deflection, cross deck fore-aft deflection due to container inertia force, and longitudinal deflection due to hull girder bending moment. A method was proposed for combining the deflection from these three components by using correlation analysis.

The bow flare impact characteristics and structural response of container ships are studied by Chen and Xiao (2010). Occurrence probability, significant and extreme value of impact pressure is predicted for the ship sailing with different speeds and within different sea states. The pressure distribution on the bow side region is analysed including the effect of speed and sea states. These impact pressures were applied to FE models to determine the stresses in the structure.

Mortola *et al.* (2011) studied a two dimensional nonlinear strip theory for the sea keeping analysis under large amplitude waves. The nonlinear system of equations of motion is numerically solved via a fourth order Runge-Kutta method. The proposed method is applied to the S-175 Container ship and the results are compared with the predictions for small amplitude waves obtained from the results published by other researchers.

Drummen *et al.* (2009a) presented an experimental and numerical study of container ship responses in severe head seas. Experimental results were obtained using a flexible model of a new container ship design. The experiments showed that, taking hull flexibility into account, the fourth and sixth harmonic of the vertical bending moments had a maximum value of between 25 % and 50 % of the first harmonic. The authors also demonstrated that hull flexibility can increase the vertical bending moment by up to 35 % in sea states relevant for design. Miyake *et al.* (2008) conducted experimental studies on the hydroelastic response, including the effects of whipping and springing, and hull structural strength of mega-container ships using a modified Wigley model with the elastic backbone having the rigidity equal to that of a 12,000 TEU container ship in regular waves. During tank tests, the authors observed the occurrence of the

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superharmonic springing resonance. Experimental results were used to validate a 3-D Rankine source method capable of analysing springing.

The coefficient of contribution method, in which the extreme response is determined by considering only the few most important sea states, is an efficient way to estimate nonlinear long-term load analyses. To efficiently find the nonlinear short-term probability distributions of the vessel responses in these sea states, response conditioned wave methods can be used. Drummen *et al.* (2009b) investigated the accuracy by comparing the short-term probability distributions obtained from random irregular waves with those from response conditioned waves. The authors also discussed how response conditioned wave methods can be integrated into a long-term response analysis. The focus was on the probability distributions of the midship vertical hogging bending moments in the sea states contributing most to the hogging moments with a mean return period of 20 years and 10,000 years. The authors concluded that the response conditioned wave methods can be used to accurately determine the nonlinear short-term probability distributions for rigid hulls, but either accuracy or efficiency is to a large effect lost for flexible hulls, when slamming induced whipping responses are accounted for.

7 OFFSHORE STRUCTURES

The offshore oil and gas technology is moving to deep and ultra deep water. The demand for FPSOs has increased significantly in recent years. For FPSO conversions rather than new builds, which offer significant economic benefits for operations in benign environments, determining the remaining fatigue life of the structure is an important consideration. Similarly, for drilling and exploitation in deep water, the semi-submersible drilling platforms show a series of advantages in performance and as such they are dominating offshore installations for oil and gas exploitation in deep water. Among these kinds of units, the early 21st century design, sixth-generation semi-submersible drilling platforms, capable of operating in deep waters up to 3,000 m, is becoming dominant in the industry. Also, fatigue has been the determining design factor for tubular joints commonly used in fixed offshore platforms. Thus, there is a significant body of research in the area of fatigue available in the literature. Finally, recent studies in the area of uncertainty in risk and reliability assessment of offshore structures are reviewed.

7.1 Design Trends, Developments and Challenges

Quasi-static push-over analysis is used to evaluate the maximum quasi-static load that a fixed offshore structure can withstand. The quasi-static approach idealises the dynamic nature of wave forces acting on the structure. Memarpour *et al.* (2009) compared quasi-static and dynamic methods in measuring the ability of an offshore structure to resist loads that exceed design values. Wind, wave and current loads were applied quasi-statically by gradually increasing the magnitude of the loads until collapse of the structure. In the dynamic analysis, cyclic wave loads and monotonic wind and current loads were applied in phases to represent a storm. For the offshore platform studied by the authors, the quasi-static analysis resulted in a higher ultimate strength than the dynamic analysis.

Jacket platforms in the Bohai Gulf are often victims of random ice induced vibrations. Liu *et al.* (2009) presented a study where two different approaches, namely: the failure probability-based approach and the expected loss-based approach, were considered to determine the short-term dynamic ice cases for dynamic analysis of ice-resistant

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jacket platform in the Bohai Gulf. Considering the variation in the ice environments and the variability of ice-resistant structure's properties, the random ice spectrum and the pseudo-excitation method (PEM) are employed to improve the efficiency of the procedure. Pushover analysis was also adopted for the study of jackup platform seismic behaviour under earthquake loads for different working conditions (Jin and Liu, 2010). Comparison between structural capacity spectra obtained from dynamic time history analysis method and pushover analysis method verified the validity of the pushover analysis method.

Research on strength analysis of a semi-submersible platform was presented by Li *et al.* (2011a). The authors demonstrated that a beam model to carry global strength analysis of semi-submersible platform yields the same result using combined shell/beam model. Thus, they argued that beam model to the estimation of the strength of the whole structure at basic design stage for rapid and efficient solution can be adopted.

Kumar *et al.* (2010) presented a review study on the installation engineering of topside modules on ship shaped offshore floating structures. The study covers the investigation of governing technical parameters for heavy lifting, followed by installation phase and hull integration covering necessary structural modifications to deck structure. The interrelationships amongst a number of key parameters/aspects of installation process of a topside module such as weight control, heavy lifting and rigging, local FEM analysis of lifting points and members, installation tolerance and design of fine guides, are studied.

Elshafey *et al.* (2009) presented a study where the response of a scale model of a jacket offshore structure was investigated both theoretically and experimentally. The effects of varying the structure's weight, and the characteristics of the wave loading were investigated. Excellent agreement between the experimental and theoretical results was obtained. Elshafey *et al.* (2010) investigated the damage detection in offshore jacket platforms subjected to random loads using a combined method of random decrement signature and neural networks. The random decrement technique is used to extract the free decay of the structure from its online response while in service. The free decay and its time derivative are used as input for a neural network. The output of the neural network is used as an index for damage detection. Early damage detection can be achieved by observing changes taking place in the signature, thus, preventing the occurrence of unpredicted structural damage. The authors used only the random decrement corresponding to the fundamental natural frequency as the method is most effective in identifying damage occurring in members which most influence the fundamental natural frequency of the structure. It was suggested that the methodology introduced can be used in conjunction with traditional inspection techniques to reduce the overall inspection costs.

The module stool is a key structure to link the module and the deck in floating production, storage and off-loading (FPSO). The welded joints of the module stool should be guaranteed to possess enough toughness against cracking and rupture. A paper by Miao *et al.* (2010) describes the testing and approval of welding procedure for a low temperature (-18° C) crack tip opening displacement (CTOD) test on the weld centre and the fusion line of the module stool of a large FPSO, to be used in the Bohai offshore oil field.

Before a jack-up can operate at a given location, a site-specific assessment of its ability to withstand a design storm during operation must be performed. During this

18th International Ship and Offshore Structures Congress (ISSC 2012) - W. Fricke, R. Bronsart (Eds.)

assessment, the complex state of stress and strain under a spudcan is usually simplified to a value of foundation stiffness that is integrated as a boundary condition into the structural analysis. Soil stiffness is a critical parameter affecting the foundation and structural load distribution and displacements, and hence determining the jack-up natural period and dynamic response. The level of spudcan stiffness is an area of intense interest and debate. Cassidy *et al.* (2010) investigated appropriate stiffness levels for numerical simulation. Utilising results from a detailed "pushover" experiment of a three-legged model jack-up on dense sand, the authors compared the experimental pushover loads and displacements on the jack-up and spudcans to numerical simulations using different assumptions of spudcan stiffness. Constant stiffness levels are shown to be inadequate in simulating the experimental pushover test.

Baarholm *et al.* (2010) presented a study for predicting design response of offshore platforms by combining contours of significant wave height and peak period together with platform response distributions. To aid their research, the authors carried out model tests on Troll A platform with increased topside weight at Marintek. A comprehensive analysis program, including model test and numerical calculations, were carried out by the authors in order to establish a reliable set of design loads for the modified platform. The study revealed a need for verification of the applied percentile level for the design loads and suggested the necessary steps for the verification process.

Alati *et al.* (2011) focused on the comparative fatigue analysis pursued on typical tripod and jacket support structures for offshore wind turbines located in Mediterranean area. The theoretical basis has led to simplified methods. The method demonstrating how to compute the separate wind and wave responses while still accounting for the inherent, mutual interaction between aerodynamic loading and hydrodynamic response.

Shao (2010) investigated the fatigue life of welded tubular joints in offshore platforms by the magnitude and distribution of the hot spot stress. The number of fatigue loading cycles for a tubular joint sustained before failure is determined by the magnitude of the hot spot stress whereas the initiation position and the propagation direction of the surface crack are determined by the location of the hot spot stress. The hot spot stress distribution along the weld toe for a tubular X-joint subjected to axial loads is analysed using finite element method. The effect of geometrical parameters on the magnitude and the distribution of the hot spot stress were investigated through consideration of 112 X-joint models.

Notaro *et al.* (2011) focused on bow impact scenarios when the OSV hits and penetrates into the FPSO side shell. The variation of energy absorption and damage extent has been studied as a function of different physical parameters. The detailed model of the midship area of FPSO has been created in ABAQUS and was impacted by OSV which was considered as a rigid body. The study showed that likely collision scenarios for OSV's operating close to a FPSO may lead to penetration and rupture of the side shell. This may be critical for single skin vessels with respect to environmental consequences.

7.2 Uncertainty, Risk and Reliability in Offshore Structural Analysis

Connecting advanced structural and reliability analyses can improve the structural design process which results in the development of efficient systems. Reid (2009) illustrated aspects of 'realistic' reliability assessments for bridges that are applicable to offshore structures. The differences and implications of using 'notional', 'realistic' and 'actuarial' failure probabilities were discussed. Notional probabilities are ascertained from a reference set of modelling assumptions and are used to calibrate codes

18th International Ship and Offshore Structures Congress (ISSC 2012) - W. Fricke, R. Bronsart (Eds.)

to accepted standards, but are not necessarily accurate for failure probability. In comparison, the modelling assumptions used to form realistic probabilities align with realistic assessments of actual structural behaviour. However, Reid (2009) advises that risk-based optimisation should be based on actuarial probabilities, which are based on probabilistic models validated with failure observations of a group of structures.

Karadeniz *et al.* (2010) presented a calculation system of integrated algorithms for the reliability based optimisation of the offshore jacket structure. The methodology is composed of a structural analysis package (SAPOS), a reliability analysis program based on the first-order reliability method and an optimisation program based on sequential quadratic programming using the International Mathematics and Statistics Library.

Reliability assessment on mooring system of deepwater platform in catastrophic ocean environment was presented by Chen *et al.* (2010). A probabilistic model of breaking strength is developed for a mooring chain.

8 CONCLUSIONS AND RECOMMENDATIONS

The committee reviewed recent works concerning topics identified by the committee mandate. A summary of current publications relevant to quasi-static analysis methods applied to ship structures was presented. The summary included strength assessment approaches, calculation procedures, composites, ship structures, and offshore structures.

From the review of the recently published literature, the committee members' observation was that nowadays whenever a problem or question arises that involves dynamics, the standard procedure is to either seek an answer from existing quasi-static references such as papers published by Paik and other readily available sources or to use any one of the many available finite element programs that have full dynamics capabilities, thereby avoiding the approximations and uncertainties that arise when modelling a dynamic problem quasi-statically. This is viewed as a very positive situation by the Committee. Researchers have developed the methods and tools needed to deal with dynamic problems over many years, and they are now readily available to anyone needing them. However, this does not mean that there are no further questions to resolve about quasi-static modelling; there are many.

The review included quasi-static modelling of a dynamic problem with reference to loads and response. In particular, references were made to ice loads and collision loads and the linearisation/simplification approaches to determine the corresponding responses.

Recent studies on calculation procedures for wave loads, fluid-structure interaction, and modelling were discussed. An attempt to approximate a dynamic wave load case as quasi-static was identified. Consideration of structures as coupled to the surrounding flow has led to theoretical and computation modelling of flexible panels and SPH methods. Approaches to model non-linear stiffened structures and composite behaviour were also reviewed in the literature.

Recent research studies on advance structural modelling and analysis techniques for evaluation of yielding, buckling fatigue and ultimate strength capacity of the structures are discussed. Current research on compressive buckling strength is focused on determination of ultimate strength behaviour of unstiffened and stiffened panels under axial compression, lateral pressures and plate bending. Ultimate strength behaviour of plates with large openings is discussed. Fatigue and ultimate strength assessments

18th International Ship and Offshore Structures Congress (ISSC 2012) - W. Fricke, R. Bronsart (Eds.)

of deteriorated (corroded) structures are found to be the focus areas of the current research.

Finite element modelling has been used to simulate the structural response of a range of ship structures, from single sandwich panels through to partial or full ship models. Maritime applications of FE analysis included failure prediction (buckling, fatigue, ultimate and residual strength) of steel, aluminium and composite structures, comparison of computational analysis to test and full scale trial data. FE analysis was often utilised as a tool in a systematic procedure, such as for determining material or damage behaviour for use in another analysis.

In the realm of ship structures, issues related to design, maintenance and monitoring, and classification society rules have been presented in the literature. The requirement for safer and more durable naval structures has been increasingly recognised. Within design development, particular areas of research included designing fatigue optimised shapes, the effect of high waves from large ships on nearby structures, and the choice of hull-forms and materials for naval operations as well as for passenger ferries. The uncertainties associated with the reliability based quasi-static assessment of ship structures are discussed for intact and damaged ships. Of concern to ship maintenance and realisation of efficient systems, corrosion modelling, structural health monitoring, and reliability assessments have been identified as important themes.

Recent works on steel sandwich panels covering aspects such as bending and shear characteristics of laser-welded sandwich panels, structural optimisation, and ultimate strength have been reviewed. The modelling issues related to the interaction between the sandwich panels and the girder system, are also reviewed. In recent years, there has been a significant emphasis placed on understanding the behaviour of composites used in the maritime industry. The fire structural response of polymer composites and crashworthiness of sandwich structures have received particular attention. The review included response analysis of various applications such as composite propellers, composite patches on naval steel vessels, composite panels with holes, etc.

The current developments in areas of Green Shipping, Energy Efficiency Design Index, Cleaner Alternative propulsion, safer ships, Northern Sea Route and Panama Canal Expansion are reviewed. As the effects of global warming are becoming more recognised by the industrial nations combined with the depletion of fossil fuels, the efforts to reduce green house gas emissions are increased. LNG as fuel onboard is a promising technology amongst the near term green shipping technologies. However, there are some storage, safety and operational concerns using LNG as fuel which will impact on ship design. Also, it appears that the industry has some concerns that LNG does not reduce CO_2 emissions on a like-for-like basis with other fossil fuels when carbon foot print from well to flue emissions is considered due to release of methane from shale-gas production.

A comprehensive review of passenger vessels and container vessels in relation to quasi-static response evaluation has been provided. The experience database collected by the maritime industry is challenged by larger ships and new trades. The size of container vessels and passenger vessels increased dramatically and the committee focused on and reviewed recent works concerning strength and analysis methods.

Review on the offshore structures included analysis of fixed offshore structures under ice loads and design storm loads, and the push-over analysis, analysis of topside modules securing arrangements to deck on FPSOs, fatigue analysis of support structures for offshore wind farms, etc. Review of the offshore structures reliability analyses is

18th International Ship and Offshore Structures Congress (ISSC 2012) - W. Fricke, R. Bronsart (Eds.)

also included. The quasi-static push-over analysis of offshore structures resulted in a higher ultimate strength than the dynamic analysis. The study on the collision analysis between offshore support vessel (OSV) and FPSO indicated that the collision may lead to rupture of the side shell of FPSO which may be critical for single skin FPSO in relation to environmental consequences.

Future recommendations of topics for review are:

- Interconnectivity and model exchange bi-directionally between 3-D product models and FE models
- Advance methods for mesh generation of FE models
- New FE techniques
- Advance methods to account for corrosion and fatigue in assessing structural strength
- Reliability based inspection and maintenance and life-cycle design concepts
- Development of new rules and regulations by regulatory bodies
- Impact of technologies to reduce greenhouse gas emissions on structural design
- Structural aspects of specialised ships
- Structural aspects of offshore structures

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VOLUME 1

COMMITTEE II.2

DYNAMIC RESPONSE

COMMITTEE MANDATE

Concern for the dynamic structural response of ships and floating offshore structures as required for safety and serviceability assessments, including habitability. This should include steady state, transient and random response. Attention shall be given to dynamic responses resulting from environmental, machinery and propeller excitation. Uncertainties associated with modelling should be highlighted.

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KEYWORDS

Dynamic response, slamming, whipping, springing, damping, vibration, noise, underwater noise, explosion, shock, excitation, propeller, vortex-induced vibration, ice-induced vibration, lock-in, prediction, natural vibration, forced vibration, linear response, non-linear response, countermeasures, measurement, segmented models, hydro-elasticity, resonance, monitoring, model tests.

18th International Ship and Offshore Structures Congress (ISSC 2012) - W. Fricke, R. Bronsart (Eds.)

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CONTENTS

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1 INTRODUCTION

The role of the engineer in society is to guide the wise use of scarce resources (e.g., natural resources, human resources, capital, etc.) in order to sustain and improve the human condition, while minimizing direct or collateral damage to the environment and losses from accidents (casualties, injuries, environmental damage, damage to property, etc.).

In structural design, this leads to an optimization process that seeks a balance between the use of materials and the probability of undesirable consequences arising from structural insufficiency. This process trends towards light, slender, and flexible marine structures. In some cases (e.g., deep water risers), we are near the very limits of what can be done because the structural deadweight alone dominates the demand on the structural capacity of our materials.

Light, slender, and flexible structures are inherently prone to dynamic responses. The potential exciting mechanisms are legion, and include: waves, vortex-induced vibration (VIV), ice, internal flow, machinery, propellers, and blast. Dynamic responses exacerbate fatigue, contribute in some cases to extreme lifetime loads, adversely affect habitability, and result in airborne and underwater radiated noise that degrades the environment and interferes with some marine operations.

The overarching trends observed by the 2009 II.2 Dynamic Response committee remain valid; however, there are conflicting imperatives. One challenge is to ensure sufficient energy for a growing world population along with the transportation essential to a globalized economy. The other is to reduce the impact on the environment, most especially as regards the emission of greenhouse gases. The continuing and accelerating trend towards reduction in the extent and thickness of Arctic sea ice is stimulating new interest in commerce on the Northern Sea Route, and increased activity to access and exploit offshore resources in the Arctic Ocean basin. These prime motivating forces are manifest in the maritime and offshore communities through:

- increases in ship sizes, to benefit from economy of scale,
- offshore oil and gas development in ever deeper waters, such as those associated with the Brazilian pre-salt deposits,
- renewed interest in deep water ocean mining,
- growing interest in offshore renewable energy (wind, wave, current, and thermal), especially as realized through increasing development of offshore wind turbine fields and an interest in moving wind turbines into deeper waters using floating foundation concepts,
- greater shipping and offshore activity in ice-covered and/or ice-infested waters.

These trends contribute to the continued, active research into dynamic responses that range from whipping and springing, to VIV or flow-induced vibrations as they apply to slender structures such as deepwater risers, or the ice-induced vibrations of offshore structures. Vibration is particularly crucial in the fatigue of offshore wind turbines.

The Deepwater Horizon explosion has served to remind us of the continued importance of responses to explosion and blast.

As a further means of fulfilling our mandate to elucidate uncertainties, the 2012 II.2 committee has undertaken a benchmark study regarding whipping responses.

The 2012 II.2 committee has chosen to divide this report on dynamic response, at the highest level, into ship structures and offshore structures.

The 2012 II.2 committee collected over 440 references and considered even more. This report cites and reviews 258 references.

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2 SHIP STRUCTURES

2.1 Wave-Induced Vibrations

Wave-induced vibration of ships can occur in two different forms, denoted as springing and whipping. Whereas springing represents a resonant periodic vibration response to high frequency harmonic wave excitation components, whipping is characterised by transient vibration response caused by slamming impulses. Researchers further differentiate between linear springing, where the encounter frequency of seaway components with short wave lengths is in resonance with the natural frequency of the basic hull girder mode, and nonlinear or sum frequency springing, where the periodic vibration excitation forces act with a higher order of the wave encounter frequency. The former can be predicted by linear hydrodynamic theories, while the latter depends on second order hydrodynamic effects; e.g., superposition of different wave systems. In spite of the periodic sum frequency excitation forces having a smaller intensity per unit wave height than the linear forces, they may become of greater importance because they originate from considerably longer waves with higher energy content.

2.1.1 Whipping

Full scale measurements and model tests have been intensively conducted in recent years. These tests and measurements were mainly focused on unconventional larger ships, such as container ships, naval frigates, and LNG carriers. Much research focused on the effect of wave-induced vibration on fatigue performance of the vessels. Furthermore, research was conducted for the wet deck slamming for high-speed catamarans.

Hydrodynamic Excitation, Response, and Load Analysis

Ogawa *et al.* (2009) developed a practical prediction method for wave loads in rough seas that took hydroelastic vibration into account. Comparison with the experiments for a post-Panamax container ship and a mega container ship demonstrated that using this method, taking into account the time-varying sectional hydrodynamic forces, gave favourable agreement with measured wave-induced vertical and torsional moment under rough sea conditions.

Tiana *et al.* (2009) investigated the hydroelastic response of a large bulk carrier. The numerical programs THAFTS and NTHAFTS, which were developed based on linear and non-linear three-dimensional hydroelasticity theories, were used to analyze the rigid body motions and structural responses of a large bulk carrier travelling in regular and irregular head waves. The influences of the forward speed effect and the nonlinear hydroelastic actions on the motions and structural loads of this large bulk carrier were quantitatively discussed.

Mikami *et al.* (2009) extended the nonlinear strip method, which was proposed by one of the authors for an elastic body using a method of superposition of elastic mode functions, which enabled investigation of whipping phenomena due to wave impulses. Computed and measured whipping bending moments were compared. The effects of green water-on-deck were investigated through application of a practical computational model.

Miao *et al.* (2009) focused on the investigation on the failure of the *MSC Napoli* using two-dimensional (2D) symmetric (i.e., vertical bending) hydroelasticity analysis. The aim of the investigation was to assess the influence of whipping-induced loads on the structural strength of this containership. The calculations were carried out in head regular and long-crested irregular waves. Both cases included the effect of

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bottom slamming only. Global wave-induced loads were evaluated along the hull, with particular focus in the vicinity of the engine room. The investigation showed that whipping due to bottom slamming was only important for severe seas. It also showed that the keel stresses in way of the engine room could be as large as the keel stresses at amidships.

Storhaug *et al.* (2009) reported on the contribution of whipping on the 4400 *TEU* container vessel, *MSC Napoli*. Based on some measurements from a similar 4400 *TEU* vessel in both full scale and model tests, it was confirmed that whipping can increase the dynamic loading in sea states similar to those *MSC Napoli* encountered. The measurements also illustrated that it was difficult to state exactly how much the whipping contributed in a specific sea state.

Using a 2D hydroelastic method, Denchfield *et al.* (2009) predicted the vertical plane hydroelastic response (motions, loads and elastic hull girder deflections) of a Leander class frigate in long-crested regular, irregular and rogue waves. Predicted motions are compared with test measurements from a rigid model in head irregular and rogue waves. The effects of forward speed and slamming in rogue waves were examined.

Derbanne *et al.* (2010) developed an efficient hydroelastic model based on the state of the art numerical techniques. The model coupled the 3D hydrodynamics with either non-uniform beam or 3D FEM structural dynamics. This model was demonstrated to have been very efficient in terms of the CPU time. The computational results were compared with several experimental campaigns and validated.

Zhu *et al.* (2010) presented a numerical model for studying the tank wall boundary condition on the measured load effects of a backbone model. Comparisons between numerical calculations and experimental data in the towing tank showed that this kind of numerical model was efficient and reliable for evaluating the tank wall interference. It was demonstrated that the wave reflections from the tank walls substantially change the hydrodynamic forces and pressures on the backbone model, as compared to the values that would be measured in open seas.

Gaidai *et al.* (2010) proposed a method for prediction of extreme stresses measured in the deck amidships of a container vessel during operation in harsh weather using the full scale measurement data. The method opens up for the possibility to predict simply and efficiently both short-term and long-term extreme response statistics.

Lee *et al.* (2011) reported time domain springing and whipping analyses for a 10,000 *TEU* class container ship using computational tools as a part of a joint industry project. The results from the computational analyses in regular waves have been correlated with those from model tests undertaken by MOERI. It was demonstrated that the wave induced vertical bending moments with whipping vibration were reasonably well predicted by the three-dimensional, nonlinear hydroelasticity method.

El Moctar *et al.* (2011) used an implicit two-way coupling scheme between a VoF free surface RANS CFD solver and a 6-DOF motions structural FEM model, to study combined springing and whipping in regular and irregular waves of a 10,000 *TEU* 321 *m* containership. The effects of forward speed and directional spreading were studied. Comparisons were made with experimental results from the (2009–2010) WILS-II JIP segmented model tests. Damping was also investigated.

Kirtley *et al.* (2010) expanded the valid domain for design parameters in order to more fully encompass the validation cases for a naval frigate and the ITTC S-175 containership, and to extend the range of application beyond bottom slamming to include bow

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flare slamming. The underlying model is that of a non-uniform Timoshenko beam with infinite frequency Lewis form hydrodynamic added mass. The non-dimensional prediction equations are simple quadratic polynomials in eight independent variables. The coefficients were determined by ordinary least squares regression applied to over 25,920 parametric ship designs, for maximum midship bending moment, the two-node, 'free-free' natural frequency, and the time at which the peak whipping bending moment occurred. The independent variables are basic design characteristics such as beam-to-length ratio, block coefficient, waterplane coefficient, nondimensional midship structural inertia, and other nondimensional values available during early design. Confidence intervals for prediction were provided.

Dessi *et al.* (2010) related the slamming excitation and the whipping response to each other using a wavelet transform. The analyzed data were collected with model tests using two scaled and segmented elastic models of a fast ferry and a cruise ship. The extraction and evaluation of the excitation level due to slamming loading was clarified via the construction of the envelopes of the whipping response and the calculation of its time average.

Kim *et al.* (2011a) developed an innovative and efficient method to generate independent non-identically (*inid*) distributed phase sets in order to create irregular design wave profiles to be used as inputs to nonlinear time-domain simulations suitable for use as samples in a Monte Carlo approximation of a ship lifetime exposure. The Acceptance-Rejection (A-R) method was applied to rapidly generate an ensemble of phase sets that reproduced an *a priori* specified extreme value distribution with fidelity. The authors designated this approach the Design Loads Generator (DLG) method.

To demonstrate application of the method, the nonlinear seakeeping program LAMP2 was used to predict the combination of nonlinear wave bending and whipping bending moments for two different ships, the Joint High Speed Sealift (JHSS) and a naval combatant. Model tests of the JHSS were conducted with a segmented model, and those of the naval combatant with a structurally scaled polyvinyl chloride (PVC) model. LAMP2 was used to generate an ensemble that comprised 288 independent, five-minute simulations, which resulted in a composite 24-hour record. These simulations were compared in Weibull space with corresponding data from model tests. Extreme value distributions generated from model tests and those predicted using the DLG method were shown to compare favourably.

Wet Deck Slamming and Whipping Vibration

Davis *et al.* (2009) conducted a wavelet analysis to identify slamming events during multi-hull sea trials. Maximum loads, load impulses, and energy imparted to the structure by slams were evaluated. A segmented hydro-elastic model was developed to simulate the main whipping mode, elastic links in the model facilitating measurement of bending moments, and determination of slam loads. It was found that energy is transferred to the whipping mode, which has a damping ratio in the range 0.02 to 0.06, depending upon forward speed.

Thomas *et al.* (2009) investigated slam events of high-speed catamarans in irregular waves. Slam events experienced by high-speed catamarans in irregular waves were characterised through experiments using a hydroelastic segmented model. It was tested in irregular head seas at two speeds corresponding to Froude numbers of 0.32 and 0.60. Slams identified in the test data were analyzed with respect to kinematic parameters. Slams were found to have a large range of magnitudes; however, the majority of events

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were of relatively low severity. Immersion of the centrebow to the two-dimensional filling height of the cross-section between the centrebow and demihulls was shown to be a better indicator of slam occurrence than immersion to the top of the archway.

Fatigue Associated with Whipping

During this period, many research studies have sought to clarify the effect of whipping on both the extreme load and fatigue damage accumulation. Many of these studies, however, investigated the effect of whipping on the fatigue damage only by means of estimating the increase in the number of cycles. Most recent studies did not investigate the effects of whipping vibration on the mechanism of fatigue crack propagation. Furthermore, some studies reported large amplitude wave loads that exceeded the current criteria, such as IACS/S-11. They did not, however, necessarily clarify the effect of vessel operation, such as voluntary and involuntary speed reduction or course change. Therefore, those studies indicated certain discrepancies between real structural strength in real sea state and the evaluated structural performance.

Oka *et al.* (2009a, 2009b) examined fatigue strength of a large container ship, taking the effect of hull girder vibration into account. With few reports of hull fracture attributed to such vibrations, the resulting cyclic stress effects were unclear. In order to gain insight into the fatigue loading including hull girder vibration Oka *et al.* performed their analysis utilizing both data obtained from tank tests using a backbone type elastic model, and full scale stress measurements.

Although the long-term fatigue damage was very low, it was demonstrated that hull girder vibration due to whipping had a notable effect on fatigue damage. Therefore, it was important to accurately estimate the level and probability of occurrence of whipping stress. The effect of the operational factors on fatigue damage was also quantitatively clarified.

Storhaug *et al.* (2010a) reported on model tests in head seas of a 340 m, 8,600 TEU container ship using a new flexible model design to investigate how springing and whipping affected extreme loading and fatigue at different cross sections. Storhaug *et al.* (2010b) reported on similar studies of a 360 m, 13000 TEU twin island container ship, and Storhaug *et al.* (2011a) extended those studies to bow quartering seas with and without wave spreading.

The studies of the 8,600 TEU container ship investigated exposure in different trades. The results confirmed that fatigue damage from wave-induced vibrations could be of considerable magnitude relative to the conventional wave damage for the different trades. The maximum whipping response was also found to be relatively high. With whipping, the IACS rule levels may easily be exceeded in storms.

The results for the 13,000 TEU container ship confirmed that wave-induced vibrations dominate the fatigue damage for the East Asia to Europe trade in head seas.

Storhaug *et al.* (2011a) found from model tests that the extreme loading in bow quartering seas was higher than in head seas, which was well above IACS rule loads for vertical bending by more than 80 % in hogging. In reality, this may have been reduced somewhat by higher damping. Damping from full scale measurements needs further investigation.

Further, the effect of the vibrations was investigated on torsion and horizontal bending, as the model was also allowed to vibrate with realistic frequencies in other modes in addition to vertical bending. From comparison of extreme horizontal bending and torsion with and without whipping vibrations, it was clear that the effect of whipping

18th International Ship and Offshore Structures Congress (ISSC 2012) - W. Fricke, R. Bronsart (Eds.)

on these modes was considerable. Even though the damping for these model tests was below the expected damping in full scale, and the vibration mode and structural response differed from a real vessel, the measurements suggested that the effect of vibration should be further investigated on real ships.

Storhaug *et al.* (2010a, 2010b, and 2011a) recommended that wave-induced vibration be considered during the design phase, and made the observation that prudent seamanship is important to the minimization of whipping during storms.

Storhaug *et al.* (2011b) used model tests to consider wave-induced vibrations during the design of the world's largest bulk (ore) carrier. It was determined that the combined effect of whipping and springing vibrations more than doubled the fatigue damage compared to that associated with the wave induced loading alone. A procedure was developed to take the vibrations into account, which resulted in reasonable scantlings based on in-service experience with similar designs and trades. A structural verification for the design loads has been performed.

Heggelund *et al.* (2010) assessed fatigue damage accumulation on an LNG carrier from full scale measurement during a period of about twelve months. Based on the measurements, the vessel was found to be in actual operation less than half the time during the period. The fatigue rate was lower than that predicted by component stochastic fatigue analysis, and the fatigue life was predicted to be longer than the design life of 40 years. The contribution from vibration was found to be large; e.g., 30–50 % of the total damage. The highest fatigue damage was obtained in rough seas and in the full load condition. Most fatigue damage was accumulated in head or following seas. It was found that speed reduction in rough seas acted to reduce fatigue damage below that predicted at constant service speed. Furthermore, measurements from wave radar were compared with scatter diagrams used for design. The measured data indicated that the sea states were shifted towards a lower mean zero-crossing period.

Heggelund *et al.* (2011) reported on the fatigue accumulation determined from full scale measurements from sixteen voyages between Asia and Europe aboard an 8600 *TEU* vessel, over a period somewhat exceeding a year. Based on the measurements, it was confirmed that the fatigue loading of critical details was dominated by the vibrations. The fatigue loading level in the deck during a storm was higher than ever before measured. Also, whipping response was found to result in high extreme loads that were above IACS rule values.

Torsional and horizontal vibrations were also observed. Vibration was found to contribute significantly to side shell fatigue, but overall side shell fatigue loading was at a comfortable level.

The full scale measurements did, to some degree, confirm previous model tests of the same vessel, but the vessel had been routinely operated at reduced speeds. The fatigue loading on this route was at a comfortable level, which was partly due to reduced speeds, but also the encountered sea states may have been less severe than those on the route-specific scatter diagram.

Matsuda *et al.* (2011) investigated fatigue crack propagation behaviour under variable amplitude loading with different frequency components, such as the wave bending moment superposing slamming loads. Numerical simulation of the fatigue crack propagation based on an advanced fracture mechanics approach with the RPG (Re-tensile Plastic zone Generating) load criterion was improved to extract the effective loading sequence for the fatigue crack growth.

18th International Ship and Offshore Structures Congress (ISSC 2012) - W. Fricke, R. Bronsart (Eds.)

The numerical simulations of fatigue crack growth curves under the loadings superimposing damping amplitude components with high frequency like slamming loads were compared with the measurements. These comparisons validated the proposed treatment of extracting the effective loading sequences for the fatigue crack propagation from random loading sequences.

Hull Structural Response Analysis

For the analysis of hull structural response, the structural model must reflect the hull's dynamic properties in the frequency range of interest; i.e., the natural frequencies, the associated mode shapes, and the damping characteristics. Depending on the application, a variety of methods is used for this purpose:

a) Dynamic amplification factors in combination with quasi-static calculations.
b) Analytical formulae valid for impulsively or harmonically excited vibrations of 1- or 2-DOF systems.
c) Timoshenko beam finite element (FE) models reflecting one or several hull girder vertical bending modes.
d) Same as Item c, but extended to simulate also torsional and horizontal bending vibration modes.
e) 3D FE models of the complete hull for more complex hull structures.
f) Same as Item e, but with local FE mesh refinements for specific assessment purposes; e.g., stress concentration effects or local deck panel vibration.

In recent years, various approaches were utilized to analyze the hull structural response. That research focused on unconventional larger ships, such as large container ships. Furthermore, the effect of structural discontinuity on structural response of large container ship was investigated.

Dessi *et al.* (2009) investigated the correlation of model-scale and full-scale tests aimed to determine the bending response of a navy vessel in waves. The model tests were carried out with a segmented-hull elastic model scaling the mass, the sectional moment of inertia, and the shear area of the original ship. In order to assess the reliability of the experimental technique at model-scale, 1D and 3D FE models were built, analyzed, and compared to highlight how the load segmentation and the reduction to 1D models could have affected the experimental predictions. To evaluate the correlation of model-scale and full-scale, the vertical bending moments measured on board the ship during the full-scale trials were compared with those determined with the segmented-hull tests and with the simulations using a 3D finite model of the ship structure.

Senjanović *et al.* (2009) dealt with the methodology of hydroelastic analysis based on a mathematical model, which included structural, hydrostatic, and hydrodynamic sub-models. The modal superposition method was used, and ship natural modes were determined by a sophisticated beam model based on the advanced thin-walled girder theory, which took shear influence on torsion into account, as well as the stiffness contribution of transverse bulkheads. The mathematical model was checked by model test of a flexible barge. The developed numerical procedure was applied in the case of a very large container ship. The 1D FEM model was verified by correlation of dry natural vibrations with those obtained from the 3D FEM model.

Iijima *et al.* (2009) studied symmetric and anti-symmetric modes of vibrations of a generic open ship experimentally and theoretically. First, a new design strategy for a scaled hull girder model of open ships considering the configuration of the natural frequencies of symmetric and anti-symmetric modes was developed. A backbone beam

18th International Ship and Offshore Structures Congress (ISSC 2012) - W. Fricke, R. Bronsart (Eds.)

approach with several cut-outs was found to accommodate an appropriate torsional stiffness, as well as vertical and horizontal bending stiffness. A hydroelastically-scaled model was designed based on FE Analysis (FEA). The hydroelastic vibration characteristics in regular waves were confirmed by tank tests. Numerical calculations were also performed to investigate the hydroelastic vibrations in symmetric and anti-symmetric modes.

Kaydıhan *et al.* (2011) conducted a hydroelastic investigation into the dynamic response characteristics of two Handysize bulkers, one Handymax bulker, one Panamax bulker, and two Capesize bulkers, respectively. Detailed 3D finite element structural models were prepared to compute the dry and wet frequencies using FEA, and then compared with those calculated by using a higher-order 3D hydroelasticity theory.

Cabos *et al.* (2011) investigated a modal approach to the coupled computation of the fluid flow and the motion and elastic deformation of a floating body. Compared to earlier approaches that relied on a beam approximation of the ship, torsional elastic deformations could be considered. In this approach, the equation of motion for the ship must be solved in the moving coordinate system. This approach led to full system matrices that depended on ship translational acceleration, and rotational velocity and acceleration. The additional computational effort for these small nonlinear sets of equations was nevertheless small, since only a few modes were applied. The rigid body motion was also a result of this set of equations.

Bogaert *et al.* (2010) investigated the interaction between the NO96 membrane containment system and breaking waves. The data obtained from the full scale impact tests in the Sloshel project were used. It was demonstrated that it was not straightforward to define the interaction type by a comparison of observed load durations and predefined mode shapes. As an alternative, it was investigated whether the type of interaction could be deduced from its effect on the load, and on the response with respect to a quasi-static interaction.

Ogawa *et al.* (2011) conducted a whole ship finite element analysis system from wave loads to structural strength in a realistic sea state. Methodology for the rational analysis of structural strength by means of such a whole ship analysis, particularly from the viewpoint of loads, was examined. It was verified that the evaluation, without the effect of ship operation, may overestimate the stress induced by waves. Consequently, for the rational evaluation of strength in waves, the effect of operation on wave loads should be considered.

Senjanović *et al.* (2011) dealt with a numerical procedure for ship hydroelastic analysis, with particular emphasis on improvements of the present beam structural model. The structural model represented a constitutive part of hydroelastic mathematical model, and generally it could be formulated either as a 1D FEM or 3D FEM model.

Furthermore, the improvements included accounting for shear influence on torsion, contribution of bulkheads to hull stiffness, as well as determination of effective stiffness of the engine room structure. This procedure was demonstrated using a large container ship. In this case, validation of 1D FEM model was checked by correlation analysis with the vibration response of the fine 3D FEM model. The procedure related to determination of engine room effective stiffness was checked by 3D FEM analysis of a ship-like pontoon that had been made according to the considered ship characteristics.

2.1.2 Springing

Analytical studies of springing have primarily been conducted for unconventional larger ships such as large container ship, ultra large ore carrier, LNG carrier, and

18th International Ship and Offshore Structures Congress (ISSC 2012) - W. Fricke, R. Bronsart (Eds.)

so forth. Different hydrodynamic effects exist that might cause higher order excitations, but whether they are practically relevant is yet not fully understood. These excitations include:

- 2nd and 3rd order excitations resulting from non-vertical side walls of flared hull sections,
- higher order excitations due to the occurrence of higher order wave contours compared to the linear Airy wave,
- 2nd order excitations due to the variation of the sectional hydrodynamic mass for sections in wave troughs and crests, respectively,
- 2nd order excitations due to the superposition of incident waves with reflected waves or other wave systems.

Much research was conducted on the mechanism of springing and its effect on the fatigue stress.

Hull Excitation Load Analysis

Kim *et al.* (2009a) investigated the springing response of a flexible floating barge under an oblique wave. A time-domain Rankine panel method represented fluid motion surrounding a flexible seagoing vessel, and a finite element method was used for structural response. For accurate prediction of the structural response under an oblique wave, special attention was given to the structural model, such as the effect of warping distortion and bending-torsion coupling. The Vlasov assumption was followed for a deformable beam element to take into account the effect of warping distortion, so that the cross section of the beam deformed out of its original plane without changing its cross-section contour.

The coupled equation for both the fluid and structural domain was solved by using the implicit iterative method. Accuracy of a developed computer program was verified through the comparison with experimental data, which resulted in good correspondence between the two results.

Wang *et al.* (2010) conducted an experimental investigation of springing responses of an ultra large ore carrier in full and ballast load conditions. Springing was observed in both regular and irregular head waves. It was confirmed that springing may commence beginning from low sea states. By the analysis of springing phenomena and its mechanism, good knowledge of characteristics of wave-induced responses of large ships in short waves was examined.

Miyake (2009, 2011) presented an estimation of hydroelastic response of ultra-large container ships with verification by comparison with experimental results. Time domain numerical simulations were conducted by means of the latest nonlinear strip method. Tank tests using a 12,000 *TEU* ultra-large container ship in regular and irregular waves were carried out to investigate the influence of hydroelastic responses on the hull structural strength of ultra-large container ships and to verify the validity of numerical simulations. It was found that the applied nonlinear strip method was a suitable way to estimate the hydroelastic responses such as whipping and springing of ultra-large container ships. Furthermore, it was found that the influence of springing on the hull girder strength of mega-container ships may be small, since the shorter wavelengths that generate springing were not associated with maximum wave heights.

Kang *et al.* (2010) carried out the time-domain springing analyses for a 263,000 m^3 LNG carrier and a 10,000 *TEU* containership using a newly developed program, WISH-FLEX. Using this numerical method, the physical problem was modelled in the time

18th International Ship and Offshore Structures Congress (ISSC 2012) - W. Fricke, R. Bronsart (Eds.)

domain by fully coupling a boundary element method for the fluid domain and a finite element method for the structure domain. The detailed method of idealizing the ship into a beam model was described, and wave elevation around ship and pressure on hull surface were compared between the cases of rigid body and flexible body. Also, the motion responses and loads were compared with the towing-tank test. It was clearly shown that hull girder loads of the flexible body were significantly different from those of the rigid body.

Kim *et al.* (2009b) conducted comparisons among different numerical approaches for the ship hydroelasticity problem, particularly focusing on linear springing phenomenon. Both the Rankine-panel-based time domain approach and wave-Green-function-based frequency domain approach were cross-compared with each other for both a flexible stationary barge model, as well as a modern merchant ship model. The motion of flexible hull was represented by Vlasov-beam based finite element method. Based on the present comparative study, the pros and cons of each method were discussed.

Fatigue Associated with Springing

In this period, considerable research was conducted on the fatigue performance associated with springing. Most, however, investigated the effect of springing on the fatigue performance only by means of counting the increase of number of vibration cycles. They did not investigate the effects of springing vibration on the mechanism of fatigue crack propagation. It seems, therefore, that there were certain discrepancies between real fatigue performance in real sea state and the evaluated fatigue performance in those studies.

Jung *et al.* (2007) investigated the influence of wave-induced ship hull vibrations on fatigue damage. The strip method was employed to calculate the hydrodynamic forces and moments on the hull. The hull was modelled as a Timoshenko beam that accounted for the rotary inertia and shear deformation.

Fatigue analysis was also performed to evaluate the fatigue life of the ship, including springing effect. Wirsching's approach was applied for the wide band bi-modal stress spectra induced from springing. Applications to recent ships were performed and the influence of springing response on the fatigue damage was examined.

Wang *et al.* (2009a) investigated the effect of springing on fatigue damage. A design-oriented procedure was presented for springing induced fatigue load. The procedure included a springing susceptibility assessment and a detailed analysis of springing induced fatigue load. In the detailed analysis, a quadratic strip theory and a non-uniform beam model were employed. The procedure was applied to a number of container carriers, and influential parameters on springing induced fatigue load were evaluated.

Boutillier *et al.* (2010) conducted a fatigue damage calculation of an ultra large container ship (ULCS) due to quasi-static wave response and springing response. The validation of this method was performed by calibration with respect to the rain flow method, which the authors generally considered to be the most accurate method for fatigue damage calculation. It also revealed that the difference in fatigue damage estimates based on the spectral method and the rainflow method increased as the stress process became more broad-banded.

Cusano *et al.* (2009) examined the effect of springing on ship design. Based on the hydrodynamic and structural analysis, it was established that the evaluation of the

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bending stiffness of large fast craft, such as high speed ferries and luxury mega-yachts, should address the risk of springing. It was also established that whipping vibrations may significantly contribute to the total bending moment of ocean-going vessels characterized by large bow-flares, such as cruise or container ships.

2.2 Machinery or Propeller-Induced Vibrations

2.2.1 Propeller Excitation

Cao *et al.* (2011) addressed the problem of propeller-induced vibrations being transmitted to shafting bearings and the surrounding structure. In particular, the authors noted the problems of lateral and axial periodic excitation of the propeller shaft due to the propeller running in a non-uniform wake, and these excitations then being transmitted to the shaft bearings and to the surrounding structure. A model scale experimental approach was used, with a relatively simple cylindrical shell structure housing a simplified propulsion system. A comparison of the experimental results to an FEA analysis of the same model, using ANSYS, is also included. While the paper does not provide full detail of the experimental procedure, the longitudinal and lateral vibration responses measured at various locations on the structure (including at shaft bearings and on the shell) were presented, and generally good agreement between experimental and analytical results was demonstrated. The principal conclusions of this study noted the significance of the effects of structure/shafting coupling, and identified the rear bearing as being the main culprit for the transfer of vibrations from the propeller-excited shafting to the shell structure.

2.2.2 Machinery and Shafting Excitation

Lin *et al.* (2009) provided a study on the vibration control of ship structures, with particular focus on the requirement to effectively control machinery-induced noise and vibration propagation at low frequency in faster and lighter ships. The example for this study was a $30\,m$ aluminium crew vessel with transverse ring frames at $1\,m$ spacing. The FEA analysis was conducted using MSC/NASTRAN. To reduce calculation time, only the engine room and the keel of the ship were included to calculate the frequency response. Furthermore, because the wavelength of the structure-borne sound in the low and medium frequency ranges (of interest) was much greater than the physical dimensions of the machine isolators (e.g. engine mounts), these excitations were idealised as point sources. Under these assumptions, the input mobility of the engine bed was calculated in the $0 - 250\,Hz$ frequency range for out-of-plane and in-plane excitation forces, and torsional and bending moment excitations with and without the hull and deck plates were included in the FEA model. These results were also compared to the results generated for the corresponding infinite and finite beam (where the length of the finite beam is taken to be that of the total length of the engine bed). Since there was no significant difference between the cases including or excluding the deck and hull plating from the frequency range of interest, it was concluded that the energy flow to the ship's structure could be estimated from the knowledge of the simple structural components alone (i.e., neglecting hull plating).

Using the established, frame-only FEA model, two approaches to passive vibration control through the vessel from the machinery excitations were examined. The first approach considered modifications to the engine bed sections in order to change the mobility at the source location. Five variations were considered and compared to the original design and, while not every case showed an improvement over the original design for the full frequency range of interest, the authors concluded that the results

18th International Ship and Offshore Structures Congress (ISSC 2012) - W. Fricke, R. Bronsart (Eds.)

demonstrated that power injection (to the ship structure from machinery) could be reduced by proper designs. This is a useful finding for naval architects in combating noise and vibration problems on board ships.

The second approach considered the control of wave propagation through the ship structure by imposing irregularity to the ring frame spacing. In this study, the energy propagation to the forward end of the ship from the aft machinery was compared for the original frame-only hull configuration and for a new configuration in which two of the ring-frames just forward of the engine room were moved; one $0.1\,m$ aft, and the other $0.1\,m$ forward, to create a minor irregularity in the frame spacing. The results showed that the peak responses were reduced at the forward location of the ship due to this minor change. The authors concluded that the work was meaningful for the vibration control of ship structures at low frequency, where active and traditional passive control methods have had little success.

Magazinović (2010) reported on a novel regression-based method to assess the key torsional vibration responses for marine engines being installed on ships. While the method only provided statistical approximations and, therefore, should not be taken as a substitute for ordinary torsional vibration analysis, the method provided a novel procedure for fast and effective assessment of key torsional vibration responses for designers and shipyards, so that significant redesign of shafting and structure during later stages of the design or build can be avoided. It also increased computational efficiency for investigations of shafting design scenarios.

The method used a response surface methodology, representing the design space using regression fitting, applied to a limited set of fully calculated system responses over a limited set of the design space. In this case, a least-squares fitting of the data to quadratic polynomials, in 15 unknown coefficients, was used to represent the results. The input variables used were limited to shafting stiffness, propeller mass moment of inertia, and turning and tuning wheel mass moment of inertia. The results considered were for natural frequencies and mode shapes, and forced vibrations.

Although the metamodel required significant time and effort to build, the method was shown to be sufficiently accurate as a preliminary design tool. Once the metamodel was developed for a particular engine, it could be reused repeatedly for various shafting designs.

Jia (2011b) provided a limited study into using genetic algorithms (GA) to calculate the natural flexural frequencies of a ship's tail shaft. The study concluded that, for shafting systems with complex bearing supports and shafting elements, the GA solution method provided a computationally efficient means to isolate the roots (natural frequencies) of the coupled equations of motion for the discretized shaft elements and supporting bearings.

Godaliyadde *et al.* (2010) described, in detail, a novel approach to making a subjective risk assessment of the likelihood of the levels of ship hull vibration (SHV) resulting from the combined machinery, shafting, and propeller arrangement in the ship design. The motivation for investigating the method stemmed from the fact that the complete machinery and propulsion arrangement on board ships is a complex multi-component system, often with high levels of uncertainty in terms of the quantitative data for the contribution of each component to the eventual level of the SHV. Therefore, the approach adopted used a fuzzy rule base approach, combined with the uncertainty treatment method, *evidential reasoning (ER)*, which allowed both quantitative and qualitative criteria, under uncertainty, to be dealt with systematically and consistently.

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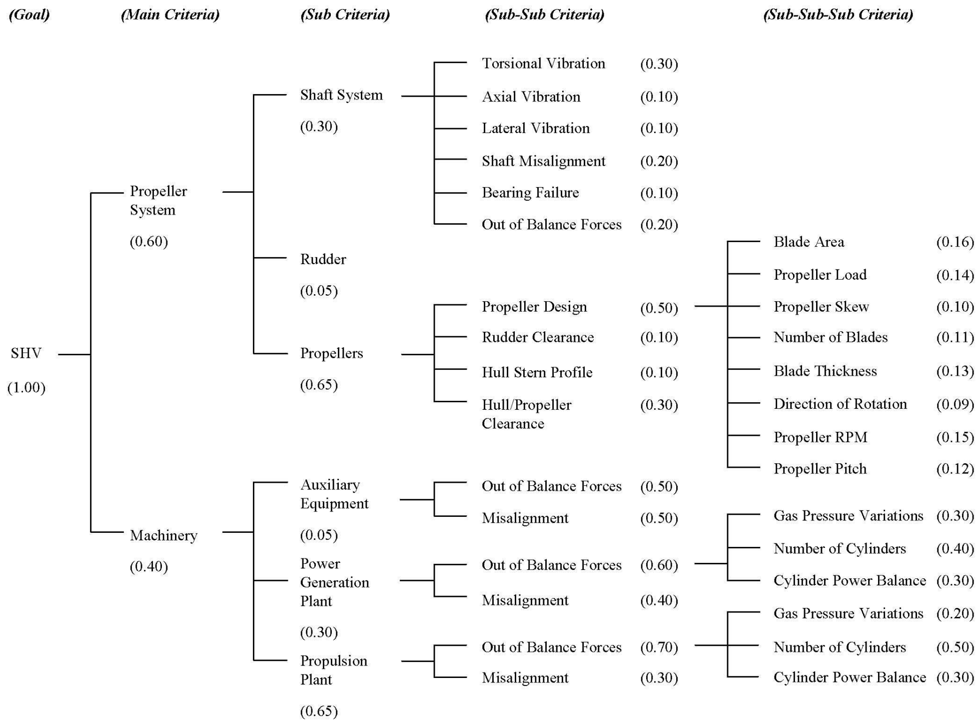

Figure 1: Hierarchical SHV model (Godaliyadde *et al.*, 2010)

Taking a bottom-up approach, in which the SHV model is broken down into subsystems contributing to SHV (i.e., machinery and propeller systems) and then further down into increasingly more detailed components levels, a five-level hierarchical model was used (see Figure 1). At each level, all subcriteria contributing to the component at the level above were assigned a weighting factor, reflecting their relative importance to that system in terms of contributing to SHV. In this study, the weighting factors were assigned using expert knowledge that was based on the opinions of two expert academics and two industry experts.

The actual characteristics of the components and subcomponents were then described in linguistic terms called assessment grades; e.g., excellent, reasonable, marginal, etc. Then, working sequentially from the bottom of the hierarchy of dependencies, a mapping process that accounted for the weighting factor of each subcomponent and the expertly-judged assessment grade for the subcomponents provided the assessment grade to the component above, until the risk estimation for SHV was determined, with the uncertainty for each outcome expressed in terms of a percentage of Belief Degree.

In this study, the method was validated using a case study where the method was applied to a real ship, for which the component assessment grades were, therefore, known, and the model results suggested that there was a "High" risk estimation of SHV with 23.38 % Belief Degree, and a "Very High" risk estimation of SHV with 65.79 % Belief Degree, and the ship itself was reported, after measurement, to have high-level SHV. The authors concluded that the method was suitable for both ship design and selection for reduced SHV.

Cho *et al.* (2010) performed a study to examine the magnitude and direction of vi-

18th International Ship and Offshore Structures Congress (ISSC 2012) - W. Fricke, R. Bronsart (Eds.)

bration energy flow due to the various excitation sources of the propulsion system, including the unbalance force and moment acting on the crankshaft of the main engine, the longitudinal thrust variation force acting on the thrust block, and the vertical propeller forces. The study was carried out for a 4,100 *TEU* container ship and used a visualisation of a structural intensity analysis to elucidate the most dominant transmission paths of vibration energy from the propulsion system elements. For the particular ship analysed, the longitudinal engine room bulkhead was identified as the dominant transmission path, but more generally, the authors noted the usefulness of the visualisation of structural intensity for assessing (and countering) vibrations due to propulsion system components.

2.2.3 Consequences of Propeller- or Machinery-Induced Vibration

Kirkayak *et al.* (2011) report on structural dynamics model tests of the vibrational characteristics of a two-tier stack of 20 $foot$ (6.058 m) ISO containers. The model experiments were performed at 1:4 scale ratio on a shaking table at the NYK-MTI experimental facility, Yokohama, Japan. Realistic mass, stiffness, and corner fitting gaps were modelled. he gaps at the corner fittings were the major source of system nonlinearity. Experiments with vertical base motion were conducted at 5, 10, 15, and 20 Hz model-scale. Assuming Froude scaling, these correspond to 2.5, 5, 10, and 20 Hz full-scale, which spans from frequencies associated with whipping and springing, to those associated with propeller or some machinery-induced vibrations. Good agreement was found between the experimental results and finite-element predictions. The results showed strong dependence on the corner fitting gaps and on the container payload.

2.3 Noise

Noise control is traditionally a concern for crew and passenger habitability. Recently, concern has also arisen regarding airborne noise control for the residential areas near ports and along the coasts due to heavy ship traffic. Also, reducing adverse impacts to marine wildlife due to noise radiated from vessels has become an issue. Recent research for ship noise is respectively reviewed for interior noise, and air- and underwater-radiated noise, in the next three subsections.

2.3.1 Interior Noise

Modern analysis methods to predict ship interior noise have been introduced to consider the multiplicity of sound generation and propagation mechanisms in ships, which are mainly frequency-dependent vibroacoustic phenomena. In the previous ISSC 2009 report, the advances in the analysis methods such as the transfer path analysis (TPA), the statistical energy analysis (SEA), the hybrid deterministic-statistical methods such as the combined SEA and finite element analysis (FEA), and the power flow finite element analysis (PFFEA) for mid- and high-frequency ranges were reviewed. A variety of publications since the last ISSC report can be found on the numerical methods for more accurate and efficient prediction of vibroacoustic behaviours except TPA, which are mainly aimed at extending the theoretical basis and/or reducing computational burden. Publications can be also found on the experimental and/or numerical evaluation of acoustic insulation components.

Analysis Methods and their Applications

The validity of SEA was among the main concerns in the early development of the theory due to the assumptions of a large population of modes, wide-band and uncorrelated excitations, large modal overlap, diffuse field, equipartition of energy, and

18th International Ship and Offshore Structures Congress (ISSC 2012) - W. Fricke, R. Bronsart (Eds.)

conservative and light coupling. Many literatures already discussed each assumption for the extension of SEA. Bot and Cotoni (2010) presented a validity diagram of SEA using the four dimensionless parameters of mode count, modal overlap, the normalized attenuation factor, and the coupling strength. For a valid SEA model, the former two parameters must be high and the latter two parameters must be small.

Knowing the dominant energy transmission paths is useful to establish proper noise countermeasures. For this purpose, Guasch *et al.* (2009, 2011) presented a systematic algorithm to find the dominant energy transmission paths in a SEA model by using a modified graph theory to find the set of so-called K dominant paths. The authors demonstrated its usefulness for a SEA model of a two-floor building, with 12 identical rooms per floor.

In the case of adding details to the SEA model by the use of FEA for the analysis of mid-frequency (MF) range, one limiting factor was the calculation time for solving large FE models of industrial size. Another limitation was the loss of accuracy when only subcomponents were considered, which depends on the selection of the boundary condition at the interface of the subcomponent. Ragnarsson *et al.* (2010) proposed a wave-based boundary condition to reflect more accurate behaviour of a subcomponent model, instead of classical boundary conditions. The boundary condition for the MF analysis was derived by the wave-based substructure analysis and the modal reduction for the remaining structure for the low-frequency range via the modal analysis for a full FE model.

Cotoni *et al.* (2008) proposed a more general SEA subsystem formulation based on a combination of finite elements (FE) to represent a unit cell of section, component mode synthesis on the unit cell to reduce computation burden, and periodic boundary conditions to the unit cell. The method enables the SEA parameters to be efficiently computed for very general structural panels compared with the directly combined SEA and FEA. Langley and Cordioli (2009) extended the hybrid deterministic-statistical method using SEA and FEA to apply to coupling over the domain of a SEA subsystem, termed "area junction." This enabled, for example, a statistical structural component to be coupled to a FE acoustic volume.

Vergote *et al.* (2011) proposed a framework for coupling deterministic wave based method (WBM) with SEA models by an extension of the hybrid FEM-SEA framework, which might be computationally more efficient than the hybrid FEM-SEA framework.

For the precise prediction of vibroacoustic behaviour of plate structures in high frequency range by PFFEA, Park and Hong (2008) presented power flow models to analyze transversely vibrating Mindlin plate, whose model was derived by the energy governing equations for far-field propagating out-of-plane waves in the plate.

Kim *et al.* (2011c) presented a new energy flow governing equation considering the near field acoustic energy term and spherical wave characteristics. A numerical analysis scheme was applied using the indirect BEM for application to the analysis of the acoustic energy density and intensity of complex structures in medium-to-high frequency ranges.

A numerical example to predict the mid-frequency (MF) acoustic power radiated in water of a warship using the technique of virtual SEA instead of experimental SEA was presented by Borello (2010). In the virtual SEA approach, the dynamics of the structure was reduced to a statistical frequency response function (FRF) matrix between sets of observation nodes of the in-vacuum FE model. An algorithm reordering

18th International Ship and Offshore Structures Congress (ISSC 2012) - W. Fricke, R. Bronsart (Eds.)

FE nodes from the FRF matrix was applied for the partitioning into subsystems with weak coupling. Then the FRF matrix computed between all nodes was compressed and the SEA parameters (modal density, mass, and coupling loss factor) were identified from the compressed FRF, which encapsulated the FEM dynamics in the MF range into the parametric SEA model. The computational expense of virtual SEA modelling was mitigated by the automation of low-level tasks.

Performance of Acoustic Insulation Components

Because of their high stiffness-to-weight ratio, lack of corrosion, high thermal insulation, and ease of assembly, lightweight partitions have been increasingly used instead of metal structures for the construction of ship cabins. Zhou and Croker (2010) presented the experimental and predicted sound transmission loss values obtained from SEA for two foam-filled honeycomb sandwich panels. Experimental modal densities, total loss factors, radiation, and internal loss factors were also presented.

Cha and Chun (2008) presented a mass-spring-plate model to predict the insertion losses of floating floor, of which upper plate and mineral wool were assumed as a one-dimensional mass-spring system lying on the simply supported elastic floor. The predicted insertion losses for seven different floating floors agreed well with that measured from the tapping machine test at a mock-up for simulating cabins of cruise ships. For a floating floor with a viscoelastic layer to reduce structure-borne noise in ship cabin, Song *et al.* (2009) proposed an analytical model that treated a viscoelastic layer and its lower and upper steel plate as a three-layered sandwich plate, and the mineral wool layer on steel deck as a single panel. The combined effects of all the layers were evaluated by the boundary conditions at the interfaces of the mineral wool and the assumed mode method. The proposed model well simulated experimental results, and structure-borne noise was reduced by $10 - 15\,dB$ at medium to high frequencies by using a constrained viscoelastic layer.

2.3.2 Air Radiated Noise

Recently, air radiated noise from ships has become a rising concern due to complaints from inhabitants of populated areas near ports, channels, and coasts. The prediction of airborne noise pollution produced by moving or stationary ships requires the information on source characteristics, sound attenuation during propagation, and an assessment method at receiving positions for time-varying and time-rated noise. Such kinds of predictions have been widely applied for the assessment of road, railway, aircraft, and industrial noise sources.

Badino *et al.* (2011) identified the main sources of airborne noise from ships as funnels, air intakes, air dischargers, and openings that put the internal sources (ventilation systems, engines) in communication with the external environment. Sound attenuation during propagation outdoors depends on propagation distance, reflecting and intervening objects, and weather conditions. Various calculation methods, such as ISO 9613-2 (1996), and numerical methods based on geometrical acoustics, have been published. Various commercial software packages have also been used for noise simulations on open deck spaces of ships.

Kumar and Nikam (2008) investigated the influence of the air-intake rain protection louver on the noise generated by the engine room air-intake of offshore supply vessels. From numerical simulation on the flow field using a finite volume unstructured computational fluid dynamics code and on-board measurement and experiment, the noise level could be significantly reduced by making the angular orientation of the louver slats in-line with the flow and increasing the spacing between the slats.

18th International Ship and Offshore Structures Congress (ISSC 2012) - W. Fricke, R. Bronsart (Eds.)

Biot and Moro (2011) presented a prediction procedure of ship's outdoor airborne noise in harbour and numerical simulation results in nominal octave-band centre frequencies from 63 *Hz* to 8 *kHz* for a cruise ship. In the simulation, a commercial code based on a hybrid beam tracing method of geometrical acoustics was used. They considered that the outdoor noise sources of ships during harbour stay were the funnel top due to diesel generator engine exhaust, outer openings of the inlets/outlets of the HVAC (Heating, Ventilation and Air-Conditioning) system, including intakes for air supply to diesel engines and auxiliaries and outlets of extractor fans. The other noise sources, such as cargo handling, ancillary onboard devices, and activities, were also discussed, but disregarded in the simulation because of their low contribution to overall noise.

2.3.3 Underwater Radiated Noise

Underwater radiated noise (URN) is low frequency noise (under 100 *Hz*). URN travels long distance under the water surface and comes mainly from mechanical vibration (ship hulls, engine and shafting, wind/tidal turbine farm piles, etc.) and marine propeller/thrusters, either with or without the presence of cavitation. For non-cavitating cases, non-uniform wake at the propeller is the main cause of force and pressure fluctuations that lead to vibration and noise. Non-uniform wake also contributes to unsteady cavitation and all forms of cavitation can, to varying degrees, create substantial noise.

Section 2.3.3 briefly presents the recent research work and studies since ISSC2009 on URN. This section is divided in to 4 minor topics: 1) URN due to hydrodynamics of propeller in operation; 2) the URN created by mechanical vibration (such as engine, propeller shaft, air duct, etc.); 3) URN impact on marine life, and 4) recent experimental and numerical methods/models on measuring, signal processing, analyzing, and predicting URN.

URN due to Hydrodynamic Forces of Propellers, Non-Cavitation Case

Marine propulsion systems generating non-cavitation URN can also be divided into two different categories: a) mechanical noise due to fluctuation of axial forces along the propellers shaft via thrust bearings, and b) hydrodynamic noise due to the fluctuation of the fluid pressure field acting on the propeller blades and nearby hull surfaces.

The thrust of a propeller at a constant revolution speed and fixed geometry is a function of inflow velocity only. In general, the 3D detailed wake in the propeller plane (usually expressed in cylindrical coordinates by radial, axial and tangential components) is non-uniform. The nominal wake is the wake in the absence of the propeller and the effective wake includes the velocities induced by the working propeller. Depending on the propeller design, large fluctuations in thrust may occur as the blades pass through a highly non-uniform wake, resulting in significant blade frequency fluctuations in the axial bearing force. The fluctuation of the axial force along a usually long propeller shaft causes axial vibration and, in this case, the long shaft acts as a compression spring along the shaft centre, though transversal vibration may also occur.

Merz *et al.* (2009) described the situation in detail for a submarine example. The URN often is a combination of tonal and broadband random noise sources, and the prevalence of the sound sources is dependent on frequency band and speed. Here, both cavitating and non-cavitating cases were considered and, in the cavitating case, the frequency was dependent on depth as well. At a large distance from the hull, as absorption increases with the increase of frequency, lower frequency sounds are dominant. Propeller shaft speed and number of blades are the main contributors,

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and determine the frequency of the tonal components. Tonal components are also slightly dependant on the blade thrust fluctuation and thickness. Tonal components, along with the broadband noise, provide important information for the detection of the identity of the vehicle and its speed.

Depending on natural frequencies, the harmonic thrust fluctuations of a non-cavitating propeller can lead to excitation of local structural vibrations and to global ship hull vibrations.

The pressure fluctuations on the propeller blade surface create pressure fluctuations on the objects nearby (the hull, for example). This is analogous to a fluctuated force with both strength and direction, pointing at the ship hull, within a few diameters of the propeller. These kinds of fluctuating forces can be simulated and predicted by using a dipole (doublet), with strength fluctuating harmonically at blade passage frequency.

Caresta *et al.* (2010) studied how to mitigate the sound radiated by a submarine hull in bending vibration under harmonic excitation from a propeller. In the study, minimization of the sound radiation was performed using a cost function based on Active Vibration Control (AVC) and Active Structural Acoustic Control (ASAC). An array of actuators was placed circumferentially on an end plate mounted on the prow of the submarine hull. The force magnitude of the inertial actuators was spatially modulated at the fundamental frequency to actively control the excitation of the bending vibration. AVC was used to apply one or more secondary forces to reduce the structural vibration excited by the primary force. Reduction of vibration using AVC can reduce the noise level. ASAC was used to attenuate the sound radiation in one or more directions. Results were obtained and showed that, at a blade passing frequency (BPF) of $27\,Hz$, the sound pressure level was reduced substantially, from $45\,dB$, re $1\,\mu Pa$ with no control applied to $30\,dB$, re $1\,\mu Pa$ with both ASAC and AVC controls.

A numerical method was presented recently to predict non-cavitating propeller noise using a hydro-acoustic approach incorporating the Detached Eddy Simulation (DES) and the Ffowcs Williams-Hawkings (FW-H) equation (Pan and Zhang, 2010). This study paid special attention to broadband noise, instead of tonal noise. The broadband noise or the self-noise were deemed to be created by the blade surface pressure fluctuations due to the shed blade trailing edge and tip vortices and flow separation under blade heavy load condition. Predictions of the sound directivity were obtained and presented though the acoustic results were not validated.

URN due to Hydrodynamic Forces of Propellers, Cavitation Case

All forms of cavitation generate URN. Among the most common forms of cavitation (tip), vortex cavitation generates high frequency URN and sheet cavitation generates low frequency URN, usually of larger magnitude. Park *et al.* (2009) report on an experimental study, performed in a relatively small cavitation tunnel, to identify the locations of the noise sources generated by a cavitating propeller. A new signal processing technique, Matched Field Processing (MFP) was applied to the identification process. The MFP involved convolution of source signals. A virtual source was devised and included in the formulation of the method to detect the noise source of a cavitating propeller. The frequency of the virtual source was modulated from 3 to $15\,kHz$. The cavitation number for a $0.2\,m$ diameter model propeller was varied between 2.2 and 12.6. The study showed that the sheet cavitation volume was the main contribution to the propeller generated low frequency noise. It was recommended that

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the research be repeated using the same method in a large cavitation tunnel capable of accommodating a ship model with propeller.

Kehr and Kao (2011) presented an efficient numerical time-domain method for predicting the pressure on the hull, and both the near and far underwater acoustic fields, due to unsteady propeller sheet cavitation in a non-uniform wake field. Dipoles and monopole acoustic sources were distributed on the rotating propeller surface and the wave equation was solved in the presence of a rigid ship hull and reflecting free surface. In this work, the unsteady cavitation volumes were predicted using the PUF-3A unsteady lifting surface theory developed at MIT. Predictions for a container ship were compared to predictions obtained by the Laplace equation and with experimental results from the HYKAT large cavitation tunnel at HSVA.

2.4 Shock and Explosion

Explosions in air or in water produced by accidents or intentionally by hostile attacks within or immediately nearby a ship's hull can cause catastrophic damage on the ship structure and the shutdown of critical life safety systems. Explosions in air may more frequently affect local structures or sub-systems directly blasted by the shock pressure wave, while the whole ship structure can be more seriously damaged by underwater explosions: the shock wave can only locally damage the hull, but the gas bubble can induce resonance phenomena in the hull girder, up to its collapse. It becomes of significant importance to simulate the structural response to such loads in order to provide a shock- and explosion-resistant design of the ship structures.

2.4.1 Local Response

Some studies have been identified that are aimed at evaluating the local dynamic response of ship structures subjected to blast loads, from a simple stiffened steel panel, to composite plates, up to an entire mast.

Yang *et al.* (2010) investigated the dynamic response of one-way stiffened plates with clamped edges subjected to uniformly-distributed blast-induced shock loading. A singly symmetric beam model was used, based on the rigid/perfectly plastic assumption and taking into account the bending moment/axial force capacity interaction. Their relation for singly symmetric cross-section was derived and explicitly presented. The study led to assessment of the deflection condition that a plastic string response must satisfy; e.g., the linearized interaction curve and associated plastic flow rule. The dynamic response of the plate under blast loads has been calculated by means of two FE solvers (ANSYS and Abaqus/Explicit) and by the developed theoretic method to assess its functionality and suitability. The possibility of replacing an arbitrary blast load by a rectangular type pulse was assessed.

Chirica *et al.* (2011) analysed the protective capacity of ship hull structures made of composite materials (flat plates layered by two different orthotropic E-glass reinforced polyester plastic) subjected to a spherical charge explosion. The methodology, which was to apply the blast pressures caused by a close-to-surface explosion while accounting for space and time variation, was based on previous literature. By performing parametric direct-integration nonlinear dynamic analyses and assessing the structural failure of the composite layers by the Tsai-Wu criterion, the behaviour of those plates to blast loading was assessed versus explosive magnitude, distance from source of explosion, and plate thickness. Despite some criticalities in accounting for the effect of damping, the study allowed some guidelines to be drafted for the design of composite blast-resistance panels.

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Xiaobin *et al.* (2010) developed a method for the evaluation of the dynamic response of a structure subjected to air explosion and a time and space varying shock loading. The method was based on a numerical Flux-Corrected-Transport (FCT) algorithm, which was able to evaluate the shock wave propagation time history and to calculate the load in a format suitable for FE codes. The air-structure coupling was taken into consideration. The method was applied to a naval mast, which always needs an accurate design as it is essential for ship safety and combat capability. The structure of the mast was modelled by Lagrangian plate elements in the FE code LSDYNA, and loaded by the computed pressure time history on each element. The dynamic behaviour of the mast was calculated under the design blast load to verify the capabilities of the method and to provide a reference for an explosion-resistant mast design.

2.4.2 Global Response

A few publications related to the global response of ship structures to shock/explosion loads have been identified. Underwater explosion (UNDEX) analysis of ships is one of the most complicated numerical analyses, both for load calculation and for fluid-structure interacting response.

Sinha and Sarangdhar (2008) focused on a fast method to simulate and analyze UNDEX effects on ships at a design level. The FE Software ANSYS was coupled with IRUNDEX, software for the Underwater Explosion analysis of structures. The software calculated the loads by taking into account the initial shock wave, the pulsating gas bubble, and their spherical distribution; the pressure time histories calculated at any ship location were automatically applied to the FE model. By replicating already known test cases, the method capabilities were assessed versus mesh density, load discretization, time step, and nonlinearities due to the geometry and the material. Finally, the UNDEX response of a floating shock platform was calculated and analysed considering different charge weights.

Xing *et al.* (2008) presented an improvement of their Fluid – Structure Interaction Analysis Program (FSIAP), a mixed finite element method for the dynamic analysis of fluid structure interaction systems subject to earthquake excitations, explosion waves, and impact loads. The variables of acceleration in the elastic solid and pressure in the fluid were adopted as the arguments. The boundary conditions on the interface of two different fluids with different mass density were implemented, the frequency shift technique for fluid-structure interaction system was mathematically demonstrated, and a substructure-subdomain technique to solve the large vibration problem was adopted. The case of a LNG tank excited by a pressure wave was presented, which showed that a number of internal and external sloshing frequencies existed due to large area of free surface on the external water. The authors highlighted that sloshing effects induced by UNDEX pressure waves have to be accounted for in designing large LNG ships.

2.5 Damping and Countermeasures

Damping properties can be tailored in a wide range by modifying the constituent materials, lamina thickness, ply orientation, stacking sequence, or fibre fraction in multilayered structures, and also by changing skin thickness or core depth in sandwich constituents. Matter *et al.* (2011) showed that, among simple damping formulations, the hysteretic or structural model was much more pragmatic than the viscous one for the steady state vibration or modal analysis of fibre reinforced composites under normal working condition. A mixed numerical-experimental identification procedure for evaluating the elastic and damping properties of sandwich laminates with a soft core was described. It was concluded that, although the constitutive model chosen

18th International Ship and Offshore Structures Congress (ISSC 2012) - W. Fricke, R. Bronsart (Eds.)

was based on a frequency independent hysteretic damping, the proposed identification method was generic and could be extended to alternative constituent models. Increased complexity required an improved effort on the numerical, experimental, and identification levels.

Lee *et al.* (2009) conducted experiments to investigate the structural response of a Mark III type insulation system against sloshing impact actions. A series of compressive load tests were carried out in low strain range. The temperature effect was considered. It was found that the lower the temperature, the smaller was the displacement under the same pressure. This meant that the damping effect of an insulation system, including RPUF (Reinforced Polyurethane Foam), became smaller as the temperature decreased. The damping effect was analyzed using parameters like strain rate, loading rate, and spring constant. It was found that spring constant tends to converge as the loading rate was increased and temperature decreased.

Den Besten *et al.* (2009) developed an analytical 2D mathematical model for the local structural response of a hydrodynamic impact-loaded sandwich structure with vibration isolation and structural damping properties. The structural response was determined by solving a semi-analytically hydroelastic coupled sandwich flexible core model and hydrodynamic impact model. It was found that, compared to stiffened panel hull structures, the bending stresses were low. Also, less fatigue damage sensitivity was observed because of the sandwich construction principle (absence of a stiffener-girder connection). Structural damping properties of the foam material were of reduced importance for fatigue damage sensitivity.

Passive vibration reduction methods, like elastomeric dampers or tuned vibration absorbers, were limited in their overall reduction performance. To further decrease the vibrations, Kauba *et al.* (2008) designed a complete control system for the active control of a marine engine mount. The control system was implemented and tested on a rapid control prototyping system as a Multiple Input Multiple Output (MIMO) Filtered Reference Least Mean Squares (FxLMS) algorithm. Test runs of the experimental rig with varying engine speed were conducted. After the laboratory testing, the active vibration control system was mounted to the vessel and final measurements during operation of the ship were performed.

2.6 Monitoring

Kivimaa and Rantanen (2007) presented results obtained by monitoring the dynamic hull responses for two extreme load cases. The motivating concern was that, in the development of high-speed craft, there was a lack of information on full-scale wave loads and hull beam responses in actual operational conditions. To address this deficiency, an integrated monitoring system was developed and applied to a fast monohull, SuperSeaCat4 ($LOA = 100.3\,m$, $V_s = 37\,kn$). Details of the monitoring system were provided, and a selection of the measurements from a monitoring campaign was presented. This monitoring system used stain gauges, accelerometers, a differential global positioning system (DGPS), and a wave radar, so that the dynamic global wave-excited dynamic responses of vertical bending moment, torsional moment, and shear force could be observed at four locations along the hull. The authors emphasized the importance of synchronising data streams in order to fully understand the hull behaviour in conjunction with prevailing conditions.

Grasso *et al.* (2011) also considered the development, installation, and load time-histories from hull monitoring systems. They advocated the use of a temperature-compensated, laser based optical sensors in preference to electrical stain gauges. The

18th International Ship and Offshore Structures Congress (ISSC 2012) - W. Fricke, R. Bronsart (Eds.)

design and installation of a load monitoring system for two distinctly different vessels were considered. For a bulk carrier, the hull girder bending moments and local stresses in selected 'hot spots' were of interest, whereas for a tug boat conducting ice-breaking duties, local stress levels of the structure in the bow region were targeted. The report provided detail on the use of FEA in identifying the optimum location of the sensors for each case. The report also described the algorithms for the supporting onboard software of the systems. Because the monitoring systems were only recently installed at the time of publication, a brief strain time history from the tug boat was provided as example data.

Mathisen *et al.* (2009) principally focused on the contribution of whipping to the total hull bending stress. They analysed the time series of deck stresses in a containership (4,400 TEU, $LBP = 281\,m$) in severe stationary conditions. Six segments of data were selected with relatively severe hull stresses (in sea states, $H_s = 5.5\,m - 6.6\,m$), for which the conditions could reasonably be considered to be stationary (i.e., relevant parameters such as sea state, variability in stress levels, etc., were effectively time invariant). They observed that, in a number of cases, the extreme hogging stresses were above the design rule stress. In addition, using low-pass filtering to separate the high frequency (vibratory) stress components due to 2- and higher modes from the wave-frequency stresses, they showed that the vibratory (whipping) contributions made a significant contribution to this total stress ($\sim 35\,\%$). The authors recommended that further analysis of this type be carried out as data becomes available for container ships.

Davis *et al.* (2009) were principally interested in the slamming behaviour and subsequent whipping response of fast wave-piercing catamarans. From a monitoring perspective, while full detail of systems were not provided, the authors stated that they comprised a set of three strain gauges set to record axial stain along the length of main keel members for each demihull of the various INCAT wave-piercing catamarans used. Furthermore, they demonstrated the use of wavelet analysis of strain time histories to identify even small slamming events that were not easily identified from the strain time-history alone. From sea trials data, the subsequent transfer of the slam event to the whipping vibration mode and its subsequent decay was identified. In addition, tests on a segmented model were able to replicate the frequency and damping observed at full-scale reasonably well, and gave a clear indication of the overall mechanics of the slam process.

2.7 Uncertainties

Dessi *et al.* (2009) investigated the correlation of model-scale and full-scale tests aimed to determine the bending response of a navy vessel in waves. A preliminary analysis on the correlation of model-scale and full-scale experimental data about the global ship behaviour was carried out. Moreover, a theoretical procedure, based on the successive comparison of a chain of intermediate numerical models filling the gap between the real ship and the segmented hull, was outlined and applied in the case of regular wave excitation. These are the first steps toward the definition of a general procedure capable of tuning the model-scale data that, being affected by the load segmentation and by the reduction of the structural complexity, needed some kind of correction function depending on the space coordinates and the frequency.

Section 4 of this report also provides insight into uncertainties regarding slamming and whipping.

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2.8 Standards and Acceptance Criteria

This section focuses on noise, vibration, and shock acceptance criteria and procedures for their measurement. International standards with regard to habitability, underwater noise radiation, and shock test for ships are discussed.

2.8.1 Habitability

The ILO MLC (2006) sets minimum standards, applicable to new buildings as well as ships in operation, to address the health, safety, and welfare of seafarers. The regulations are subject to the implementation into national laws, which are expected in 2013 after the expected ratification in 2012. The convention specifies requirements with respect to preventing the risk of exposure to hazardous levels of noise and vibration. The limits for noise levels defined in IMO Resolution A.468 (XII) 1982 are commonly understood as satisfactory for compliance with the noise aspects of the convention. Because MLC 2006 does not define limit values for vibration exposure, this should be addressed by the national legislations. Most of the flag states that ratified the convention so far did not concretise the convention in this respect. To ensure clearness and avoid interpretations of the convention's compliance, the Committee encourages concretisation of acceptance criteria.

Guidance for complying with the convention's requirements is provided in the ABS guideline (2009) that gives assessment criteria and measurement methodology for obtaining a voluntary class notation. GL's Harmony Class for Cargo Ships Certificate (2009) also includes an ILO-MLC Noise Compliance certificate. In general, the new voluntary class notation introduces three harmony categories to allow for a graduation of noise and vibration levels, with different requirements valid for ships with different deckhouse positions.

In 2007, EU started an initiative to update IMO A.468(XII), with the aim to incorporate mandatory noise level limits for work and living spaces via amendments to SOLAS Regulations II-1/36. Under discussion are noise exposure levels, maximum noise levels, and limits for airborne sound insulations.

2.8.2 Underwater Noise

In recent years, a growing concern on the effects of ship generated underwater noise on the marine fauna can be observed. The Committee (ISSC 2009) encouraged standardization for the measurement of underwater noise. Two standards were published in the meantime, and one is under development.

ANSI S12.64 (ANSI 2009) described requirements for the measurement of underwater noise. The underwater sound pressure level measurements shall be performed in the far field and then corrected to a reference distance of 1 meter. The standard offers three grades of measurement, each with a stated applicability, test methodology, uncertainty, system repeatability, and complexity. The standard does not specify or provide guidance on underwater noise criteria.

With *DNV Silent*, Det Norske Veritas published in 2010 a voluntary class notation for vessel-related underwater noise radiation to ensure a low environmental impact and/or to ensure hydro-acoustic operational capability for vessels relying on hydro-acoustic equipment. The notation has five sub-notations: Acoustic (A), requirements for vessels using hydroacoustic equipment as important tools in their operation, e.g., survey vessels, ocean research vessels, pipe layers, diving vessels, naval vessels, etc.; Seismic (S), requirements for vessels carrying out seismic surveys using acoustic streamers; Fishery (F) requirements for vessels engaged in fishing; Research (R) requirements for

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research and particularly noise critical operations based on the recommendations in ICES Cooperative Research Report No. 209; and Environmental (E) requirements for any vessel demonstrating a controlled environmental noise emission. The rules specify requirements for maximum underwater noise emission for a given set of operating conditions.

ISO is currently developing a new standard, ISO 16554, *Measurement and reporting of underwater sound radiated from merchant ships*, following a request from the Marine Environment Protection Committee (MEPC) of the IMO. MEPC established a Correspondence Group to identify and address ways to minimize the introduction of incidental noise into the marine environment from commercial shipping and, in particular, develop voluntary technical guidelines for ship quieting technologies, as well as navigation and operational practices (Dambra 2010). ISO plans to publish the standard in 2012.

2.8.3 Shock

The American National Standard Institute (ANSI) published the standard ANSI S62-2009, *Shock Test Requirements for Equipment in a Rugged Shock Environment*. It defines ten thresholds of shock severity for equipment whose normal use subjects it to a certain shock. The shock severity thresholds shall be defined by drop height and half sine shock pulse or, alternatively, by velocity change and pseudo velocity shock response spectra (Lang 2010). The standard also defines criteria for compliance in case of other tests than drop shock tests producing other pulses than half sine pulses.

3 OFFSHORE STRUCTURES

3.1 Slender Structures

This section covers wave-induced loading on slender structures (risers, umbilicals, pipelines, mooring lines, and etc.) and current-induced vibrations, known as VIV. The strengths and weaknesses of the current state of the understanding of these complex fluid-structure interactions are discussed and studied by a number of institutions, and some of the many contributing authors will be mentioned in the coming subsections.

3.1.1 Wave-Induced Vibrations, Slender Structures

For preliminary design of risers and mooring lines, dynamic analysis of wave and floater-induced response is frequently based on application of regular waves with given amplitude and period. For more comprehensive concept verification, a stochastic model of the ocean surface and wave kinematics is typically applied. The corresponding dynamic response will hence also be of a stochastic nature, which implies that suitable probability distributions of local maxima and extreme values need to be identified. As the response processes in general are of a non-Gaussian nature, this may frequently become a challenging task. Such response analyses, in general, need to be repeated for multiple sea states. This implies that considerable CPU efforts are required, unless some kind of selection of important sea states is performed.

Martins *et al.* (2009) considered the fatigue and ultimate limit states of steel risers. The first part showed a comparative study of three approaches for statistical analysis of extremes. These approaches were respectively based on design storm analysis, environmental contour representation, and full long-term statistics. The contributions to fatigue damage and long-term extreme statistics from different sea states were also considered. Several full time-domain analyses were performed for two example steel catenary riser configurations located in Brazilian waters. The most important sea state blocks for each limit state were identified.

18th International Ship and Offshore Structures Congress (ISSC 2012) - W. Fricke, R. Bronsart (Eds.)

Steinkjer *et al.* (2010) addressed the topic of how to select proper simulation lengths and blocking of the scatter diagram, which is essential to obtain reliable fatigue life estimates of non-linear riser systems. The paper presented methods for evaluating the statistical uncertainty of the fatigue damage estimate. These methods were demonstrated to be capable of describing the statistical uncertainties in short-term, as well as long-term time-domain fatigue damage estimates. Based on the obtained results, recommendations were given on simulation length in order to obtain the target reliability on the fatigue damage estimate.

Baarholm and Haver (2010) outlined a method to determine the long-term extremes by considering only a few short term sea states with application to a flexible riser configuration of the lazy-wave type, which was located in the North Sea. The sea states had a certain probability of occurrence, and were identified by a contour line in the (H_s, T_p) plane. The purpose of the contour line approach was to predict load and response levels, which corresponded to a given annual exceedance probability, without having to carry out a full long-term analysis. The advantage with this concept was that the environmental representation and response analysis was decoupled. This was very convenient if the problem under consideration were of a very non-linear nature; in particular, if characteristic values for design were to be established directly from model tests. The method seemed to give results of reasonable accuracy for most problems.

In Chen *et al.* (2009a), a methodology claiming to have a considerable potential for saving of computation time was considered. The focus was on Steel Catenary Risers (SCR), with the main response of concern located in the sagbend region near the touchdown. The methodology built on time traces of the host vessel motions, and the correlation between the vessel/porch motion and the SCR sagbend response.

Cheng *et al.* (2010) applied a methodology based on *L-moments*, which was proposed in order to a) select the probability distribution applicable to SCR response and b) estimate the extreme response during severe environmental conditions. The methodology was validated by modelling different responses for SCRs that were suspended from a deep-draft semi-submersible located at different water depths.

In Ayers *et al.* (2009), a method for qualification of polyester rope was proposed by application of test sequences representing 20 Katrina hurricanes. The test aimed at measuring both strength reduction and maximum elongation over a series of 20 hurricanes. A superior rope design would minimize cyclic wear, and an adequate splice design would demonstrate no appreciable splice slippage. A typical 20-hurricane test could be run continuously and be completed in about 4–5 days, so testing would be economical.

Spanos and Nava (2009) proposed a novel coupled six-degree-of-freedom analytical model for a Spar system with top tensioned risers. The model accounted for the interactions among spar hull motions, the riser motion, and the moonpool. This model involved six coupled nonlinear differential equations comprising nonlinearity terms associated with stiffness and damping, as well as the inertia terms. The results pointed out the importance of considering the moonpool coupling effect in the spar heave dynamics. Furthermore, the statistical linearization approach results exhibited good agreement with the nonlinear time domain analysis results.

In Naess *et al.* (2009), two methods for the prediction of extreme TLP tether tension from finite time series records were considered. The study was motivated in part by the observation that a significant part of the tether tension during storm conditions was associated with the ringing response, which was a conspicuously narrow band

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response process due to the very low damping in heave. The time series of the tether tension was, therefore, characterized by strong correlation between the neighbouring response peaks of the ringing bursts.

Felisita *et al.* (2010) performed a comparison of analysis methods in connection with installation of umbilicals (with each method corresponding to application of a different model for the wave spectral density). The objective of the study was to select the most suitable analysis method taking into account different types of installation operations. The comparison between different spectral models and different installation methods was based on several limiting criteria, including top tension, compression, minimum bending radius, and the tension at the touchdown point. Both the JONSWAP and the Torsethaugen spectral densities were applied in order to model the wave environment of the North Sea.

The large Vortex-Induced Motion (VIM) due to current acting on a circular-shaped mono column platform induces low-frequency stress variations on the SCRs connected to it. These stresses, together with stress variations associated to wave effects, must be accounted for in the fatigue analysis of these risers. Sagrilo *et al.* (2009) described a methodology for computing the fatigue damage in SCRs due to wave-frequency and VIM load effects based on a combination damage formula provided by DNV (2005). The wave frequency and VIM fatigue damages were calculated separately (by a time-domain Rainflow approach) and the combined damage was evaluated by means of the DNV formula. The results obtained in this work showed that the large low-frequency vortex-induced motions on the mono column platform caused more fatigue damage on the top of the SCRs. In the remaining SCR length, the fatigue damage was caused mainly by wave-frequency effects.

3.1.2 Current-Induced Vibrations, Slender Structures

The existing VIV prediction schemes are based on a number of hypotheses, experimental facts, and data like strip theory, energy balance, correlation length and, most importantly, the use of lift force coefficient databases. Recent advances in observing the VIV motions on experimental risers with high confidence showed that some of these assumptions may not be valid. One important source of the discrepancies between theoretical estimates and experimental observations arose from the use of experimentally-obtained lift coefficient databases. In Mukundan *et al.* (2009), they described a method to improve the modelling capability of riser VIV by extracting empirical lift coefficient databases from field riser VIV measurements. Their results showed that this method significantly reduced the cross flow response error.

Franzini *et al.* (2009) presented measurements of VIV of inclined cylinders with both circular and elliptic cross sections that aimed to check the validity of the normal velocity correction.

Vandiver *et al.* (2009) examined experiments on a tensioned long flexible riser that showed travelling wave VIV was dominant at high mode numbers as opposed to standing waves.

A full scale VIV test was carried in the Gulf of Mexico using the drilling riser standalone monitoring system. The drilling riser was exposed to excessive eddy loop current. Beynet *el al.* (2008) described the test set-up and measured VIV response. This included observations of cross flow VIV, in-line VIV, and additional response at higher frequencies not currently predicted with industry VIV analysis tools.

Liu *et al.* (2009) presented the results of a study to compute the VIV behaviour of a free-standing hybrid riser (FSHR) using a time domain analysis method, ABRAVIV,

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which had been benchmarked by field measurements and model test data for top tensioned risers and SCRs. This was the first application of the method to a FSHR. Comparisons between numerical and experimental results were presented. In addition, results from frequency domain analysis were also presented.

The gap between predicted and measured VIV fatigue damage can be very large. In an effort to more effectively understand and manage the vortex-induced vibration fatigue integrity of its drilling risers, British Petroleum (BP) instrumented a number of mobile offshore drilling units (MODUs) and offshore production platforms worldwide. Tognarelli (2008) presented several aspects of the findings from those monitoring campaigns. The measured data were used to expose some of the physical details of full-scale riser response, whose omission from predictive design tools and methods may have contributed to the observed wide gap between predicted and measured fatigue damage. To characterize the size of the gap, the data were compared to calculations using the most commonly used industry VIV analysis software, MIT's SHEAR7. The work demonstrated the inherent level of analysis over-conservatism with respect to full-scale, unsuppressed drilling risers in the field when typical analysis parameters were utilized.

Tognarelli *et al.* (2009) described BP's benchmarking of SHEAR7 version 4.5 (hereinafter SHEAR7 v4.5), and introduced the concept of time-sharing between the modes, which made spatial overlap elimination between the modes unnecessary. The concept of time-sharing was based on observations from the Gulf Stream, DeepStar-funded, slender pipe experiments. Comparisons were made between predicted and measured VIV fatigue damage for several full-scale drilling risers to demonstrate the efficacy of a calibration for the latest version. In addition, comparisons were made between VIV fatigue damage predictions using SHEAR7 versions 4.4 and 4.5 for drilling risers, as well as for a typical deepwater SCR in typical design Gulf of Mexico loop currents. The version-to-version differences were illustrated and explained. Finally, results of sensitivity studies conducted with respect to the new parameters in SHEAR7 v4.5 were presented. A key finding was that, while the predictions on average were similar from version to version, the scatter in predictions that led to requirements for large safety factors was largely unimproved.

Further, Yang *et al.* (2008) compared the measured responses from ExxonMobil's 2003 VIV model tests to simulations of the test conditions using the newest version of SHEAR7 v4.5, applying the concept of time shearing. The study indicated that the new time-sharing model, in general, generated prediction results with reasonable bias and scatter for bare risers. The prediction errors for straked risers were still high, however, even when the most favourable parameters were selected for the analysis.

Soni *et al.* (2009) presented results from a novel type of experiment. Trajectories for cross sections in a flexible beam were found from classical VIV experiments and then used as forced motions for a cylinder that was sufficiently large to obtain reliable data for hydrodynamic forces. By proper processing of the measured forces, hydrodynamic coefficients for relevant frequency components were found. The main purpose of Soni and Larsen (2009) was to compare the results as hydrodynamic coefficients and the vortex patterns found from dedicated experiments for both harmonic and periodic trajectories, and thereby investigate the potential for using coefficients from harmonic tests as the basis for empirical models.

The motion induced by vortex shedding on slender flexible structures subjected to cross-flow was considered in Violette *et al.* (2010). This phenomenon of vortex-induced

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vibration was analysed by considering the linear stability of a coupled system that included the structure dynamics and the wake dynamics.

A new form of VIV suppression device, the AIMS Dual-fin Flow Splitter (ADFS), has been developed, tested, and benchmarked against bare-pipe, 5d and 15d pitch strakes, and conventional teardrop fairings in Schaudt *et al.* (2008). Both model tests and simulations (SHEAR7) were carried out. Relevant coefficients were compared, as well as the effect on fatigue damage using various VIV suppression devices.

Another measure to reduce VIV was the use of a slit. Results of this methodology are reported in Baek *et al.* (2009).

Aglen *et al.* (2009) investigated the measured VIV for a free spanning pipeline model. The pipeline was exposed to uniform current and is free to vibrate in both cross-flow (CF) and in-line (IL) direction. The purpose of this investigation was to understand the behaviour of the free spanning pipelines with respect to response amplitudes, frequency and modal composition, and to identify characteristic cross-section trajectories.

The vibration frequency and lock-in bandwidth of tensioned, flexible cylinders experiencing VIV were studied by Lee and Allen (2010). The tests revealed that the top tension and structural stiffness (both lateral and axial) can have a significant impact on vibration frequencies.

An inverse finite element method was presented in Mainçon *et al.* (2008) for the estimation of load and response of linear dynamic structures based on measurement data. It produced load and response estimates that exactly verified dynamic equilibrium while the loads are reasonably small and the response is in reasonable agreement with the measurements. iFEM was used to process measurement data from VIV experiments on a reduced scale riser model in shear current. The technique allowed for visualisation of the distribution, and a history of hydrodynamic forces and excitation and damping zones.

Cunha *et al.* (2009) presented an analytical solution, experiments, and parameter investigation for the vibration of a simply-supported beam due to vortex shedding. The in-line and cross-flow fluid forces were coupled to the beam equation as harmonic non homogeneous terms. Experimental results of 2 DOF VIV of a flexible small scale pipe in a uniform stream were presented for perpendicular and oblique (at 60 degrees of the translation direction) pipe.

Recent advances in CFD methods and the availability of powerful computational resources have made numerical simulation a viable option for VIV prediction. In Bhattacharjee *et al.* (2009), a numerical 2-D simulation was conducted for near seabed cross-flow VIV of subsea pipelines. An advanced meshing technique, capable of handling moving boundaries, was used to discretise the fluid domain. This approach, in conjunction with a structural model, was employed to simulate the complex case of VIV in a pipeline in close proximity to the seabed.

The fatigue damage on a top-tensioned riser induced by in-line vibration and cross-flow vibration was addressed in Tang *et al.* (2009) using a statistical methodology and also the amplitude ratio.

The field data from a long flexible model riser was used to study the fatigue crack growth due to the stresses generated by high mode VIV in Iranpour (2008).

A method to estimate the fatigue damage using a monitored marine riser based on the data from a limited number of sensors was studied in Mukundan *et al.* (2009).

18th International Ship and Offshore Structures Congress (ISSC 2012) - W. Fricke, R. Bronsart (Eds.)

The analysis showed that the travelling wave characteristics of riser VIV response were captured by the reconstruction methodologies. The effect of higher harmonic components were found to influence the riser fatigue life, however, and may or may not have been captured by the method depending on the available number of sensors and the bandwidth of the observed VIV response.

Bhalla and Gong (2008) presented a method that has been developed to identify if vortex-induced vibration (VIV) occurs in well jumper systems. A methodology to identify whether the vertical legs or all of the legs of the jumper need to be straked was presented. In addition, the technique aimed to recognize when certain legs of a given jumper system may require suppression, thus leading to a jumper design whose safety was not compromised while in the production mode, as well as minimizing downtime and identifying potential savings from probable fatigue failures.

Current induced vibration in the form of VIV and galloping produce hydrokinetic energy. The focus of the work in Lee and Bernitsas (2011) was to convert this energy into electrical energy. The experimental research supported the development of the VIVACE (Vortex-Induced Vibration for Aquatic Clean Energy) converter. The hydrodynamics of the VIVACE converter has been improved continuously since its invention in 2005.

Bernitsas and Raghavan (2008) and Bernitsas *et al.* (2008) studied the use of surface roughness to reduce VIV and break down the span wise correlation. The work was limited to studying the location of the roughness in the form of sandpaper. It was concluded that the use of roughness can reduce/suppress VIV and, to some extent, decrease the range of synchronization. The use of passive turbulence control to harness kinetic energy was studied in Chang and Bernitsas (2011). A multi-cylinder configuration was studied in Kim *et al.* (2011b). The use of multi-cylindrical configuration was an important step forward in making the VIVACE converter to a real three-dimensional device.

3.1.3 Internal Flow Induced Vibrations, Slender Structures

High frequency internal flow induced vibrations have been reported on flexible and rigid pipelines and risers, and may cause fatigue and severe damage to the pipes themselves or to the supporting structures. These vibrations resulted from the internal flow vortex shedding as mono- or multi-phase fluid was conveyed in the pipes. Severe vibration has also been reported in tie-in spools subjected to slug flows. Prediction of internal turbulent flow in LNG pipe transfer systems has also been reported as critical, especially as the maritime transportation of cryogenic LNG increases worldwide.

A collection of practical applications for vibration induced by cross and parallel flows, as well as by internal fluid flow, was presented by Kaneko *et al.* (2008). The effect of the internal flow on a vertical riser subjected to VIV was numerically investigated by Keber and Wiercigroch (2008). Guo and Lou (2008) carried out experiments to assess the effect of internal fluid flow on the vortex-induced vibration. They found that the vibration frequency decreased and the riser response amplified as the internal flow speed increased. Shang-mao and Li-ping (2009) employed DNV-RP-F105 to investigate the effect of internal flow velocity and functional loads on vortex-induced vibration response. It was found that internal flow velocity was less important for VIV response than other functional load factors, such as the effective axial force. Namba *et al.* (2009) carried out a series of experiments for modelling the dynamic interactions between the internal fluid and the structure's response on a hung-off rigid riser under axial motion. Yamamoto *et al.* (2009) developed an experimental study to address

18th International Ship and Offshore Structures Congress (ISSC 2012) - W. Fricke, R. Bronsart (Eds.)

the interaction between the pipe dynamics and its internal mono-phase flow. Blanco and Casanova (2010) investigated the interaction between the internal slug flow and vortex-induced vibration in the fatigue life of submarine pipelines. In some cases, the riser dynamics can be influenced by the slug flow and the fatigue life may be different if each flow is considered separately.

Frohne *et al.* (2008) described a new LNG flexible pipe transfer system and reported that one of the main difficulties is to predict the turbulent internal flow behaviour and, consequently, its associated pressure drop in the corrugated configuration of flexible pipes. Pisarenco *et al.* (2009) investigated the friction factor in flexible hoses used for cryogenic LNG transport.

Analytical and numerical formulations have also been proposed. Bao and Wen (2008) employed a differential quadrature method to analyze the stability of a subsea pipeline subjected to both vortex and internal flow induced vibrations. Olunloyo *et al.* (2008) developed analytical methodology to assess dynamic stress propagation in subsea pipeline systems. Athisakul and Chucheepsakul (2009) employed a variational formulation based on the extensible elastica theory and the work-energy principle to investigate the influence of fluid conveyance on the dynamic response of marine risers. Pinto and Levi (2009) presented a numerical model to assess the dynamics of free hanging risers. The effects of external excitation due to vortex shedding as well as the effects of internal flow were taken into account. Liu and Xuan (2010) developed flow induced vibration analysis of supported pipes conveying pulsating fluids using precise integration method (PIM). In Grant's MSc dissertation (2010), a finite element analysis was employed to investigate flow induced vibrations in pipes, and to capture the critical fluid velocity that induces pipe instability. Osheku *et al.* (2010a) obtained closed form results to assess flow induced acoustic waves in offshore pipelines. Osheku *et al.* (2010b) proposed an analytical formulation to address the vibration of subsea gas pipelines. Aspects of the fluid-structure-mud interaction were included. Finally, Cheng and Vandiver (2010) presented theoretical formulation for the dynamic analysis of top-tensioned risers, which may consist of outer and inner casings and tubing, thus the response is internally coupled by the centralizers or the fluid flow (or both). If the design is optimum as far as the fluid-structure coupling is concerned, the inner pipe may absorb the vibration of the outer casing.

Multi-phase flow induced vibration continued to be a major topic for research. Bordalo *et al.* (2008) developed model tests to investigate the influence of oil and gas mixtures on the motion of slender risers in catenary configurations. The internal flow momentum may have imposed natural whipping displacements, therefore the riser fatigue life may have been compromised. The flow induced dynamic loading depended on the flow rates of the oil and gas phase distribution. Cooper *et al.* (2009) investigated the fatigue design of flowline systems with slug flow. The slug induced fatigue problem and techniques for predicting fatigue damage during design were presented. Belfroid *et al.* (2009) studied the flow induced pulsations in flexible risers, which can cause singing in offshore and subsea installations. Operational and design guidelines to mitigate this phenomenon in existing facilities and recommendations for adequate design were reported. Casanova and Blanco (2010) addressed the effect of soil properties on the vibration of pipeline spans subjected to slug flows. The results showed that the complex pipe-soil interaction is a key parameter in assessing the vibration response and fatigue life. Yamamoto *et al.* (2010) carried out experimental tests to assess the internal flow rate and pipe's oscillating frequency on the riser response. Mono-phase and bi-phase fluid of liquid and solids in suspension were used. Zhao *et al.* (2010)

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developed a methodology to predict the fatigue life of rigid tie-in spools (pipe bends) subjected to the passage of slug flows. Nielsen *et al.* (2011) presented a new carcass profile to prevent the internal gas flow vortex-induced singing behaviour in flexible risers. Under certain operational conditions, these pulsations may yield severe structural vibrations and potential fatigue failure on the top connection, such as reported on Statoil's Åsgard B platform.

3.2 Very Large Floating Structures

Very large floating structures (VLFS) technology allows the creation of land from the sea without the need for a massive amount of fill materials. These kinds of structures have been gradually appearing in many parts of the world for applications such as floating bridges, floating piers, floating performance stages, and floating storage.

In Jiao *et al.* (2009), a two-dimensional composite strategy was applied in order to couple a linear global solution with a nonlinear local analysis of pontoon-type VLFS. The effect of air cushion and resulting slamming pressure was considered. The numerical results were also compared with experimental data and other numerical solutions. The bottom slamming of a VLFS was also studied in Greco *et al.* (2009) by means of theoretical and numerical methods.

In Korogi *et al.* (2009), a new type of mobile VLFS (which is referred to as a VLMOS) for the purpose of generation of wind-energy was assessed. Towing tank tests were performed with a 1/100 scale model of the structure. Wang *et al.* (2009b) considered the hydroelastic response of interconnected beams that model a longish VLFS. The study investigated the design of the mechanical joint in order to reduce the hydroelastic response. A further extension of the analysis was provided by Wang *et al.* (2011) where one-, two-, three-, and four-line hinge connectors along two directions for a square-shaped VLFS are considered.

In Chen *et al.* (2009b), hydroelasticity theory considering the second-order fluid forces was addressed. The influence of the magnitude of the frequency increment on the computed response was analyzed. It was found that the second order response in some cases may be of the same magnitude as the first-order response.

Jin and Xing (2009) applied a mixed mode function – boundary element method for analysis of the dynamic behaviour of an integrated model of an aircraft – VLFS – water interaction system that was excited by aircraft landing impacts.

There seemed to be a steady development both with respect to VLFS concepts of practical relevance, as well as more refined computational methods. This trend is expected to continue also through the next decade.

3.3 Other Offshore Topics and Applications

Field observations from offshore installations, along with laboratory investigations and numerical simulations, continued to provide improvements to our understanding of structural dynamic response. Several of the selected research findings that follow are for fixed offshore structures, which represent a large proportion of all offshore installations. Many of the insights and observations for fixed offshore structures will also be relevant to floating offshore structures.

3.3.1 Wind-Induced Vibrations, Offshore Structures

Significant cracking has arisen in flare booms located on various platforms in the North Sea. Moe and Niedzwecki (2009) carried out an experimental investigation to examine the possible cause of vibrations for the Heimdal flare boom. Large vibrations of

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around 50 mm amplitude had been observed for tubular bracing members. The vibrations only occurred in special wind conditions where the direction was parallel to the faces of the flare boom. The observed amplitudes and frequencies of vibration were not consistent with the predicted behaviour of stand-alone members for the encountered wind speeds. It was postulated that the bracing members could be susceptible to wake-induced vibrations caused by the larger diameter chord members located upwind. A set of experiments was carried out to investigate the behaviour of an elastically supported circular cylinder located downstream from a larger cylinder of around twice its diameter. Maximum measured amplitudes of vibration in the experiments were approximately twice those of a stand-alone cylinder and occurred at higher wind speeds. A permanent solution for Heimdal was to fit shrouds and post-tensioned ties.

Jia (2011a) presented a practical approach for calculating wind induced fatigue damage for tubular structures, such as flare booms, based on nonlinear dynamic analysis. Realizations of spatially correlated random wind fields were used to generate dynamic responses in the time domain whilst taking geometric and load nonlinearities into consideration. Crosswind components of a turbulent wind field were shown to be an important contributor to the calculated fatigue damage. The damage was also shown to be sensitive to the chosen wind grid size. A larger grid size produced a more correlated wind field, leading to increased dynamic response and over-prediction of fatigue damage.

3.3.2 Wave-Induced Vibrations, Offshore Structures

Offshore platforms may be exposed to wave impacts and slamming in extreme wave conditions. Vertical wave loads on decks due to insufficient air-gap are a major concern for many in-service platforms. Improved engineering tools and methods for the prediction of loads from wave impact on FPSOs and offshore platforms in severe sea states were described in Stansberg and Baarholm (2010). A brief presentation of the tool development was reviewed, and numerical examples were demonstrated. Applications of improved engineering methods and procedures included wave-in-deck on jacket platforms, wave amplification with wave impact on large-volume platforms, green water/bow flare slamming on FPSO, and impact on columns, Stansberg *et al.* (2010).

Reliable estimates of the magnitude and duration of the impact loads are important in assessing structural and global response of an offshore platform. In Kota and Moan (2010), a Gaussian formulation of incident wave-kinematics was applied to derive a joint probability density function of deck-wetting (or exceedance) duration and its spatial extent.

Ringing vibration of dynamically sensitive offshore structures has received considerable attention in the past. A revival of practical interest in this area may be emerging in relation to the assessment of dynamic response for monopile structures supporting offshore wind turbines. Zang *et al.* (2010) investigated the loading on a bottom founded vertical circular cylinder when subjected to focussed wave groups (including breaking and non-breaking conditions), with particular attention given to the harmonic content at higher frequencies. A Joint Industry Project concerned with the dynamic response of offshore wind turbines was underway at MARIN, but its findings have yet to be published (Snieckus, 2011).

3.3.3 Current Induced Vibrations, Offshore Structures

Current induced motion (VIM), on a multicolumn structure is studied in Waals *et al.* (2007). The paper discussed the dynamic behaviour in current of multicolumn floaters and the associated complex flow patterns for both TLP and semi-submersibles.

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Holmes (2008) compared CFD simulations with wind tunnel experimental data for a towed bare spar. It was suggested that the use of wind tunnels for selected geometries might offer an inexpensive means to improve existing modelling techniques.

Roddier *et al.* (2009) investigated the effect of Reynolds number and hull appurtenances on spar vortex-induced motions (VIM) for a vertically moored 6-DOF truss spar hull model with strakes. Tests were performed at three different experimental facilities, at three different geometric scales: 1) University of California, Berkeley (scale 142.8:1); 2) Force Technology, Denmark (scale 65:1); and 3) David Taylor Model Basin, Bethesda (scale 22.3:1). Froude numbers were varied from 0.10 to 0.26 with the associated Reynolds numbers. As a result of the range of model sizes, the tests at the University of California and Force Technology were both accomplished at subcritical Reynolds Numbers, and those at David Taylor Model Basin were performed a supercritical Reynolds Numbers. Overall, the three test series covered a Reynolds number range from subcritical 4.1×10^4 to supercritical 1.7×10^6. In order to assess the effect of appurtenances and current heading on strake effectiveness, four different configurations were tested: 1) hull with chains and pipes, with anodes; 2) hull with anodes but no chains and pipes; 3) hull with strakes but no other appurtenances; and 4) hull with chains and pipes but no anodes. The strakes were present in all configurations. Altogether, 822 tests were performed.

3.3.4 Ice-Induced Vibrations, Offshore Structures

Offshore installations in ice-infested waters may encounter moving sea ice features. Ice actions due to these moving sea ice features will produce dynamic loads, even while the intact ice sheet moves at constant velocity and crushes against a structure. Ice-structure dynamic interaction can cause the structure to suffer severe vibration problems, which are known as ice-induced vibrations and have been reported in full scale vertical and conical structures.

Two successive research projects in the period from 1999 through 2003, known as LOLEIF and STRICE (http://www.strice.org), respectively, investigated ice-induced vibrations of vertical structures. The findings from these two projects have been integrated into the latest ISO 19906 (2010).

Yue *et al.* (2009a) observed that the ice failure mechanism associated with ice crushing depends on ice speed, and classifies as ductile, ductile-brittle transition, and brittle failure, respectively. Resulting dynamic ice forces can be classified into three modes responsible for quasi-static, steady-state, and random structural vibrations, respectively.

Xu *et al.* (2011) discussed the main factors that that influence the typical dynamic ice sheet, conical interaction process (obtained in Bohai Bay) covering ice velocity, ice thickness cone diameter slope angle and friction coefficient, and water depth, and made a comparison with other field data obtained from Kemi-1 and Confederation Bridge.

Compared to the bending failure of ice against conical structures, the crushing failure of ice on vertical faces is complex and difficult to investigate at full scale. Thus, crushing failure is best investigated in the laboratory and by theoretical analysis. In general, ice testing facilities attempt to jointly satisfy both Froude and Cauchy scaling laws. However, Palmer and Dempsey (2009) pointed out that, for ice moving slowly against stationary structures, Froude scaling was irrelevant. With only the Cauchy scaling to satisfy, it was not necessary for model ice to be made weaker and more

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ductile by contaminants such as urea. They concluded that ice was best modelled by ice, especially for ice action on a stationary structure.

Määttänen *et al.* (2011) performed near full-scale model tests to study ice crushing phenomena against a compliant stiffened plate structure. In order to have repeatable and homogeneous model ice properties, the ice blocks were manufactured by a snow ice technique with low salinity water impregnation under vacuum in the mould. Natural snow was used for ice crystal seeding, and to promote unidirectional freezing from below. Altogether, 22 ice blocks were crushed with different ice velocities and plate compliance.

Based on 11 sets of published data from vertical-sided structures, Palmer *et al.* (2010) presented a dimensional analysis of the problem, and showed that there was a correlation between the different kinds of cyclic movement and a dimensionless parameter akin to reduced velocity in VIV that can be used to link one to the other. This has been observed in both full-scale structures and models. Kärnä *et al.* (2011) pointed out that the time-varying nature of ice actions and the corresponding ice-induced vibrations should be considered in the design. The potential for dynamic amplification of the ice action effects due to frequency lock-in of ice failure and natural frequencies should be assessed. Particular attention should be given to dynamic actions on narrow structures, flexible structures, and structures with vertical faces exposed to ice action. Thus, some related models and approaches were proposed to solve the ice-induced vibrations for vertical structures.

Using advanced methods, analyses can be continued after complete material failure, and failed sections can be retained in the model without violating the law of conservation of mass. Kolari *et al.* (2009) proposed a new approach for the modelling of interaction, where the failure of material was modelled with anisotropic continuum damage mechanics (CDM) model and the failure mode was assumed to be brittle. The CDM model was used to predict direction of a crack evolution, while the proposed model update technique was applied to propagate the crack in finite element geometry. The proposed approach was used to simulate the ice failure process during the tensile test and the level ice acting on a conical structure. Gürtner (2009) and Konuk *et al.* (2009) developed a cohesive element method to study the dynamic ice-structure interaction processes when a level ice sheet moves against a vertical flexible cylinder. The model was implemented using LS-DYNA software. This cohesive element based framework could offer a reliable and rational methodology for solving ice-structure interaction problems that can capture the characteristics of the ice failure process and the ice-induced vibrations.

When an offshore installation is deployed into ice-covered waters, ice-induced vibrations can occur regardless of the water line geometry (vertical or conical), the structure dimension (narrow or wide), and the structure property (compliant or stiff). The nature of ice-induced vibration derives from the dynamic ice action, and there is no fully rigid structure in practice. Numerical simulation tools have been used in ice engineering, mainly to predict dynamic ice action effects in structure design. The dynamic ice action is still not fully understood, so further studies on this topic are still needed. Furthermore, the dynamic process of ice acting on a vertical structure is much more complex than the dynamic process of ice acting on the conical structure, especially for narrow compliant vertical structures, as the frequency lock-in phenomenon may occur under given ice conditions and structural characters.

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3.4 Noise

Noise and underwater sound due to exploration, construction, transport, drilling, and production are important for offshore activities. Identifications of pertinent mechanisms, multiple potential noise sources, and noise paths from vessels and drilling platforms are necessary for implementation of effective treatments. Hence, the subject of noise can be divided into two major branches in which specific sources and noise makers are identified, and possible treatments for those sources, mechanisms, and paths are considered.

Noise creation from various oil and gas industry activities can be summarized under the following main titles, such as seismic exploration, pile driving, explosives, propellers and thrusters of vessels, machinery noise of vessels, dredges, post trenching, hand tools, platforms, hovercraft, aircraft, and pipelines (Spence *et al.,* 2007).

An experimental study was conducted on the combined acoustic and hydrodynamic variables in a moonpool by Sadiq and Xiong-liang (2008) using a hydrophone near the free surface inside the moonpool. The acoustics were monitored during the change of the free surface due to increased forward speed, with the aim of comparing the results obtained for circular- and square-shaped moonpools. It was found that noise reached higher levels in the square-shaped moonpool in comparison to the circular-shaped one, and that changes in the in-flow wave period, the wave height, and the angle of attack for the square moonpool had significant effects in the change of the sound level.

The impact on marine species of underwater noise due to pile-driving for wind turbines was studied by Bailey *et al.* (2010). Presented in detail are the methods of research and the results regarding the background noise, the pile-driving noise, the source level, and the sound propagation model, including their potential impact on the marine mammals off the north east coast of Scotland. It was observed that the level of noise from pile-driving was detectable above the background noise levels even in a distance of 70 km, and it was suggested that higher background noise levels recorded at the turbine site are likely to be a result of the pile-driving vessel and the support ships. An impact on the behavioural habits of marine mammals due to pile-driving operations has also been observed in the form of divergence from their natural routes.

In order to cover a wide-range of frequencies, Gang *et al.* (2011) applied combined structural FEM, acoustic FEM, and SEA, in hybrid methods to predict the noise and vibration for a semi-submersible design. The applied prediction process for noise and vibration requires the definition of sources of vibration and noise and an assessment of the source spectrum for both. An acoustic finite element or boundary element model was used in both the low-and mid-frequency range. In the low frequency range, the acoustic finite element/boundary element method was hybridized with a structural finite element model. In the mid frequency range, the acoustic finite element/boundary element method was hybridized with a SEA model. Also, the SEA was used in the high-frequency range. It was found that 45-percent of the cabins' noise levels were above the noise limit established for the original design. Application of the absorption and high insulation materials resulted in reduced sound levels in the living quarters, which met the technical requirements.

Eijk and Elferink (2011) carried out an extensive dynamic analysis to achieve stringent control on noise and vibration levels for an offshore reciprocating compressor system. In their work, dynamic analysis and the efforts taken in compressor, skid, motor, piping, and deck design to meet the very stringent specified requirements that ensure a safe and reliable system for the long term operation, is presented in detail. A

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wide range of optimization has been carried out on compressors and drivers, pulsation dampers, and orifice plates in the on-skid compressor piping, anti-vibration mounts. The characteristics of the system, as optimized to meet the criteria [the API Standard 6(8)], are given in a very long list at the end of the paper.

Lloyd *et al.* (2011) presented a paper concerning the modelling of noise sources for use in the assessment of noise influence on marine life. They focused on improving noise source prediction of tidal turbines rather than the development of impact assessment techniques. Categorization of hydrodynamic tidal turbine noise sources was presented as a flowchart. This categorization was also provided in a table under the items of source, origin, importance, frequency type, and directivity. The predicted maximum far field sound pressure level (SPL) was not found to be high enough to cause threshold shift in marine animals based on standard measures. The suggestion was that it was very important to develop new comprehensive models in assessing the environmental impact of turbines for their certification, and that the present model could be a starting point.

3.5 Shock and Explosion

In offshore units, current interest is in structural response following extreme explosive loads arising from gas explosions and underwater explosion. Most explosions on offshore installations are gas explosions. Gas explosions and fires are extremely hazardous in offshore installations, which have serious consequences for health, safety, and the surrounding environment. Two examples are the Piper Alpha accident, which occurred on 6th of July 1988 (Cullen, 1990), and the Deepwater Horizon accident, which occurred on 20th of April 2010 in the Gulf of Mexico (Paik and Czujko, 2011). The latter explosion and subsequent sinking resulted in a tremendous outflow of oil.

The aim of blast analysis is to predict the dynamic response or structural damages of structural members, piping, equipment, cables and other appurtenances on offshore installations under blast loads. Both analytical and numerical methods can be used for blast response analysis due to gas explosion (Mohamed and Louca, 2008). In general, the numerical method is better suited for brief blast transient analysis, particularly involving large deformation and plasticity, which can include non-linear material and geometry, strain rate effect, and etc.

3.5.1 Internal Explosion

Internal explosions usually occur in a largely confined space, such as inside enclosed modules, or in an oil tank, or a leg of a platform. Overpressure is usually created by the expansion of gas in a confined volume as it burns and exceeds the vent capacity of the space. The presence of obstacles in the path will further enhance the overpressure generation and destruction (Pula *et al.,* 2006).

The presence of obstacles in the path will further enhance the overpressure generation and destruction (Pula *et al.,* 2006). Vik *et al.* (2011) and Middha and Hansen (2009) used the computer tools FLACS (Ultimate Strength for Offshore Structures) (USFOS, 1993–2001) and USFOS FLACS (Flame Accelerator Simulator) (FLACS) to simulate the response of platform under explosion. Yasseri *et al.* (2003) gave a reliability of explosion resistant design method. A blast wall installed on a North Sea installation was selected as a case study to demonstrate the proposed method. Lee and Yoon (2011) studied the dynamic characteristic of a simple beam under the blast load by using nonlinear dynamic FE analysis, and a safer and less costly approach was suggested.

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3.5.2 External Explosion

External explosions include gas explosion in unconfined or partially confined and highly congested spaces (Pula *et al.*, 2006), and blast wave acting on nearby offshore units.

Ignition of any vapour cloud under the process area of an FPSO (Floating Production Storage and Offloading) vessel and some offshore modules will lead to an explosion referred to as a partially confined explosion (Paik and Czujko, 2009). In this case, overpressure generation is mainly due to turbulence generated by the obstacles, such as process equipment in the path of the expanding gas. Available empirical models can be used for modelling this kind of explosion, as they have been tested and validated for these conditions. A review of all the empirical models and their comparison with experimental data has been carried out by Fitzgerald (2001).

The prediction of the received loading onto nearby structures caused by the resultant blast wave has been given attention. Louca and Mohamed Ali (2008) investigated the behaviour of a typical offshore topside structure subjected to blast loading caused by hydrocarbon explosions. Monti and Molinari (2011) presented an engineering approach to assess the structural integrity of a submarine pipeline subjected to an underwater explosion, taking in due account the loading due to the shock wave and the gas bubble pulsation. Zhang *et al.* (2006) simulated the dynamic characteristics of an underwater explosion bubble near boundaries, and solved the interaction of bubble and elastic-plastic structure by coupling with FEM.

3.6 Damping and Countermeasures

Various studies have explored the possibility of using passive and active methods to mitigate dynamic responses in the elastic modes of offshore structures. Proven systems in land-based structures have led, naturally, to the consideration of applications in fixed offshore structures. The concepts are also relevant to floating offshore structures, particularly tension leg platforms in deep water that are subject to springing and ringing responses in the elastically restrained modes of heave, pitch, and roll.

Recent interest has considered the effects of system uncertainty on the effectiveness of devices. It is possible that optimization of a device with a deterministic representation of system parameters may be lead to overestimation of performance. Taflanidis *et al.* (2009) investigated the use of mass dampers for tension leg platforms with emphasis upon reducing the response of closely spaced modes and incorporating uncertainty in the modelling of the structural system and environment. It was shown that a dual mass damper system in each hull column provided an improved performance compared to a single mass damper in reducing the heave and pitch responses, especially when the modes had different natural frequencies.

Colwell and Basu (2009) considered the use of tuned liquid column dampers in monopile structures for supporting offshore wind turbines. A significant reduction in peak responses and improved fatigue performance was predicted. It was pointed out that space limitations in the horizontal direction might make other types of damper suitable. Chakraborty and Debbarma (2011) investigated the effect of uncertain but bounded system parameters on the optimal design of liquid column vibration absorbers for the earthquake response of land-based structures. While uncertainty in the loading had exerted a dominant influence on the structural safety, it was shown that uncertainty in the system parameters could play an important role in an optimized design of the dampers.

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Lackner and Rotea (2010) developed a simulation tool for the assessment of passive, semi-active (tuneable over time), and active control of floating structures for the support of offshore wind turbines. Tuned mass damper systems were fully coupled with the dynamics of the wind turbine model. Load reductions beyond those achieved with passive systems were achieved at the expense of active power consumption. It was postulated that the load reduction potential might be better than that associated with individual blade pitch control. Stewart and Lackner (2011) investigated the effect of actuator dynamics in the control of active mass dampers for floating wind turbine systems. It was shown that control-structure interaction could strongly influence the required levels of actuator power and torque, and that lowering the control motor gear ratio could reduce the interaction. Namik and Stol (2011) investigated the use of individual blade pitch control for wind turbines on floating barge and tension leg platforms. The proposed control strategy was shown to be capable of reducing the tower loading on tension leg platforms to levels comparable with onshore turbines.

Yue *et al.* (2009b) investigated the use of tuned mass dampers for mitigating ice-induced vibrations in fixed steel jacket structures. Such damping devices were suitable for retrofitting applications, and could be oriented to align with the primary direction of the response to ice loading. Simulations indicated that the tuned mass damper could be a very effective means of reducing vibrations. An alternative approach, which is more suited to incorporation at the design stage, was to use steel rubber isolator bearings placed between the substructure and the topsides. Xu *et al.* (2009) conducted an experimental investigation into the fatigue properties of such isolators in cold conditions. Their experimental data provided some guidelines for design, and a basis for fatigue life assessment.

Ibrahim (2008) provided a comprehensive review of nonlinear passive vibration isolation in relation to the protection of structures from severe earthquake ground motion, shocks, and impact loads.

Countermeasures for slender structures can be found in Section 3.1.2.

3.7 Monitoring

The development and employment of new monitoring technologies has progressed steadily. Initially, a review is presented for its applications in large offshore structures; i.e., fixed and floating platforms for exploration and production purposes. Secondly, slender structures such as risers, umbilicals, pipelines, and mooring lines are addressed.

3.7.1 Monitoring of Large Offshore Structures

Structural monitoring can aid in assessing offshore platform structural integrity. There are two main categories of such monitoring: (i) online and (ii) offline procedures. Examples of both types of monitoring systems are considered here.

In Rijken and Leverette (2009), full-scale measurements of Vortex-Induced Motion (VIM) of a deep draft semisubmersible with four square columns were presented. A comparison between the field observations and design guidance was also provided.

Black (2009) discussed structural vibration monitoring as an aid in assessing offshore platform structural integrity. If the platform's natural period increases over time then, in the absence of a change in mass, that can indicate a loss of structural integrity. Zhang *et al.* (2009) and Zhang *et al.* (2010) described full-scale measurement for many years of platforms in Bohai Bay that were subject to ice loading. For the same area, Xu and Yue (2010) addressed the dynamic ice forces that occurred during ice and platform

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interaction. By application of ice load measurement panels and video cameras, the forces which act on a narrow cone were analyzed.

Matos *et al.* (2010) described a comparative study between full-scale measurements and theoretical predictions for the second-order pitch and roll low-frequency motions of the semi-submersible platform *P-52*. These observations were seen to contribute with important feedback to future designs.

In Peters and Adegeest (2010), online monitoring during transports of large heavy cargo, i.e., jack-up rigs or semi-submersibles, was described. This provided a valuable tool to ensure a safe and economical voyage.

3.7.2 Monitoring of Offshore Slender Structures

In-situ monitoring provides critical information during operational and extreme conditions for SCRs, flowlines, flexible pipes, umbilical cables, and mooring lines. Usually, data processing encompasses remote (standalone), hardwired, and acoustic methods. These systems can be crucial for the structural integrity management of the riser system and provide feedback information useful for establishing recommendations for new designs. They also give important phenomenological insight into the complex hydroelastic-soil-riser interaction behaviour. More often, integrity monitoring strategy has been included as selection criteria for riser systems.

Maheshwari *et al.* (2008) reviewed existing programs and level of success for riser integrity monitoring systems and discussed the pros and cons of hardwired, stand-alone, and acoustic techniques. Job and Hawkins (2008) presented a monitoring program developed to assess the vibration and marine currents in freespan flowlines in the Gulf of Thailand. Lanan *et al.* (2008) described the Oooguruk offshore arctic flowline monitoring system. El Hares *et al.* (2011) presented an integrated pipeline integrity monitoring system. Watson *et al.* (2011) reviewed requirements for monitoring pipelines susceptible to lateral buckling and walking. Elshafey *et al.* (2011) developed an online monitoring system based on longitudinal strain measurements. Taby *et al.* (2011) discussed the employment of an on-board monitoring system capable of visualizing online the pipe static configuration during lay operations. Karayaka *et al.* (2009), Edwards *et al.* (2011), and Enuganti *et al.* (2011) presented monitoring systems employed in steel catenary risers. Legras and Saint-Marcoux (2011) described the requirements of an integrity management program for hybrid riser towers.

As far as slender structures are concerned, most of the recent developments on monitoring have been dedicated to fatigue in flexible pipes. Fibre optic sensing was the dominant technique, but the industry is seeking other solutions such as acoustics and magnetic fields.

Rabelo *et al.* (2009) presented a monitoring program to assess the annulus condition of Petrobras Marlin Sul flexible risers. Sas *et al.* (2008) described the West Africa deepwater Agbami production flexible riser system. Weppenaar and Kristiansen (2008) described existing and potential applications for fiber optic monitoring of flexible pipes, such as temperature along the pipe and strain monitoring at discrete points, as well as calculation of remaining pipe lifetime.

Real-time monitoring may also become a valuable tool for failure detection and predictive maintenance. Cour *et al.* (2008) showed how to manage the risk of fatigue failure in flexible risers with a condition monitoring technique using optical fiber technology. Soares *et al.* (2009) described an acoustic testing technique for detection of flexible pipe tensile armour wire rupture. Weppenaar *et al.* (2009) presented a real-time system for

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fiber optic gas chemical monitoring inside the annulus of flexible risers, based on the novel Quartz-Enhanced Photoacoustic Spectroscopy (QEPAS) technology. For sour service conditions, precise corrosion fatigue may be calculated combining the input from the gas monitoring system with data from strain and temperature monitoring.

McCarthy and Buttle (2009) showed an ongoing project for real-time magnetic inspection technique for flexible risers. It was non-invasive, and may be able to detect the load and broken wires as well. Corrignan *et al.* (2009) presented a joint program carried out by Technip and Schlumberger Subsea Surveillance to develop a new monitoring technology for detection of failure or conditions leading to failure of tensile armour wires in flexible pipes. The system was based on a clamped composite structure with embedded optical fibers. Morikawa *et al.* (2010) described Petrobras' ongoing inspection and monitoring programs based on acoustic emission, measurement of residual magnetic field, optical sensing, and visual monitoring with cameras. The tests conducted with optical fiber sensors provided the best results. Roques *et al.* (2010) described the measurement principle and hardware of a new system developed by TOTAL and Schlumberger to assess the flexible pipe annulus condition. Field test results for various risers in a West Africa field were shown. Dahl *et al.* (2011) discussed recently developed monitoring technology that employed embedded optical fibers for integrity management of flexible risers during their service lives. O'Brien *et al.* (2011) presented the results of the SureFlex JIP. Documents on the *State-of-the-Art of Flexible Pipe Integrity* and a *Guidance Note on Flexible Pipe Integrity Assurance* are publicly available. The paper compiled an extensive survey that included operational use worldwide, along with damage and failure incidences.

3.8 Uncertainties

Uncertainties exist in system models and system parameters. In areas involving complex physical phenomena (e.g., vortex-induced vibrations), there is a continuing need to develop improved models and work towards better comparisons with full-scale measurements. There are important areas of practical application, however, involving satisfactory system models, where an assessment of uncertainties in system parameters (e.g., mass, stiffness, and damping) could play an important role in determining the effectiveness of an engineering design. An interesting example is the optimisation of a system employing tuned mass dampers, where the uncertainty in system parameters can undermine the confidence in the ability to tune the system at the design stage. Taflanadis *et al.* (2009) incorporated uncertainty in system parameters in their investigation into the possible use of mass dampers in tension leg platforms (see Section 3.6). The subject area is often referred to as uncertainty in structural dynamics, and is a field of growing interest; i.e., Mace *et al.* (2011). Practical application of the emerging methods within the dynamic analysis of offshore structures, however, appears to be rather limited at present.

3.9 Standards and Acceptance Criteria for Ice-Induced Vibrations

Since ice-induced vibration has been found in offshore structures lately, many studies have been performed. The experiences and findings, however, have been complied into recognized design codes. The following codes provide guidelines and criteria for assessing the dynamic ice action effects in design.

- API RP 2N (1995) only provides a brief statement in Section 5.4.16.
- IEC 61400-3 (2009) provides an informative annex on ice action and effects for offshore wind turbine support structures. It noted that the offshore wind turbine

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support structure usually is a compliant structure, and it paid attention to the dynamic ice loading (see Annex E.4.6, *Dynamic Loading*). It required that the wind turbine should be checked for dynamic effects from ice loading. Further, if statistical data or measurements are not available, IEC 61400-3 suggests simplified equations for dynamic load simulation. IEC 61400-3 notes the resonant dynamic ice action scenarios, and provides a criterion for tuning. As for shock impact of ice floe, IEC 61400-3 requires it to be checked with a transient load approach and suggests a load function in a piecewise form.

- DNV OS J101 (2010) also provides guidelines on the dynamic ice loading on vertical and conical structures for offshore wind turbines, but it does not mention the shock impact loading due to ice floe (see Section 4, *Loads and Load Effects*, E 500). For vertical structures, DNV OS J101 highlights a frequency lock-in phenomenon that implied that the structure becomes excited by vibrations in its natural mode shapes. The structure should be designed to withstand the loads and load effects from dynamic ice loading associated with lock-in when tuning occurs.
- ISO 19906 (2010) provides comprehensive discussions on dynamic ice action and the effect for offshore installations, covering dynamic actions on vertical structures, dynamic actions on conical structures and fatigue accumulation due to ice actions (details see ISO 19906, Annex A, A 8.2.6).

Olav Olsen a.s., KARNA Research and Consulting, and Technical University Delft (TUDelft) has initiated a joint industry project (JIP) called "Ice-Induced Vibrations," whose objective is to establish an engineering approach to assessing ice-induced vibrations for a wide range of structures and ice conditions. The JIP aims to consider not only the typical analyses of the susceptibility to frequency lock-in, but also determination of the dynamic response to various kinds of dynamic ice actions. The project has paid much attention to the frequency lock-in and aimed at new background information for updating ISO 19906. It is focused on the development of an engineering approach to the design of vertically-sided structures against ice-induced vibrations.

4 BENCHMARK STUDY OF SLAMMING AND WHIPPING

Throughout the maritime world, considerable efforts have been spent on predicting loads associated with slamming (i.e., Kapsenberg and Thornhill, 2010, or Tuitman, 2010). Up to now, little attention has, however, been paid to the accuracy of the translation from these loads to the structural responses. The ISSC 2012 Dynamic Response committee, therefore, performed a benchmark study on this topic. The goal of this benchmark was twofold: on the one hand, the degree of variation in estimates produced by different methods and organizations was revealed; on the other hand, the absolute error made in the analyses was investigated by comparison with model test measured responses.

There were six participants: two research organizations (Marin and TNO), two class societies (GL and Indian Register of Shipping), one university (Norwegian Technical University), and a consulting company (The Glosten Associates). The benchmark was blind and consisted of three different stages. Not all participants delivered results for each stage. The tasks for each stage, as well as the results, were discussed in the subsequent sections. Participants were free in choosing methods for obtaining the results. The method they used was also described in the subsequent sections.

In order to investigate the absolute error, use was made of results from tests performed at Marin with a flexible segmented backbone model (i.e., Drummen, 2008)

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Figure 2: Model of a 173 m long ferry, courtesy of CRS

of a 173 m long ferry (see Figure 2). The data was provided by Cooperative Research Ships (CRS). In CRS, Marin brought together a group of companies with a common interest in non-competitive research. The aluminium circular backbone was instrumented with strain gauges to measure, amongst others, the vertical bending moment between the different sections. The bow was built as a separate segment and connected to the forward hull segment through a six-component force transducer. This bow segment was instrumented with 23 pressure gauges to measure the detailed pressure distribution and six accelerometers to measure the local vibrations. Of the pressure gauges, five were located on the centre line of the ship, 17 on the starboard (windward) side, and one on the port (leeward) side. Ten accelerometers were fitted inside the model, one laterally and one vertical accelerometer in the centre of each segment.

4.1 Modal Parameters

For the first stage of the benchmark, participants were asked to determine the shapes and frequencies of the two and three node, dry and wet, and horizontal and vertical flexural vibration modes. At this stage, participants were provided with details of the geometry of the model, including electronic hull description, locations of cuts, dimensions of the backbone, and mass distribution.

In order to determine the shapes and the frequencies of the dry modes, Participant A used a model consisting of a backbone, modeled with beam element and links to connect the inertia of the various segments, located at their center of gravity, to the backbone. For the purpose of calculating the wet shapes and frequencies, the structural modes were mapped onto the hydrodynamic mesh, and the 3D panel method Hydrostar was used to compute the hydrodynamic coefficients according to the method described in Tuitman (2010). Participant B used a very similar structural model. For determining the wet modes, the infinite frequency added mass was determined with a 3D panel method. This mass was subsequently added to the different sections of the structural mass, effectively diagonalizing the mass matrix. Both Participants A and B determined the dry and wet modal parameters from eigenvalue analysis. The former used MSC.MARC for the dry modes, and HEFREQ (Tuitman, 2010) for the wet modes. The wet analysis was based on the mode shapes as obtained from the dry analysis. Participant B used ANSYS for both the dry and the wet cases. Participant C built a 3D finite element model of the physical model. All plating of the model, such as bottom shell, main deck, side shell, transverse bulkheads, and aluminum beam, was modeled using shell elements. Mass elements were used to model lumped mass. The added mass was calculated for 15 sections using an empirical

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method (Mukhopadhyay, 1989). The added mass was applied to the wetted surface of the hull by adjusting the density of material. The modal parameters were obtained by performing eigenvalue analyses in ANSYS. For determining the shapes and the frequencies of the dry modes, eigenvalue analysis was done by Participant D for a 2D finite element model consisting of beam elements according to the Timoshenko approach, assuming planar shear deformation. For the present purpose, displacements in vertical direction and rotations about the horizontal transverse axis were used. The structural mass was assigned as lumped mass to the nodes of the elements. The effect of added mass was included by making an implicit two way coupling (Oberhagemann *et al.*, 2008a,b) between the structural solver and a RANS solver (Brunswig and el Moctar, 2004). In each time step, the solutions on both fluid and structure domain were found iteratively. A free vibration decay test was done for the ship in water at zero forward speed in order to determine the wet natural frequency. Participant E used a beam model in NASTRAN consisting of 25 nodes. Trapezoidal weight distributions were assumed for each of the five hull segments to produce the correct longitudinal centers. Only the aluminum beam was assumed to be effective structurally. Infinite frequency added mass was estimated using Lewis form sections. The mass, as well as the added mass, was lumped to the nodes of the beam model. Modal parameters were obtained from an eigenvalue analysis in NASTRAN. Participant F also built a 3D finite element model. Although it was less detailed then the one used by Participant C, the model consisted of shell elements. The added mass was calculated separately for each of the segments. This calculation was based on the infinite frequency value of the added mass coefficient using Lewis form sections. Subsequently, it is distributed as point masses. Here, the modal parameters were found from an eigenvalue analysis in Abaqus.

The natural frequencies obtained by the participants for the wet and dry mode shapes are shown in Table 1. Here, a comparison is also made with experimental results. These were only available for the vertical modes. The parameters in water were determined by performing hammer tests in still water. For determining the dry parameters, the fully instrumented model was suspended in air in a soft spring system. The precision error (Coleman and Steele, 1989) of the wet modal parameters was reported by MARIN to be very small. The single 95 % confidence interval of the mean value of the natural frequencies was less than 2 %. Due to the spring system, the uncertainties were larger in air, particularly for the three node mode.

Figure 3 presents the shapes of the two and three node wet vertical vibration modes.

Table 1: Natural frequencies of the global flexural vibration modes in *Hz*. Experimental results are given under 'EXP,' with numerical results from the different participants under the respective letters

mode	EXP	A	B	C	D	E	F
vertical dry 2 node	7.1	6.8	7.1	7.6	6.9	6.9	8.2
vertical dry 3 node	17.7	19	19.8	25.8	19.9	19.9	21.3
vertical wet 2 node	5.1	5.1	4.8	4.7	5.1	5.0	5.1
vertical wet 3 node	11.8	12.1	11.6	11.1	-	12.4	11.9
horizontal dry 2 node	-	6.8	6.6	7.4	-	-	-
horizontal dry 3 node	-	19	16.7	24.5	-	-	-
horizontal wet 2 node	-	6.3	6.0	4.5	-	-	-
horizontal wet 3 node	-	16.6	14.8	10.9	-	-	-

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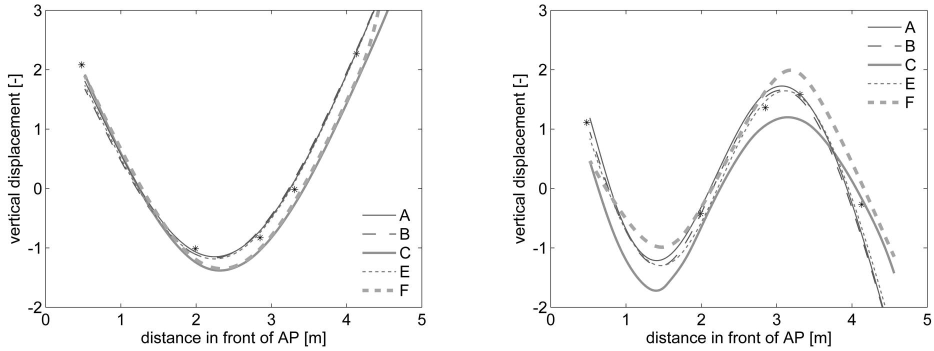

Figure 3: Shapes of the two (left) and three (right) node global vertical wet flexural vibration modes

Table 2: MAC values of mode shapes predicted by the participants compared to those measured on the physical model

mode	A	B	C	D	E	F
vertical dry 2 node	0.96	0.97	0.93	0.98	0.98	-
vertical dry 3 node	0.97	0.97	0.93	0.98	0.98	-
vertical wet 2 node	0.99	0.98	0.95	-	0.99	0.96
vertical wet 3 node	0.94	0.94	0.90	-	0.96	0.95

As can be seen from the figure, results from Participants A, B, and E were well in line with experimental results.

The modal accuracy coefficients (MAC) between the shapes determined experimentally and those determined by the participants are given in Table 2. The MAC is defined by Equation 1 as:

$$MAC = \frac{\left|\Psi_{FE}^{T}\Psi_{EXP}\right|^{2}}{\left(\Psi_{FE}^{T}\Psi_{FE}\right)\left(\Psi_{EXP}^{T}\Psi_{EXP}\right)} \tag{1}$$

where Ψ_{FE} and Ψ_{EXP} respectively denote the finite element mode shape and the one found for the test model. Two mode shapes with a MAC equal to one indicate identical modes, or full correlations. The natural frequencies determined by the participants generally agreed well with the experimental results. An exception was the dry three node mode. Results corresponded well between participants, but not with the experiments. The differences here were significantly larger than for the other modes. It was expected that the difference was related to the experimental setup, as mentioned above. No noticeable uncertainties were observed in the prediction of the added mass by comparing the performance in water and in air.

4.2 Response to Inputs

After delivering the results presented in the previous section, participants were provided with natural frequencies and damping ratios as found for the physical model. Participants were allowed to update their model. The next step in the benchmark was to apply analytical yet realistic pulses to the model. The pulses were provided to the participants as time series of the force to be applied on the model. Participants

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were asked to investigate five durations of the pulse. The investigated durations were evenly distributed between $0.5 \cdot T$ and $1.5 \cdot T$, where T was the natural period of the vibration mode under consideration. The two and three node vertical vibration modes were investigated. Each impulse was $50\,Ns$, and the time series were $60\,s$ long. The force was distributed equally in length over the most forward 10 % of the length of the model. Calculations were done for the model in water. For this stage, no comparison with experimental results was made. For each investigated pulse, participants were asked to calculate a time series of the vertical bending moment amidships.

Participant A did not update their structural model as their predictions of the natural frequencies were within 2.5 % of the experimental values. As mentioned in the previous section, the mode shapes of their structural model were mapped to the 3D hydrodynamic model. With this model, a nonlinear hydroelastic time domain simulation (Tuitman, 2010) was done. Only the first five flexural modes in vertical direction were included. The sway, roll and yaw modes were suppressed. The damping ratios for the two and three node vertical modes were set to 0.8 % and 0.7 %, respectively. The damping of the other flexural modes was set to approximately 2 %. No additional damping was added to the rigid body modes. In order to tune the natural frequencies of their model to the experimental values, Participant B adjusted the stiffness of the model. Due to this change, the natural frequencies of the wet vertical two and three node vibration modes became $5.1\,Hz$ and $12.4\,Hz$, respectively. The shapes of these modes were used together with the heave and pitch modes in a modal superposition method. Four modes were thus used to obtain the results. No damping was applied to the heave and pitch modes. The damping ratios for the two and three node vertical modes were set to 0.8 % and 0.7 %, respectively. The pulse was directly placed on the different modes in a transient dynamic analysis in ANSYS. In this way, the vertical bending moments were obtained.

Participant C changed the added mass of their model in order to tune the natural frequencies to those of the physical model. The revised model had natural frequencies of the wet vertical two and three node vibration modes equal to $5.1\,Hz$ and $11.8\,Hz$, respectively. The response was computed using Participant C's 3D wet finite element model in, again, a transient dynamic analysis with ANSYS. All the modes of rigid body motion were kept free. Distributed spring boundary conditions were applied to represent the hydrostatic stiffness. The damping ratios for the two and three node vertical modes were set to 0.8 % and 0.7 %, respectively. No damping was applied to the rigid body modes.

Participant F updated the model by adjustment of the mass distribution. The revised natural frequencies of the wet vertical two and three node vibration modes were $5.1\,Hz$ and $11.8\,Hz$, respectively. The corresponding damping ratios were 0.8 % (two node vertical mode) and 0.7 % (three node vertical mode). No damping was applied to the rigid body modes of the vessel. To obtain the vertical bending moments, an implicit dynamic analysis was done in Abaqus. The full finite element model was applied with the pulse loading distributed to the nodes along the centerline at the foremost section, which comprises 10 % of the length of the vessel.

The fatigue loading was calculated by the benchmark organizer using the Miner–Palmgren linear cumulative damage rule implemented in the form of Equation 2:

$$D = \sum_{i}^{n} \Delta VBM_i^m \tag{2}$$

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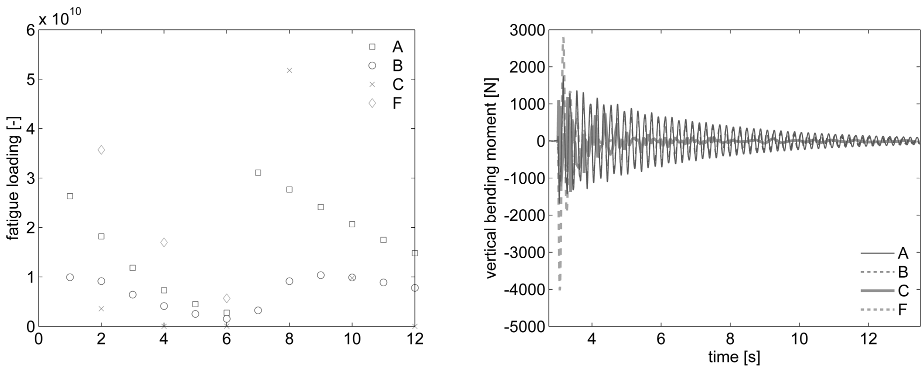

Figure 4: Fatigue loading per pulse (left) and example of time series of vertical bending moment (right). The example on the right is given for a pulse with a duration of half of the natural period of the two-node vibration mode.

where D is the accumulated fatigue loading and m is the slope parameter of the SN-curve, n is the total number of stress ranges, and ΔVBM_i is the vertical bending moment range. The slope parameter m was assigned a value of three. The bending moment ranges were determined using rainflow counting (Rychlik, 1987). The results are presented in the left plot of Figure 4. The numbers on the horizontal axis represent the type of pulse. Numbers 1 through 6 correspond to pulse durations of 0.25, 0.50, 0.75 1.00, 1.25 and 1.50 times the two node vibration period, respectively. Numbers 7 through 12 correspond to pulse durations defined by the three node mode vibration period and the same multipliers.

From the figure it can be seen that there was a considerable difference in results. Differences of up to a factor of five were seen. To investigate this difference, a typical time series of the obtained vertical bending moments is shown in the right plot of Figure 4. The figure shows that results from Participant A and B were well in line. One reason for a difference between the two could be the fact that Participant A used more flexural modes than Participant B. The available energy was then distributed over more modes, where the higher modes damp much more rapidly than the lower modes. The damping in the model of Participant F can be seen to be much higher than that of the other participants. The initial response is also significantly higher.

4.3 Response to Regular Head Waves

The third stage of the benchmark focused on a whipping analysis excited by a regular head wave with a wave height of about $5.7\,m$ and a period of $11\,s$. The model had a full scale speed of $25\,kn$. The measured wave was provided to the participants who were then asked to predict the impulsive vertical force on a defined bow area in a first step (Stage 3.1a). The measured and calculated force time histories are shown in Figure 5.

The computation of the slamming loads of Participant A was performed using twenty 2D slamming sections and a boundary element method.

Participant C applied two different approaches. Method C-1 was a hybrid approach for slamming load computation where initially vessel motions were computed using a Rankine panel method (SWAN). These motions were imposed on a model in a Reynold's Average Navier Stokes Solver (ANSYS CFX), calculating the impulsive

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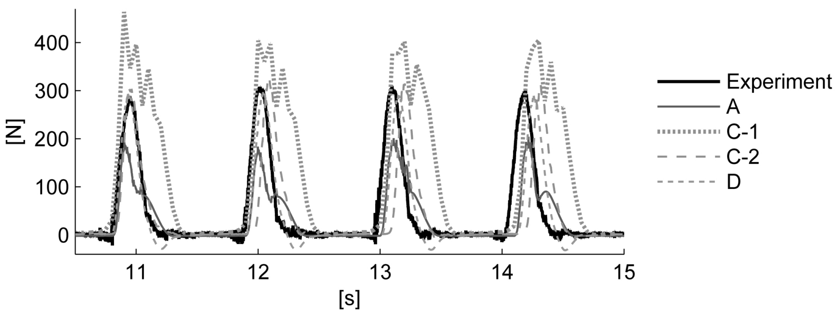

Figure 5: Measured and calculated vertical force time histories at bow area with measured wave only provided to participants

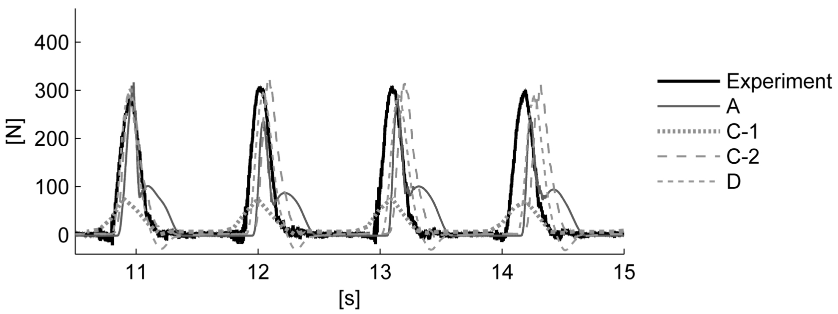

Figure 6: Measured and calculated vertical force time histories at bow area with measured wave and motions provided to participants

pressure. For Method C-2, also the motions were calculated using a RANS solver (StarCCM).

As described above, Participant D applied a fully coupled fluid-structure interaction computation based on a RANS solver (Comet) for fluid dynamics and a Timoshenko beam for structural representation.

Good agreement in amplitude and impulse shape between measured and calculated vertical force was achieved by Participants/Methods C-2 and D. To achieve better agreement, also for the two other methods, the measured motions were provided in a second step (stage 3.1b). The recalculated results are shown in Figure 6.

The agreement of the amplitude between calculation and measurement was improved by Participant A after considering the measured motions. The impulse shape still shows a second less sharp peak per wave period following the primary impulse. No improvement was achieved for Method C-1. Table 3 shows the comparison of the impulses emphasising the good agreement for method A, C-2 and D.

In a next step, the measured pressures and the impulsive force was provided to the participants. They were then asked to predict the vertical bending moment amidships. The comparison is done for the overall vertical bending moment neglecting the still

Table 3: Impulse in [Ns]

Experiment	A	C-1	C-2	D
50,8	49,7	20,8	50,3	45,6

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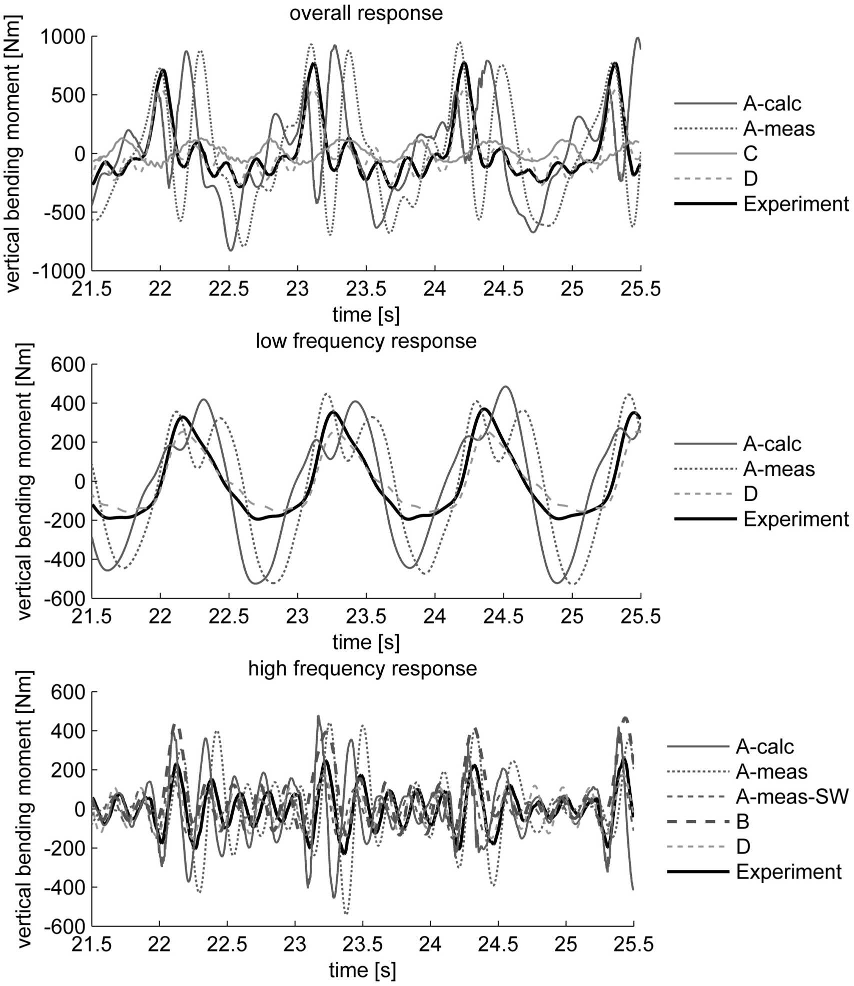

Figure 7: Measured and calculated bending moments amidships

water moment, the low frequency component representing the wave bending moment and the high frequency component representing the dynamic amplification caused by the hull girder vibration (Figure 7).

The curves A-calc and D were the bending moments directly taken from the participants' computation of Stage 3.1b. The agreement between the experiment and Participant D was good. Participant A furthermore included the measured impulse in his computation. Curve Ameas was achieved by applying the impulsive force in waves while the bending moment for curve A-meas-SW was calculated in still water. The responses for A-calc and A-meas were suffering from the second impulse following the primary impulse as shown in Figure 5. The agreement for method A-meas-SW with the experiment was good as well. Participants B and C did not include the regular wave in their computations, but applied a sequence of the measured force time history on their model. The high frequency amplitude was overestimated by Participant B. Because of the poor agreement and for better illustration, the results of Participant C were shown for the overall response only. Whereas the computation of Participant

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B took only about 3 hours, the analysis computation times for participant C and D's were more than one day.

4.4 Conclusions from Benchmark Study

From the results presented for the present benchmark, it may be concluded that the shapes and frequencies of the two and three node, dry and wet and horizontal and vertical flexural vibration modes determined by the participants, were well in line with experimental results for four of the six participants. When participants applied different realistic but analytical pulses to their model, significant differences up to a factor of five were found. On time series level, two of the four participants had results that correlated well. No experimental results were available here.

Also, the computations considering an impulse induced by a regular head wave showed significant differences between the experiment, the different participants, and applied methods. It can be concluded from the benchmark results that the more sophisticated the applied method in terms of degree of coupling and computation time, the better the agreement with the experiment.

5 CONCLUSIONS

The technical literature over the past three years has revealed that springing and whipping contribute significantly to fatigue damage of ships. Furthermore, the combination of whipping and primary nonlinear wave bending moment was found in several investigations to exceed IACS rule values. The literature also demonstrated that hull vibratory responses to waves may be important in modes other than vertical bending, specifically torsion and lateral bending. It is recommended that wave-induced vibrations be considered during the design phase.

Seamanship, both through weather routing avoidance and as applied through voluntary speed reduction, involuntary speed reduction, and heading changes, is revealed in the literature to be an important factor acting to mitigate wave-induced vibrations, particularly whipping. Therefore, lifetime exposure analyses that do not account for these seamanship effects are likely to overestimate both extreme loads and fatigue damage accumulation.

Most of the fatigue assessments in the technical literature considers only the increase in the number of cycles due to ship vibration and does not investigate the effect on fatigue crack propagation. It is recommended that future research be extended to include appropriate perspectives from fracture mechanics.

Some of the technical literature in the current period reports that extreme combined loading (nonlinear wave bending plus whipping) is, for some ships, higher in bow-quartering seas than in head seas.

Some of the researchers in the current period recommend investigation of damping based on full-scale measurements.

The 'blind' benchmark study carried out by the committee revealed both cause for encouragement and caution. Many, but not all, of the participants and methods were able to achieve reasonable correlation with the model test experiment data. Differences of up to a factor of five, however, were obtained between some predictions and corresponding experimental data. Damping assumptions were revealed to be quite important and appeared to account for much of the difference detected in fatigue loading. The benchmark study demonstrated the need for each practitioner to verify and validate their own practice, even if using industry standard tools. It is recommended that class societies and JIPs encourage validation practice by making 'truth' data available.

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It was observed in this benchmark study that the more sophisticated the applied method, the better the agreement with experiment; however, this agreement comes at a cost of increased computation time.

In both ship and offshore investigations, the literature reveals a trend towards increasing application of RANS methods and tight coupling with structural dynamics models.

Wavelet analysis methods are increasingly used to isolate transient whipping events.

The tank wall boundary condition has been revealed to have a potentially significant effect on the loads and responses measured in backbone model experiments. CFD has been demonstrated to be capable of efficiently evaluating this effect.

The first research steps have been undertake to develop a general procedure capable of correcting segmented model data for the load segmentation and the reduction in structural complexity when compared to real ships.

An efficient design loads generator has been developed that uses the acceptance-rejection method to generate an ensemble of phase sets that reproduce an *a priori* specified extreme value distribution. It has been demonstrated that this can be used to approximate the lifetime exposure for combined nonlinear wave bending and whipping.

Ratification of ILO MLC 2006 is expected soon, to be followed by national laws implementing its provisions. The convention specifies requirements to prevent exposure to hazardous levels of noise and vibration. IMO Resolution A.468 (XII) 1982 is commonly understood to establish a compliance level for noise. ILO MLC 2006 does not in itself define limit values for vibration exposure. Such limits will, presumably, be established by the national legislation implementing ILO MLC 2006. To ensure clarity and avoid interpretations of the convention's compliance, the Committee encourages concretisation of acceptance criteria for vibration.

The case of a LNG tank excited by a pressure wave from an underwater explosion has been considered. Due to the large free surface area, it was determined that a number of internal and external sloshing frequencies are excited.

When modelling machinery-induced noise and vibration, it is demonstrated that in some cases it may be possible to exclude the deck and hull plating with negligible loss of fidelity. This same study determined that non-uniform transverse frame spacing could be effective in reducing the transmission of noise and vibration.

Internal flow induced vibrations have been reported on flexible and rigid pipelines and risers, and may cause fatigue and severe damage to the pipes themselves or to the supporting structure's integrity. Internal flow is capable of inducing singing and behaviours described as whipping. Some current technical literature reports coupling between internal fluid flow and VIV induced by the external current flow.

Current induced vibrations in the form of VIV and galloping produce hydrokinetic energy. There are on-going efforts to achieve practical conversion into useful electrical energy.

There continues to be research interest into ringing in TLP tethers.

There is renewed interest in ice-induced vibrations. This report summarizes both recent research, and the standards and acceptance criteria for ice-induced vibrations.

Airborne and underwater radiated noises are both of increasing concern. Underwater-radiated noise has a potential adverse impact on marine mammals, and can also interfere with acoustic operations of the offshore oil and gas industry.

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A broad array of inspection and monitoring programs are now applied offshore, based variously on acoustic emission, measurement of residual magnetic field, optical sensing, and visual monitoring with cameras. Fiber optic technologies are showing increased application and success.

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18th INTERNATIONAL SHIP AND
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VOLUME 1

COMMITTEE III.1

ULTIMATE STRENGTH

COMMITTEE MANDATE

Concern for the ductile behaviour of ships and offshore structures and their structural components under ultimate conditions. Attention shall be given to the influence of fabrication imperfections and in-service damage and degradation on reserve strength. Uncertainties in strength models for design shall be highlighted.

COMMITTEE MEMBERS

Chairman: Jeom K. Paik
Hadi Amlashi
Bart Boon
Kim Branner
Piero Caridis
Purnendu Das
Masahiko Fujikubo
Chien-Hua Huang
Lennart Josefson
Patrick Kaeding
Chang-Wook Kim
Guy Parmentier
Ilson P. Pasqualino
Cesare M. Rizzo
Suhas Vhanmane
Xiaozhi Wang
Ping Yang

KEYWORDS

Ultimate strength; ultimate limit states; ultimate limit state design; buckling collapse; load-carrying capacity; fabrication-induced initial imperfections; in-service damage and degradation; reserve strength; uncertainties; strength model.

18th International Ship and Offshore Structures Congress (ISSC 2012) - W. Fricke, R. Bronsart (Eds.)

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CONTENTS

18th International Ship and Offshore Structures Congress (ISSC 2012) - W. Fricke, R. Bronsart (Eds.)

18th International Ship and Offshore Structures Congress (ISSC 2012) - W. Fricke, R. Bronsart (Eds.)
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1 INTRODUCTION

The basic strength members in ships and offshore structures include support members (e.g., stiffeners, plate girders), plates, and stiffened panels. During their lifetime, the structures that are constructed using these members are likely subjected to various types of loading or deformation that is for the most part operational but may, in some cases, be extreme or even accidental. The sources of such loading and deformation include fabrication-related initial imperfections (e.g., initial distortions, welding residual stress, softening in the heat-affected zone of welded aluminium structures); abnormal waves/winds/currents; dynamic pressure loads arising from sloshing, slamming or green water; low temperature in Arctic operations; cryogenic conditions resulting from liquefied natural gas cargo; ultra-high pressure in ultra-deep waters; elevated temperature due to fire; blast loads due to explosion; impact loads associated with collision, grounding or dropped objects; and age-related degradation such as corrosion, fatigue cracking and local denting damage.

Figure 1 illustrates the various types of phenomena that may occur in ships and offshore structures while they are in service (Paik, 2011). Each of these phenomena occurs in different scenarios with different mechanisms, but it is interesting to mention that all of them commonly give rise to nonlinear structural consequences that involve both geometric and material nonlinearities. For the robust design of ships and offshore structures, therefore, it is essential to accurately and efficiently identify the nonlinear structural consequences associated with such phenomena.

In the past, criteria and procedures for the structural design of ships and offshore platforms were primarily based on allowable stresses and simplified buckling checks for structural components. However, it is now well recognised that ultimate limit state-based approaches are much better methodologies for structural design and strength

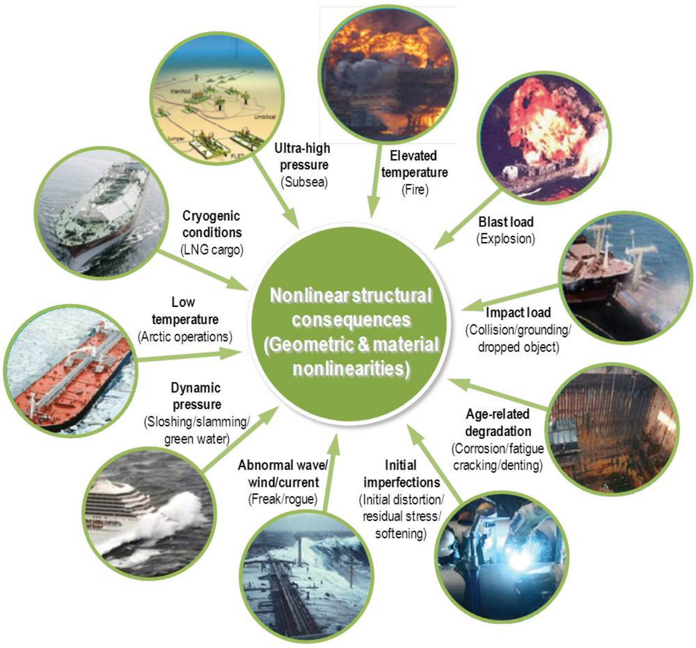

Figure 1: Various types of phenomena causing nonlinear structural consequences in ships and offshore structures (Paik, 2011)

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assessment than the traditional working stress-based approaches, as the latter are typically formulated as a fraction of material such as yield strength. This situation exists because it is difficult to determine the true margin of structural safety using linear elastic methods alone when the remaining ultimate limit states are unknown. It follows that determining the true ultimate limit state is of crucial importance to obtain consistent measures of safety that can form a fairer basis for comparisons of structures of different sizes, types, and characteristics. The ability to correctly assess the true margin of safety would also inevitably lead to improvements in related regulations and design requirements (Paik and Thayamballi, 2003).

To obtain a safe and economic structure, ultimate limit state-based capacity and structural behaviour under known loads must be accurately assessed. The structural designer can perform a relatively refined structural safety assessment even in the preliminary design stages if there are simple expressions available for accurately predicting the ultimate limit state behaviour. A designer may even desire to do this not only for the intact structure, but also for structures with premised or accidental damage as a way of anticipating their damage tolerance and survivability.

This report presents advances and possible future trends in ultimate strength computation methods for ship and offshore structural components and their system structures. Papers published since the ISSC 2009 Congress are mainly discussed here, but older publications are also included if they are considered to present fundamental and important findings in line with the mandate of the present Committee.

2 FUNDAMENTALS FOR ULTIMATE LIMIT STATE-BASED DESIGN AND SAFETY ASSESSMENT

2.1 Types of Limit States

A limit state is defined as the condition beyond which a structural member or entire structure fails to perform its designated function. Four types of limit states are relevant here (Paik and Thayamballi, 2003; ISO, 2007), namely

- Ultimate limit state (ULS)
- Serviceability limit state (SLS)
- Fatigue limit state (FLS)
- Accidental limit state (ALS)

ULS is the collapse of a structure due to a loss of structural capacity in terms of stiffness and strength that typically arises from the buckling and plastic collapse of structural components. SLS represents failure in normal operations due to a deterioration in routine functionality. Typical examples of SLS include local damage, unacceptable deformation, and excessive vibration and noise that affect the proper functioning of structural elements or equipment. FLS is the fatigue cracking of structural details as the result of stress concentration and damage accumulation under repeated loading actions. ALS is the excessive structural damage that results from accidents such as collisions, grounding, explosions, and fire – all of which affect the safety of the structure, the environment, and the personnel. This report discusses ULSs.

2.2 Factors Affecting Nonlinear Structural Consequences

Nonlinear structural consequences involving ultimate limit states can be represented as a function of various factors, namely

$$\text{Nonlinear structural consequences} = f(a,b,c,d,e,f,g,h) \tag{1}$$

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where,

a = geometrical factors associated with buckling, large deflection, crushing, or folding,

b = material factors associated with yielding/plasticity, ductile/brittle fracture, rupture, or cracking damage,

c = fabrication-related initial imperfections such as initial distortion, residual stress, and softening,

d = load types/components (quasi-static),

e = dynamic factors (strain rate sensitivity, inertia effect) associated with freak/rogue/abnormal waves and the impact pressure actions that arise from sloshing, slamming, or green water; overpressure actions arising from explosions; and impacts due to collisions, grounding, or dropped objects,

f = temperature factors such as low temperatures associated with cold water operation and/or low-temperature cargo and high temperatures due to fire and explosions,

g = age-related deterioration such as corrosion and fatigue cracking, and

h = human factors related to unusual operations in terms of ship speed (relative to the maximum permitted speed or acceleration), ship heading, and loading conditions.

2.3 Ultimate Limit State Criterion

The design condition of a structure can be expressed as follows (Paik and Thayamballi, 2003).

$$G = C_d - D_d \geq 0 \tag{2}$$

where G = a performance function, C_d = the design value of capacity (strength), and D_d = the design value of demand (load).

In ULS-based design and safety assessment, capacity is the ultimate strength and demand represents extreme actions or action effects such as those in the most unfavourable conditions to which the structure may be subjected. In accidental condition, capacity represents the residual ultimate strength of structures with damages caused by the corresponding accident.

2.4 Format Types for Structural Design and Safety Assessment

Two types of format for design or safety assessment are usually applied to ensure that a structure has an adequate degree of safety and reliability against ULSs (Paik and Thayamballi, 2003), namely

- Partial safety factor format
- Probabilistic format

The partial safety factor format considers the effects of uncertainties in the following form.

$$C_d = C_k/\gamma_C,\, D_d = \gamma_D D_k \tag{3}$$

where C_k and D_k = the characteristic values of capacity and demand, respectively, and γ_C and γ_D = the partial safety factors associated with the uncertainties of capacity and demand, respectively.

Substituting equation (3) into equation (2) yields

$$G = \frac{C_k}{\gamma_C} - \gamma_D D_k \geq 0 \tag{4}$$

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The measure of structural adequacy is determined as follows.

$$\eta = \frac{C_d}{D_d} = \frac{1}{\gamma_C \gamma_D} \frac{C_k}{D_k} \tag{5}$$

where η is a measure of structural adequacy. To ensure safety, η must be greater than 1. This report focuses on defining C_k for ship and offshore structures including plates, stiffened panels, and hull girders.

The probabilistic format, in contrast, is more rigorous when considering the effects of uncertainties. The performance function of equation (2) can be rewritten as a function of the basic variables, $x_1, x_2, \ldots, x_i, \ldots, x_n$, as follows (Paik and Thayamballi, 2007).

$$G\left(x_1, x_2, \ldots, x_i, \ldots, x_n\right) = 0 \tag{6}$$

When $G > 0$, the structure is in the desired state. When $G \leq 0$, it is in an undesired state. Based on the first-order approximation, equation (6) can be written using the Taylor series expansion as follows.

$$G \cong G\left(\mu_{x1}, \mu_{x2}, \ldots, \mu_{xi}, \ldots, \mu_{xn}\right) + \sum_{i=1}^{n} \left(\frac{\partial G}{\partial x_i}\right)_{\bar{x}} \left(x_i - \mu_{xi}\right) \tag{7}$$

where μ_{xi} = the mean value of variable x_i; $\bar{x}$ = the mean values of the basic variables $(\mu_{x1}, \mu_{x2}, \ldots, \mu_{xi}, \ldots, \mu_{xn})$; and $(\partial G / \partial x_i)_{\bar{x}}$ = the partial differentiation of G with respect to x_i at $x_i = \mu_{xi}$.

The mean value of function G is then given by

$$\mu_G = G\left(\mu_{x1}, \mu_{x2}, \ldots, \mu_{xi}, \ldots, \mu_{xn}\right) \tag{8}$$

where μ_G = the mean value of function G.

The standard deviation of function G is calculated by

$$\sigma_G = \left[\sum_{i=1}^{n} \left(\frac{\partial G}{\partial x_i}\right)_{\bar{x}}^2 \sigma_{xi}^2 + 2 \sum_{i>j} \left(\frac{\partial G}{\partial x_i}\right)_{\bar{x}} \left(\frac{\partial G}{\partial x_j}\right)_{\bar{x}} \operatorname{covar}\left(x_i, x_j\right)\right]^{1/2} \tag{9}$$

where σ_G = the standard deviation of G; σ_{x_i} = the standard deviation of variable x_i; $\operatorname{covar}(x_i, x_j) = E\left[(x_i - \mu_{xi})(x_j - \mu_{xj})\right]$ = the co-variation of x_i and x_j; and $E[\ ]$ = the mean value of [ ].

When the basic variables, $x_1, x_2, \ldots, x_i, \ldots, x_n$, can be considered independent of one another, $\operatorname{covar}(x_i, x_j) = 0$. In this case, equation (9) can then be simplified to

$$\sigma_G = \left[\sum_{i=1}^{n} \left(\frac{\partial G}{\partial x_i}\right)_{\bar{x}}^2 \sigma_{xi}^2\right]^{1/2} \tag{10}$$

The so-called reliability index for this case can be defined using the first-order second-moment method (FOSM), as follows.

$$\beta = \frac{\mu_G}{\sigma_G} \tag{11}$$

where β = the reliability index. To ensure safety, the reliability index must be greater than the target reliability index.

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For a function, G, of two parameters, C_d and D_d that are considered to be statistically independent, with mean μ_G and standard deviation σ_G, the reliability index, β, can be obtained as follows.

$$\beta = \frac{\mu_C - \mu_D}{\sqrt{\sigma_C^2 + \sigma_D^2}} \tag{12}$$

where μ_C and μ_D = the mean values of C_d and D_d, respectively, and σ_C and σ_D = the standard deviations of C_d and D_d, respectively.

In this regard, it is clear that the primary tasks that need to be accomplished by the structural design criterion of Equation (2) are how to determine C_k, D_k, γ_C, and γ_D for the partial safety factor design format, and μ_C, μ_D, σ_C, and σ_D for the probabilistic design format. The present Committee is concerned with the determination of these values in conjunction with the ultimate limit state design.

3 RULES AND GUIDELINES

3.1 International Association of Classification Societies (IACS)

The criteria for buckling and ultimate strength can be found in Section 10 of the IACS Common Structural Rules (CSR) for Double Hull Oil Tankers (2010a), which apply to double hull oil tankers of 150 m length and upward. These criteria are applied to local supporting members, primary support members, and other structures such as pillars, corrugated bulkheads, and brackets.

The characteristic buckling strength is to be taken as the most unfavourable/critical buckling mode for each structural element. Some of the different buckling modes considered include the uniaxial and biaxial buckling of plate, the column buckling of stiffeners, the torsional buckling of stiffeners, and the buckling of the web plate of primary support members.

These prescriptive buckling requirements augment various baseline assumptions and limitations. Namely, the structural elements are expected to comply with certain stiffness and proportion requirements specified in the rules, which include plate panel proportions, local support members, web and flange plates, pillars and brackets, stiffness of stiffeners, and the spacing between flange supports or tripping brackets. For corrugated bulkheads, local flange/web buckling, unit corrugation buckling, and overall buckling failure mode under axial compression and lateral pressure are to be checked.

To assess the buckling of plates and stiffened panels subject to combined stress fields, the advanced buckling assessment method is to be followed because it considers effects such as nonlinear geometrical behaviour, inelastic material, initial imperfections, welding residual stresses, interactions between structural elements, simultaneous acting loads, and boundary conditions. A more detailed description of this methodology can be found in Appendix D of the CSR for Double Hull Oil Tankers.

The buckling and ultimate strength checks for bulk carriers is detailed in Section 3, Chapter 6 of the CSR for Bulk Carriers (2010b), which applies to the hull structures of single-side skin and double-side skin bulk carriers with a length $L \geq 90\,m$. The structural elements are verified at the elementary plate panel level and the partial and total panel levels (lateral buckling mode and torsional buckling mode). Corrugated watertight bulkheads are to be checked against shear buckling in flooded conditions.

Harmonized CSR for both tankers and bulk carriers are under development, and the first draft is scheduled for review about 1st July 2012.

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3.2 Classification Societies

3.2.1 American Bureau of Shipping (ABS)

In addition to the IACS Common Structural Rules for Double Hull Oil Tankers (ABS, 2010a) and Bulk Carriers (2010b), the ABS published Rules for Building and Classing Steel Vessels (ABS, 2011b) (referred to hereafter as "ABS Steel Vessel Rules"), a Guide for Building and Classing Floating Production Installations (ABS, 2009), a Guide for Building and Classing Floating Offshore Liquefied Gas Terminals (ABS, 2010), a Guide for Building and Classing Drillships (ABS, 2011a), and a Guide for the Buckling and Ultimate Strength Assessment of Offshore Structures (ABS, 2004) (referred to hereafter as "ABS Buckling Guide") – all of which provide buckling and ultimate strength criteria for the classification of different types of ships and offshore structures other than those specified in the CSR Rules.

The criteria given in these rules/guides correspond to either the serviceability (buckling) limit state or the ultimate limit state for structural members and panels. A working stress method is adopted, where uncertainties in loads and resistances are inherently incorporated into the maximum strength allowable utilization factors. The process for the buckling and ultimate strength assessment of stiffened panels consists of three levels, namely plate panels, stiffened panels, and girders and webs, which correspond to different failure modes.

The buckling and ultimate strength of each level is expected to be greater than its preceding level to avoid the collapse of the entire structure. This is achieved, to a certain degree, through buckling control concepts that serve as the assumptions and limits of the strength criteria in the rules/guides as an effectiveness assurance and should generally be followed in design. Examples include: the buckling strength of stiffeners is generally to be greater than that of the plate panels they support; the stiffness of stiffeners with the associated effective plating is not to be less than certain values for them to provide adequate lateral stability; moments of inertia for main supporting members with their associated effective plating are to be sufficient to prevent out of plane buckling; tripping brackets are to be installed to prevent the torsional instability of deep girders and webs with wide flanges; and proportional limits are to be provided to prevent the local instability of stiffener face plates and webs.

Plates

According to the ABS rules/guides, the buckling of plate panels is acceptable as long as the ultimate strength check is satisfied because the plate panels can sustain further loading until the ultimate strength is reached. However, a buckling check is necessary to establish the attached plating width for a stiffened panel check, with the full width used for plating that does not buckle and the effective width applied if it does buckle.

Details of buckling and ultimate strength criteria for plates subject to in-plane and lateral pressure loads can be found in the various ABS rules and guides mentioned above.

Stiffened Panels

The failure modes of stiffeners include beam-column buckling, torsional-flexural buckling, and local flange/web plate buckling. Buckling state limits for a stiffened panel are considered its ultimate state limits because the compressive strength decreases quickly if any of these types of buckling occur.

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Strong Supporting Members

In general, girders are designed to be stocky (the column slenderness ratio is not greater than 0.5) so that lateral buckling can be disregarded along with torsional buckling if the appropriate tripping brackets are provided. Otherwise, the girder is to be checked against the various failure modes.

Corrugated Panels

Corrugated panels are "self-stiffened" panels with failure modes that can include flange/web plate buckling, unit corrugation buckling, and entire corrugation buckling (overall buckling) depending on the panel configuration and loading type. The buckling strength is the least value obtained from these three failure modes, considering any load type and combination.

Cylindrical Shells

A fabricated steel cylindrical shell is an important type of compression element used in offshore structures. It is stiffened against buckling by ring and/or stringer stiffeners. The criteria for calculating the buckling of ring and/or stringer stiffened cylindrical shells subject to axial loading, bending moment, radial pressure or a combination of these loads are presented in the ABS Buckling Guide (ABS, 2004).

Five failure modes are considered in the ABS Buckling Guide (ABS, 2004):

- Local shell or curved panel buckling (i.e., the buckling of the shell between adjacent stiffeners). The stringers remain straight and the ring stiffeners remain round.
- Bay buckling (i.e., the buckling of the shell plating together with the stringers, if present, between adjacent ring stiffeners). The ring stiffeners and the ends of the cylindrical shells remain round.
- General buckling, (i.e., the buckling of one or more ring stiffeners together with the attached shell plus stringers, if present).
- Local stiffener buckling (i.e., the torsional/flexural buckling of stiffeners, ring, or stringer or the local buckling of the web and flange). The shell remains undeformed.
- Column buckling (i.e., the buckling of the cylindrical shell as a column).

A higher level of failure usually leads to more severe consequences than the preceding level. Therefore, the similar buckling control requirements regarding stiffness and shell plate proportions, rings, and stringers mentioned previously are necessary to better assure the safety of the stiffened cylindrical shells.

Individual Structural Members

Individual structural members include tubular and nontubular members with uniform geometric properties along their entire lengths that are made of a single material and are used widely in offshore topside structures and various platforms for supporting major equipment. The buckling behaviour of the structural members is influenced by a variety of factors, including sectional shape, material characteristics, boundary conditions, loading types and parameters, and fabrication methods. The four different failure modes consist of flexural buckling, torsional buckling, lateral-torsional buckling and local buckling and all four are taken into account. The loading application includes any of following loads and load effects:

- Axial force in the longitudinal direction
- Bending moment

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- Hydrostatic pressure
- Combined axial tension and bending moment
- Combined axial compression and bending moment
- Combined axial tension, bending moment, and hydrostatic pressure
- Combined axial compression, bending moment, and hydrostatic pressure

The individual members are categorized into compact and noncompact sections. If an individual member is from the noncompact section, the local buckling strength is to be assessed and the effect of local buckling must be taken into account when determining the critical buckling stress of the member.

Tubular Joints

The failure mode of a tubular joint depends on the joint configuration, joint geometry, and loading conditions. These failure modes include:

Local failure of the chord:

- Plastic failure of the chord wall in the vicinity of the brace.
- Cracking that leads to a rupture of the brace from the chord.
- Local buckling in the chord's compression areas.

Global failure of the chord:

- Ovalization of the chord cross-section.
- Beam bending failure.
- Beam shear failure between adjacent braces.

In addition, a member can fail away from the brace-chord joint due to chord or brace overloading. These failure modes can be established by following the approach described in the ABS Buckling Guide (ABS, 2004).

Ultimate strength criteria are provided for the following loads and load effects:

- Axial load in a brace member,
- In-plane bending moment in a brace member,
- Out-of-plane bending moment in a brace member,
- Axial load in a chord member,
- In-plane bending moment in a chord member,
- Out-of-plane bending moment in a chord member, and
- Combinations of the abovementioned loads and load effects.

Hull Girder

The vertical ultimate hull girder strength for either hogging or sagging conditions within the $0.4\,L$ amidship region is to satisfy the limit state as specified below in the partial factor format: $\gamma_s M_s + \gamma_w M_w \leq M_u/\gamma_u$, where M_s, M_w, and M_u are the permissible still-water bending moment, the vertical wave-induced bending moment, and the hull girder ultimate strength, respectively and γ_s, γ_w, and γ_u are the corresponding load or safety factors.

The hull girder's ultimate strength, M_u, is calculated using the incremental-iterative approach. This approach assumes that the hull transverse section remains plane during each curvature increment, and that the hull structure exhibits elasto-plastic behaviour. To calculate the ultimate strength, the hull transverse section is divided into a set of individual elements that include a plate element, a stiffener element, an element consisting of a stiffener with an associated effective width of plating, and a corner element consisting of a plate's intersection with a web plate.

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The elements, while considered to be acting independently, are combined to provide the ultimate strength resistance of the hull's transverse cross-section. Each element, when compressed beyond its buckling limit, has reduced strength according to its buckling and ultimate strength characteristics. All relevant failure modes for individual structural elements such as plate buckling, beam-column buckling, torsional stiffener buckling, local stiffener buckling and their interactions must be considered to identify the weakest inter-frame failure mode. Each failure mode can be described by the load-end shortening curve, as stated in various ABS rules/guides. Numerical calculations (Sun and Wang, 2005a, 2005b; Wang *et al.*, 2011) show that the results are in good agreement when this and other methods are applied.

Buckling Analysis by Finite Element Method

In addition, the ABS Buckling Guide (2004) provides guidance for applying a buckling analysis using the finite element method (FEM) as an alternative to the formulations presented in the guide. The key issues in an FEM analysis such as the determination of the loads and boundary conditions, the development of the mathematical model, the choice of element types, the design of the mesh, solution procedures and verification and validation, are outlined in the guide.

3.2.2 Bureau Veritas (BV)

In ship assessment the ultimate strength assessment requirements consist of checking the structural strength under the worst, extreme quasi-static loading conditions (BV, 2011). For offshore floating units (BV, 2010), the requirements for resisting quasi-static loading are joined by a requirement that the unit structure be able to resist some of the impact conditions defined in the rules. Safety factors are applied to loads and strength as well to take into account the uncertainties regarding parameters and the lack of accuracy that results from simplified approaches.

Ship Structure

The BV assessment approach for ultimate strength is based on a multilevel analysis of plates, stiffened panels, and the hull girder.

When plates do not fulfil the strength criteria, provided that the plate strength failure alone does not lead to adverse consequences, the residual strength of the plate is taken into account in the stiffened panel strength. In the process of ship or floating offshore structures assessment, ultimate strength analyses are carried out after the yielding criteria have been assessed and before fatigue assessment.

Plates and Shells

The first step consists of assessing that the plates fulfil the yield stress requirements. Then a critical stress is defined, depending on the elastic buckling stress and yield stress for the different loading conditions, compression, bending, and shear along with combined compression, bending, and shear. When compression forces are unidirectional a factor F is defined. Pt B Ch 7 Sec 1 5.4.4 (BV, 2011) is used to combine criteria between compression and shear. When compression is biaxial, the criterion requires that the sum of the ratio of acting compressive stress divided by the critical stress corresponding to the direction affected by a power equal to 1.9, and the ratio of acting shear stress divided by the shear critical buckling stress also affected with a power equal to 1.9. A similar approach is provided for a curved shell.

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Stiffened Panels

Pt B Ch 7 Section 2 (Ordinary Stiffeners) considers the strength of stiffened plates against buckling (BV, 2011). Again, the assessment of yielding criteria is required before carrying out buckling assessments. The strength of a stiffened panel involves the participation of the web flange and attached plate.

If the plate between stiffeners fulfils the buckling criteria it is considered as participating in the inertia of the equivalent beam, plate, and stiffener. If not, the partial participation of the attached plate is assumed by correcting the effective plate width with the effective plate width depending on the stiffened panel buckling mode being considered. Three buckling modes are considered: bending, torsional, and web buckling. For each buckling mode a buckling stress formula is provided, and the stress that results from the loads applied to the structure only takes into account the effective attached plate being considered for that particular buckling mode. A critical buckling stress c is then defined as the minimum value of all buckling mode stress affected by an elasto-plastic correction when c is beyond half of the yield stress.

For ordinary stiffeners contributing to the hull girder's longitudinal strength, the applied compression stress is corrected to be homogeneous with the critical buckling stress.

Pillars

Pillars are also to be checked against buckling failure with the effect of load eccentricity and moment combination taken into account in the checking criteria according to Pt B Ch 7 Section 3 6.3.1 (BV, 2011).

Hull Girder

The ultimate strength assessment of the hull girder is required for ships with a length of more than 170 m and the ultimate strength of the hull girder is given in terms of the bending moment capacity M versus the curvature χ. The procedure is given in Pt B Ch 6 Appendix 1 (BV, 2011) following a Smith method, as illustrated in Figure 2.

The bending moment capacity M versus the curvature χ curve is obtained by means of an incremental iterative approach. The main longitudinal parts of the hull girder such as decks, bottoms, side shells, and longitudinal bulkheads are considered stiffened panels and modelled as stiffeners working in parallel. A curvature is applied to the longitudinal elements of the hull girder. The carrying load that corresponds to each stiffener is considered part of the stiffened panel and is obtained by considering a model that is elastic and perfectly plastic. Different failure modes are analysed for each stiffener, and at each step the strength corresponding to the weakest failure mode is kept to determine the stiffener force that corresponds to the prescribed strain resulting from the curvature χ. From these forces and the position of the stiffeners the resulting bending moment capacity is obtained.

Ship-shaped Offshore Structures

Quasi-static Loadings The requirements for quasi-static loading strength requirements are basically the same as for a ship (BV, 2010).

Protection from Explosion The scope of requirements for protection from explosion Pt D Ch 1 Sec 9 3 (BV, 2010) verify the strength of the structure against blasts due to leakages of explosive gas clouds. The principle is that the structural elements may suffer permanent deformation without any rupture, allowing the pressure waves and hot gases or liquids to be transmitted through the steel panel.

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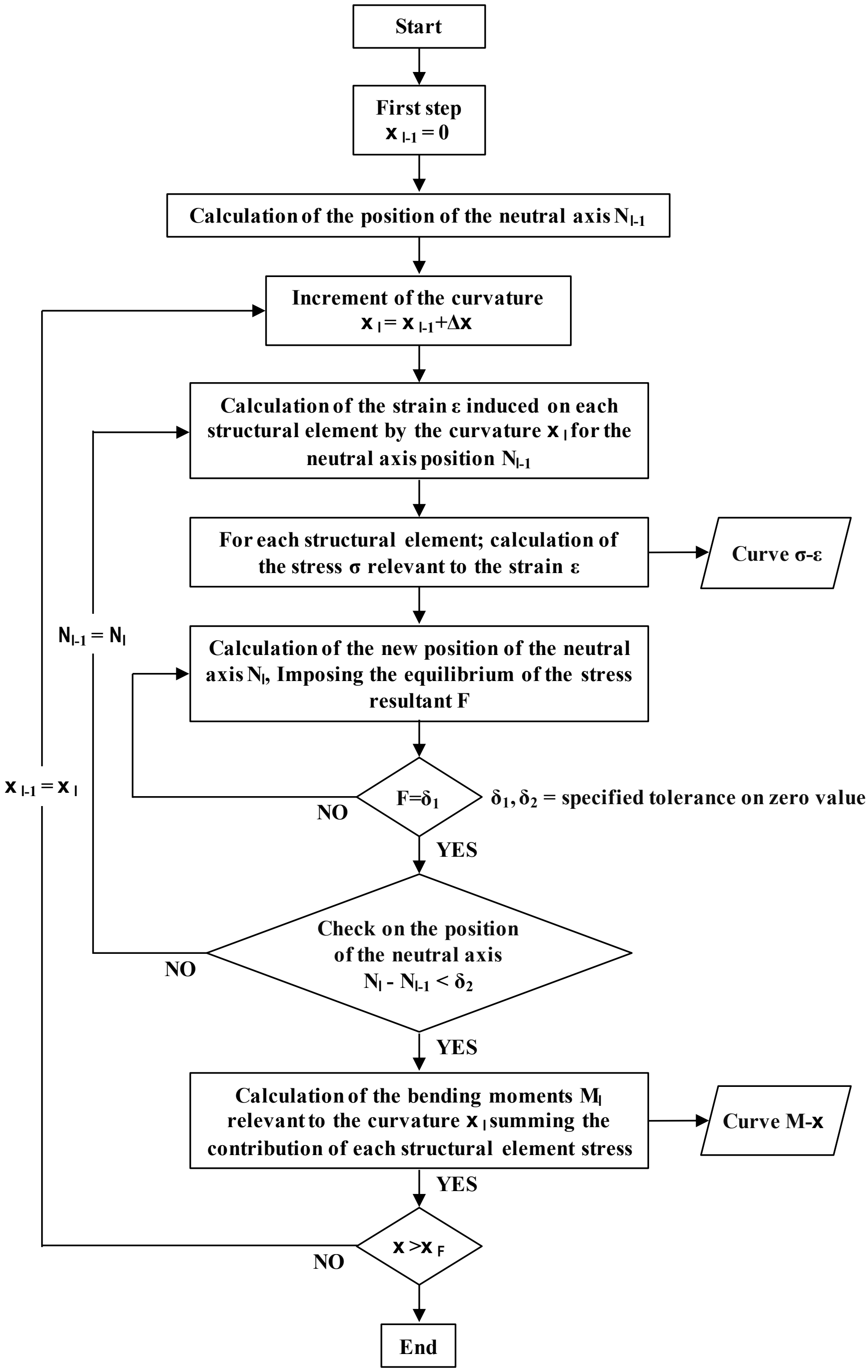

Figure 2: Flow chart of the procedure for the evaluation of the curve $M - \chi$.

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The general areas of concern are the structural element close to the turret and turret moonpool, the main deck and the superstructure front. The calculation has to consider an equivalent exploded TNT mass the same distance from the explosion location. For external explosions an empirical pressure history is provided by the rules while an internal explosion test or numerical simulation is required to determine the loads. The maximum strain resulting from an elasto-plastic finite element response calculation should be lower than 0.8 times the ultimate strain.

Minor Collision The scope of the requirements Pt D Ch 1 Sec 9 4 (BV, 2010) is to check the strength of the structure against collision with shuttle tankers or supply vessels, the dimensions of which are supposed to be small compared to the unit. The energy of the colliding vessel is expected to be absorbed by the deformed side shell of the unit without any risk of flooding. The assessment versus a minor collision supposes that the shuttle tankers and supply vessels intended to be operating over the unit's life are listed and the colliding speed is to be justified. Then, a finite element analysis is carried out to justify that the colliding energy dissipates into the unit's structure, assuming that the bow of the colliding ship is nondeformable. Alternatively, when applicable, a simplified method such as the Rosenblatt method can be used. The criterion is the first rupture of a plate in the indented area.

Dropped Objects When specified Pt D Ch 1 Sec 9 5 (BV, 2010), the deck plate resistance to dropped objects is to be checked. The safety criterion is that the structural element may suffer permanent deformations without any rupture.

The assessment versus dropped object supposes that any equipment that is likely to fall on the deck is listed and the maximum dropped heights are to be justified. The procedure consists of a step by step static indentation of the deck up to the maximum allowed strain, generally 5 % in the deformed area on the hull deck. For other decks the maximum strain corresponds to the ultimate strain. The energy of the dropping object at the moment of its contact with the deck should be lower than the absorbed indentation energy.

3.2.3 Det Norske Veritas (DNV)

Buckling strength analyses can be found in DNV-RP-C201 (DNV, 2010a, Buckling Strength of Plated Structures), DNV-RP-C202 (DNV, 2010b, Buckling Strength of Shells), and Classification Notes No.30.1 (DNV, 2010c, Buckling Strength of Bars and Frames, and Spherical Shells).

In DNV-RP-C201 (DNV, 2010a) two different but equally acceptable methods for the buckling and ultimate strength assessment of plated structures are described. This Recommended Practice is written in the load and resistance factor design format (LRFD format) to suit the DNV Offshore Standard DNV-OS-C101.

The first method, as given in Part 1, is a conventional buckling code for stiffened and unstiffened steel panels. It is an update on and development of the stiffened flat plate part of the previous DNV Classification Note No. 30.1 "Buckling Strength Analysis". Recommendations are given for individual plates (unstiffened plates), stiffened plates, and girders supporting stiffened plate panels.

For unstiffened plates, the buckling checks (in compression) shall be made according to the effective width method and the buckling resistance under various loading conditions, such as uniform uniaxial compression, shear, biaxial compression with shear, varying longitudinal, and transverse stress is listed. Different formulas for stiffeners

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being continuous or simple supported are presented for stiffened plates. Local buckling should be avoided by limiting the stiffness and/or proportions.

The second method, as given in Part 2, is a computerized semi-analytical model called a PULS (Panel Ultimate Limit State). It is based on a recognized nonlinear plate theory, Rayleigh-Ritz discretizations of deflections, and a numerical procedure for solving the equilibrium equations. The method is essentially geometrically nonlinear, with stress control in critical positions along plate edges and plate stiffener junction lines for handling material plasticity. The procedure provides estimates of the ultimate buckling capacity to be used in extreme load design (ULS philosophy). The buckling limit is also assessed because it may be of interest in problems related to functional requirements (i.e., for load conditions and structural parts in which elastic buckling and thereby large elastic displacements are not acceptable (SLS philosophy). The PULS code is supported by official, stand-alone DNV software programs. It is also implemented as a postprocessor in other DNV programs.

DNV-RP-C202 (DNV, 2010b) treats the buckling stability of shell structures based on the load and resistance factor design format (LRFD), as in DNV-RP-C201. The buckling modes for stiffened cylindrical shells are categorized as follows:

- Shell buckling: the buckling of shell plating between rings/longitudinal stiffeners.
- Panel stiffener buckling: the buckling of shell plating including longitudinal stiffeners. Rings are nodal lines.
- Panel ring buckling: the buckling of shell plating including rings. Longitudinal stiffeners act as nodal lines.
- General buckling: the buckling of shell plating including longitudinal stiffeners and rings.
- Column buckling: the buckling of the cylinder as a column. For long cylindrical shells it is possible that interaction between local buckling and overall column buckling may occur because the second order effects of axial compression alter the stress distribution calculated using linear theory. It is then necessary to take this effect into account in the column buckling analysis. This is done by basing the column buckling on reduced yield strength, as given for the relevant type of structure.
- Local buckling of longitudinal stiffeners and rings.

In contrast with the two Recommended Practices, the buckling stress analysis given in Classification Notes No.30.1 (DNV, 2010c) is based on the working stress design method (WSD).

Depending on the loading conditions, a bar may be referred to as a column (bar subject to pure compression), a beam (bar subject to pure bending), or a beam-column (bar subject to simultaneous bending and compression). Buckling modes for bars are categorized as follows:

- Flexural buckling of columns: bending about the axis of least resistance.
- Torsional buckling of columns: twisting without bending.
- Flexural-torsional buckling of columns: simultaneous twisting and bending.
- Lateral-torsional buckling of beams: simultaneous twisting and bending.
- Local buckling: the buckling of a thin-walled part of the cross-section (plate-buckling, shell-buckling).

The overall buckling of a built-up member – composed of two or more sections (chords) separated from one another by intermittent transverse connecting elements (bracings)

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– corresponding to the flexural buckling of a homogenous member is also addressed, along with the buckling of unstiffened spherical shells and dished-end closures.

3.2.4 Germanischer Lloyd SE (GL)

GL rules on buckling and ultimate strength at the elementary plate panel level, and partial and total panel level (GL, 2011a) are in line with those in the CSR for Bulk Carriers (IACS, 2010b). In addition, an assessment of hull girder ultimate strength is required by the GL rules on longitudinal strength (GL, 2011b). The ultimate vertical bending moment has to be calculated by a procedure based on a simplified incremental-iterative approach.

3.2.5 Registro Italiano Navale (RINA)

Rules for the classification of ships (RINA, 2011) essentially include the same criteria as the BV requirements, except for the following minor differences:

- RINA requires the hull girder ultimate strength check for ships with $L > 150\,m$ while BV requires it for ships with $L \geq 170\,m$;
- Partial safety coefficients on wave bending moment and material are slightly different (1.15 vs. 1.10 for moment, and 1.05 vs. 1.03 for material) ;
- BV requires an ultimate strength check in both seagoing and harbour conditions while RINA requires such checks only in seagoing conditions;
- BV rules include a specific check for curved transversally stiffened plate panels that is not reported in RINA rules;
- Minor collision criteria are not included in RINA rules.

3.3 Other Regulatory Agencies

Other agencies and authorities have also published standards for addressing ultimate strength. ISO (2007) addresses the general requirements for the assessment of ship structures based on four types of limit states, namely the serviceability limit state (SLS), the ultimate limit state (ULS), the fatigue limit state (FLS) and the accidental limit state (ALS). The API Bulletin 2U (2004) provides stability criteria for determining the structural adequacy against buckling of large diameter circular cylindrical members when subjected to axial loads, bending, shear, and external pressure acting independently or in combination.

4 DEFINITION OF PARAMETERS AND THEIR UNCERTAINTIES

4.1 Introduction

The practical aspects related to the construction and operation of ship structures have an important influence on ultimate strength assessment. Uncertainties in these aspects must be considered in addition to those related to specific numerical idealizations of a particular structure. By practical aspects, we mean material properties, fabrication-related imperfections, and the in-service effects of the structure. Classifications for these are proposed in Table 1. Both hull girder and individual structural components (stiffened and un-stiffened panels) have been considered in the table's compilation.

All of the abovementioned aspects should be quantitatively defined by means of one or more appropriate parameters. It is clearly impossible to deal with all of them in a rigorous manner without making a number of simplifying assumptions. In fact, the studies available in the open literature focus on one or, at the very most, a few although no holistic perspective is achieved even when the trend is towards more and more complex models. For example, no interaction among the various aspects is generally

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accounted for. Moreover, it is worth noting that large/full-scale experimental data focusing on such practical aspects are rather limited, especially on aspects concerning hull girder strength.

4.2 Physical Aspects

To list all of the physical aspects involved in the ultimate strength assessment and introduce uncertainties for the final results is a challenging task. Only a few examples from the literature have shown the impact of different and somewhat unusual aspects. The reader is referred to Paik and Thayamballi's (2003) book and to previous ISSC Technical Committee III.1 reports on Ultimate Strength, which summarize the state of the art up to 2009.

Garbatov *et al.* (2011) estimated the ultimate strength of stiffened panels by applying classical FEM models. However, the effect of different structural parameters on the uncertainty of results based on a Monte Carlo simulation and an ANOVA (Analysis of Variance) methodology were included in the study. A sensitivity analysis was used to determine the most relevant parameters among plate thickness, Young's modulus, the yield and ultimate tensile strain of material, the shape of initial geometry imperfection, and slenderness ratios. Moreover, the interactions between some of the considered parameters were also assessed.

The effect of intermittent welding was assessed by Khedmati *et al.* (2009a). They studied the ultimate strength of stiffened steel plates, selected from the deck structure of real ships and subjected to in-plane longitudinal or transverse compressive loads. Three different stiffener-to-plate welding procedures were considered: continuous, chain intermittent fillet, and staggered intermittent fillet welding. Detailed analyses were carried out using the commercial software ADINA and then validated by experiments. The full-range equilibrium path of the nonlinear elasto-plastic response of stiffened plates was traced.

Special attention was paid to the finite element modelling of the fillet welds as applied in practice to verify the reliability of the results by discussing the automatic-step incremental solution of a nonlinear finite element algorithm and the refinement of the mesh to appropriately represent the weld seam.

The sensitivity analysis involved several geometrical ratios, stiffener types, and boundary conditions in addition to the weld type. In comparison, the ultimate strength of continuously welded stiffened plates is more reduced in the case of chain intermittent fillet welds than it is in the case of staggered fillet welds.

Two interesting applications were recently proposed by Wang *et al.* (2009) and Suneel Kumar *et al.* (2007), both of whom considered the effect of plate openings on ultimate strength. A plate with an opening behaves in a very complex manner and is subject to yielding, buckling, stress concentration development, and fracturing.

Parametric FEM studies were carried out in both cases. Wang *et al.* (2009) considered typical manhole-shaped openings with different sizes while Suneel Kumar *et al.* (2007) assessed rectangular openings in plates under axial compression. Simplified formulae were proposed and strength reduction factors introduced that were useful for design guidance and to estimate the strength of plates on primary supporting members in way of openings. Compared to current classification societies, rules were reported showing how the rules account for the issue in cases of various structural behaviour and limit states.

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Table 1: Practical aspects affecting ultimate strength behaviour

Physical aspects	• Material properties and behaviour (Young's modulus, Poisson's ratio, hardening, yield modelling, etc.) • Overall geometry (span, spacing, slenderness, etc.) • Strength properties of components (plate thickness, cross-section of stiffeners, etc.) • Local variations of geometry (e.g. openings on plates, scallops, cut-outs, manholes, etc.) • Fabrication/initial defects (misalignments, weld imperfections, residual stresses, etc.)
Model uncertainties	• Quantitative definition of limit state modes (buckling, collapse, etc.) • Approximations of analytical models (e.g., one dimensional or two dimensional idealization) or • Approximations of numerical models (both simplified numerical analyses like the ones proposed in the software of class societies or nonlinear FEM models), e.g.: – Element types/formulations – Assumed boundary conditions – Initial shapes (necessary in nonlinear numerical analyses) • Geometrical idealizations of structures (neglected physical aspects) • Solution algorithms (iterative, incremental, nonlinear, etc.) • Interaction among components (if considered, and how it is considered in the assessment)
Ageing effects	• Corrosion (uniform, pitting, microbial, crevice, etc.) • Fractures and fatigue cracks • Local buckling • Mechanical damages (permanent set due to loading, local dimples, distortions, etc.) • Coating protection/environmental effects (e.g., cargo effects)

A similar analysis was carried out experimentally by Schleyer *et al.* (2011) in the frame of a project to study the blast loading of steel plates with penetrations as used for deck plating or bulkheads. Tests were studied by applying a simplified energy solution.

There has been increased interest in aluminium alloy structures in shipbuilding because of its lower stiffness in respect to steel, which makes the buckling behaviour of aluminium structures rather different. Khedmati *et al.* (2010a) carried out round robin FEM analyses based on previous work from the ISSC 2003 Technical Committee Report III.1 with the aim of assessing the influence of initial deflections and the heat-affected zones on the post-buckling behaviour and collapse of triple-span multi-stiffened panel, extruded or nonextruded angle-bar profiles made from AA6082-T6 aluminium alloy.

Defects and imperfections are very frequent in marine composite structures. Misirlis *et al.* (2010) performed a parametric study of initial geometric imperfections, specifically the ultimate compressive strength of square and long FRP plates. Gaiotti *et al.* (2011) presented a map of the reduction factor of the buckling strength of composite laminates containing delaminations in various positions. The two different FEM modeling strategies presented showed that results are not always the same depending on the element types.

The effect of distortion on the buckling strength of stiffened panels was considered by Chaithanya (2010) using both analytical and numerical analyses, but the effect of residual stress was not accounted for. The equivalent column model clearly showed

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the effects of distortion and slenderness on the strength of the equivalent column, suggesting that the initial distortion affects the strength of the stiffened plate structures. FE analysis of the panels modified this conclusion because the strength decreased by less than the column model predicted for relatively stocky panels.

Few large-scale tests of hull girder collapse have been carried out for obvious reasons. Gordo and Guedes Soares (2008, 2009) carried out the collapse testing of mild steel-made, externally stiffened box girders, which was followed by similar tests using high strength steel specimens. Figure 3 shows the test structural models and test results.

The residual stress relief during loading and unloading paths was analysed and its effect was found to be significant. The residual stresses were removed by performing a series of loading cycles prior to the collapse of the structure. The approximate method based on the progressive collapse of the stiffened plate elements gave a good estimation of the ultimate load supported by the structure and allowed the effect of residual stresses on the box behaviour to be reproduced.

Deviations from the analytical results were attributed to the imperfections and defects always present in a large-scale welded specimen. A comparison of the results of a previous experiment on a similar specimen made from high strength steel highlighted a much higher development of plasticity in the mild steel specimen.

The efficiency of materials and geometry is a useful concept for identifying the governing parameters affecting the ultimate strength of 3-dimensional structures under a predominant bending moment. The sensitivity of the involved parameters such as span, spacing, and column slenderness was identified as was the global efficiency of the high strength steel (HTS 690), which was of the order of 2.5 taking the normal mild steel structure as its basis.

A comprehensive analysis of uncertainties in the ultimate longitudinal strength of a cross-section from a ship's hull girder based on nonlinear FEM was carried out by

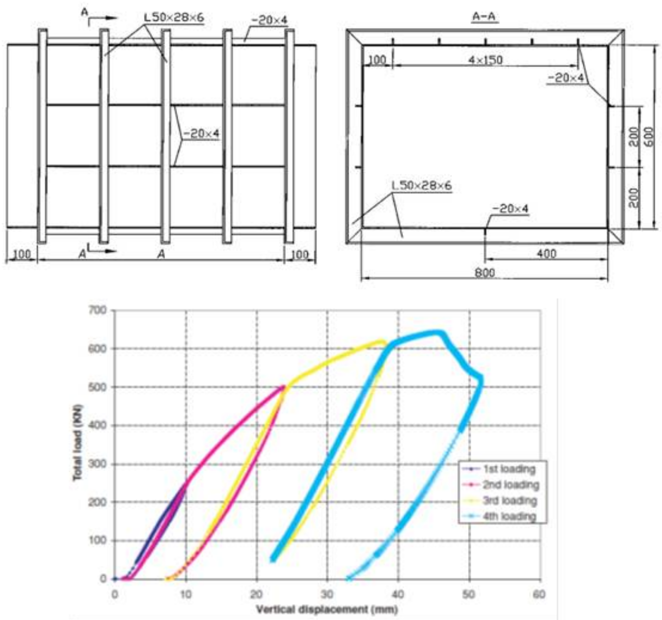

Figure 3: Structural models and measurements of the box girder tested by Gordo and Guedes Soares (2008)

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Harada and Shigemi (2006) using a refined FEM model extending over one transverse frame spacing.

Initially, a systematic variation of thickness, material yielding stress, and Young's modulus were carried out to assess variations in hull girder ultimate strength. Next, variations in the shape and magnitude of initial deflections in the stiffened panels due to welding were examined. Finally, the influence of the mesh size in FE models was considered. Uncertainty coefficients were proposed for the rules, including model uncertainties, based on the obtained results.

The effects of randomness in yield strength and in the initial imperfections in ultimate hull girder strength were also determined by Vhanmane and Bhattacharya (2011). Different levels of statistical dependence between yield strength, the initial imperfection of stiffeners, and the plating between stiffeners were considered.

Two ship structures, a VLCC tanker and a cape-size bulk carrier, were analysed and the statistics of their ultimate hull girder moment capacities were obtained through Monte Carlo simulations. Correlation had no effect on the mean value of ultimate strength, but the uncertainty increased significantly with a higher correlation between yield strength and initial imperfections. Further, the variations in hull girder strength were lower when both sources of uncertainties, yield strength and initial imperfections, were considered compared to when uncertainties in yield or in initial imperfections alone were considered.

4.3 Modelling Uncertainties

Similar to the modelling uncertainties of physical aspects, those involved in ultimate strength assessments are rather varied.

Numerical models, mainly nonlinear FEM, are typically used even if analytical models can still provide sound information. Saeidifar *et al.* (2010) introduced a highly accurate numerical calculation of buckling loads for elastic rectangular plates with varying thickness, elasticity modulus, and density in one direction that considered various boundary conditions, including the beam one (i.e., elastic support at the edges due to the presence of a stiffener). The analytical solutions obtained regarding an infinite power series were compared to a finite element analysis and the differences were lower than 3 %.

Piscopo (2010, 2011) recently improved classical analytical models for use in the analysis of rectangular plates under shear, uniaxial, and biaxial compressive loads and their combinations, considering different boundary conditions. Comparisons with FEM results highlighted that in several cases, analytical formulations – taking recent advancements into account – are as accurate as FEM analyses.

Özgüç and Barltrop (2008) analysed the hull girder strength of bulk carriers using a simplified incremental-iterative approach. Pure vertical bending moment was first examined using seven different methods. Next, the ultimate strength under coupled vertical and horizontal bending moment was considered and an interaction curve was obtained. The interaction design equations proposed by other researchers were also addressed.

The combined effect of the vertical and horizontal bending moments become important when a ship is damaged and simplified, but reliable methods are necessary to select the proper actions. The proposed simplified method is rather accurate, but it can be difficult to find a target for comparison in the case of hull girder ultimate strength.

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Rizzo *et al.* (2002) compared the ultimate strength of hull girders obtained by applying different evaluation methods to a set of deep-V, high speed craft hulls ranging from $50\,m$ to $125\,m$ in length. Namely, the ultimate bending moment of the midship section was evaluated for seven ships with the same hull forms using five different methods. An analysis of the results made it possible to estimate uncertainties in the ultimate strength evaluation to be used in the reliability analysis or rules development derived from modelling assumptions and the size of the structure.

Okasha and Frangopol (2010) examined hull strength optimization from a probabilistic perspective. In addition to their probabilistic approach to material properties and fabrication details, hull section stresses were determined using constitutive models of stiffened panels that considered a variety of possible failure modes and initial imperfections. The ultimate strength was found by using an optimization search algorithm that claimed to be as accurate as the rigorous incremental curvature method, but with less computational time. This method was then applied to a sampling simulation and the output sample was tested against several potential distributions.

4.4 Ageing and In-service Damage Effects

The impact that ageing effects have on the ultimate strength of a hull girder and its components was recently considered by the ISSC Specialist Committees on the condition assessment of aged ships and offshore structures in 2006 and 2009. These reports are an ideal source of detailed, state-of-the-art information about ageing ship and offshore structures while the book *Condition Assessment of Aged Structures* (Paik and Melchers, 2008) provides a wider overview of the matter. A few advances can be cited in the material that follows regarding the main degradation modes of ship structures (i.e., corrosion, fracture, and mechanical damage as defined by the abovementioned ISSC Committees).

A statistical investigation of the time-variant hull girder strength of ageing ships and coating life was carried out by Wang *et al.* (2008) based on data from ships in service. In particular, they analyzed the measurement of section belts carried out during CAP surveys.

Difficulties in identifying plate renewals reportedly affected the analysis. However, uncertainties in the decrease of the hull girder section modulus for tankers were identified and such data were used to derive formulae that can be useful when applied to hull girder ultimate strength assessments.

Although Ivanov's study (2009) mainly focused on hull girder loads, it – like the abovementioned paper – also considered hull girder section modulus degradation due to corrosion. The hull girder geometric properties are presented in probabilistic format as annual distributions and distributions for any given lifespan. Probabilistic models of corrosion were also combined with as-built plate thickness variation models. Finally, a risk-based inspection planning framework was offered.

Moving from hull girder to hull structural components, the work of Silva *et al.* (2011) can be cited. They recognized that corrosion wastage is not uniform because it is commonly idealised. Steel plates are actually subject to random nonuniform corrosion, so the effect of nonlinear, randomly distributed, nonuniform corrosion on the ultimate strength of un-stiffened rectangular plates subjected to axial compressive loading was numerically analysed by means of nonlinear finite element analyses. A Monte Carlo simulation generated 570 plate surface geometries for different degrees of corrosion, location, and ages and their ultimate strength was assessed. Finally, a regression

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analysis was proposed to derive empirical formulae for predicting strength reduction resulting from corrosion.

The strength and deformability of steel plates for marine use were studied by Rabiul Islam and Sumi (2011), focusing on the geometry of corrosion pits and the size effect of corroded plates. The effects of the two pit shapes (conical and ellipsoidal) was investigated through nonlinear, large deformation and three-dimensional finite element analyses for simulated corrosion surfaces, as generated by a probabilistic model of a corrosion process. Rizzuto *et al.* (2010) studied on reliability of a tanker in a damaged condition.

4.5 Conclusions on Practical Aspects in Ultimate Strength Assessment

In short, it has been briefly shown that several practical aspects have an effect on the ultimate strength assessment of hull girders and individual hull components. These are often implicitly accounted for in the assessments by safety factors, either because it is difficult to include them in the models or because their effects are simply not recognized. The following aspects can be summarized, recalling the information reported in Table 1.

As far as hull girder ultimate strength is concerned, simplified and analytical approaches can be applied in lieu of nonlinear FEM analyses. Both methods are valid in principle, depending on the aims of the calculation. Such analyses are generally carried out for comparative/optimization purposes rather than for limit state assessment.

The available experimental data that can be used as target values for the calibration of structural models is very limited, which makes it almost impossible to estimate the related uncertainties. Moreover, it should be acknowledged that it is difficult to properly include ageing effects and imperfections in the analyses. Similarly, the interactions between structural components are very difficult to simulate.

Individual structural components can be assessed using simplified and analytical approaches or FEM analyses. In this case several practical aspects can be accounted for, such as openings in plates, fabrication imperfections (dimples, distortions, residual stresses, etc.), the effect of adjacent plates (structural system strength), and ageing effects in addition to the consideration of complex situations like random corrosion.

Using survey automation and data management to build updated numerical models, structural monitoring, and other ways of measuring ships in service will possibly become the way to fill the gap between the practical aspects of ultimate strength assessment and the actual state of the art, especially considering the interactions between the various aspects that are too complex to be included in current assessment practices.

5 RECENT ADVANCES

5.1 Components

5.1.1 Plates

Paik and Seo (2009a) investigated the ultimate strength of unstiffened plate elements under combined biaxial thrust and lateral pressure using a nonlinear finite element approach. The one-bay plate model was supported along four edges with no rotational constraint and it was analysed along with the 1/2+1+1/2 bay continuous plate model with the lateral deflection restrained by supporting members. The latter was subjected to rotational restraint along the plate edges under the action of lateral pressure as

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observed. They found that the ultimate strength of plate elements under biaxial thrust was significantly influenced by the rotational restraint under lateral pressure actions, and that ALPS/ULSAP program captured this influence in the ultimate strength prediction with reasonable accuracy. Most studies on the ultimate strength of plates under longitudinal compression are related to plates having unrestrained edges that remain straight and without a net transverse load applied.

Gordo (2011) studied the influence of the in-plane restraint of unloaded edges on the ultimate strength of long plates under axial compression using plate buckling modes to model the fabrication imperfections.

It is recognized that the current design practice for perforated plates, which uses a plasticity correction such as the Johnson-Ostenfeld formula, may not be relevant, particularly when the opening size is relatively large because the critical buckling strength is significantly greater than even the ultimate strength in such cases (Paik and Thayamballi, 2003). The primary reason for this is that the large opening enhances a yielding at the net section, but the elastic buckling strength is not similarly decreased by the local increase of stresses and is sometimes even increased by the presence of larger free edges and associated stress distribution in the plate (Harada and Fujikubo, 2002). To overcome the problem, Kim *et al.* (2009) performed a series of experimental and numerical studies on buckling and the ultimate strength of plates and stiffened panels with an opening that were subject to axial compression, and they derived design-formulae for measuring critical buckling strength. Extensive comparisons of numerical test results have shown that the developed critical buckling strength formula is useful for the design and strength assessment of steel plate panels with an opening. Wang *et al.* (2009) proposed simplified formulae for assessing the buckling and ultimate strength of plates with openings based on the FEM results that introduce strength reduction factors as ratios to the strength of plates without openings.

Cylindrically curved plates are extensively used in ship structures, such as deck plating with a camber, side shell plating at fore and aft parts, and bilge circle parts. The practical method for the ultimate strength assessment of curved plates, however, has not been clearly established. Park *et al.* (2009) studied the post-buckling behaviour of curved plates under longitudinal thrust with the effect of secondary buckling using nonlinear FE-analyses and proposed a simple formula for finding ultimate strength by introducing the curvature effect to the Faulkner's plate strength formula. Park *et al.* (2011) also derived a set of simple formulae to estimate the buckling/ultimate strength of curved plates under longitudinal/transverse thrust, combined biaxial thrust, and lateral pressure based on FE results. Amani *et al.* (2011) investigated the buckling and post-buckling behaviour of curved plates under uniform shear, including the elasto-plastic regime. Imperfection sensitivity was also studied for various geometrical parameters.

Benson *et al.* (2009) investigated the strength of aluminium plates with a range of geometric and material parameters and different imperfections using nonlinear finite element analyses. Their study showed that these parameters have a significant influence on the strength behaviour of aluminium plates. Daley and Bansal (2009) dealt with ice loading, wheel loads, collision, and the grounding loads of ship plating as patch loads. The recent IACS Polar Rule requirements and two other formulations were compared to nonlinear finite element results and revealed that there are still some significant differences. Finally, ideas for the development of an elasto-plastic response formulation were presented.

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To efficiently analyse the progressive collapse analysis of plated structures, Pei *et al.* (2010a, 2010b) developed an ISUM plate element that considered the combined action of in-plane shear and thrust, and an isoparametric ISUM plate element for quadrilateral plate shape under thrust. The applicability of these models was confirmed by comparing them to FE analyses.

The edge condition of the plating in a continuous stiffened-plate structure is neither simply supported nor clamped because the torsional rigidity of the support members at the plate edges is neither zero nor infinite. In a robust ship structural design, it is necessary to accurately take into account the effect of the edge condition in analyses of plate behaviour in terms of buckling and post-buckling behaviour. Paik *et al.* (2012a) developed a new method for analyzing the geometric nonlinear behaviour (i.e., elastic large deflection or post-buckling behaviour) of plates with partially rotation-restrained edges in association with the torsional rigidity of the support members and under biaxial compression. It is also confirmed that the effect of plate edge condition is significant on the post-buckling behaviour.

The text book titled *Ship Structural Analysis and Design* (Hughes and Paik, 2010) presents the most recent theories for buckling and ultimate strength calculations of plates.

5.1.2 Stiffened Panels

With the recent trend toward the application of limit state design to the ultimate strength assessment of ships and offshore structures, continuous efforts have been devoted to the development of useful methodologies for predicting the ultimate strength of stiffened panels.

Paik and Seo (2009b), Paik *et al.* (2011b), and Frieze *et al.* (2011) performed a benchmark study on the ALPS/ULSAP method to determine the ultimate strength of stiffened panels under combined biaxial compression and lateral pressure. The plates' initial deflections with the shape of the elastic buckling mode and the column-type and sideways initial deflections of stiffeners with the shape of the buckling mode were assumed. The predicted ultimate strength correlated well with more refined ANSYS nonlinear finite element computations, assuming the same shape and magnitude of initial deflections.

Zhang and Khan (2009) carried out an extensive nonlinear finite element analysis of the plates and stiffened panels of ship structures under axial compression and developed some simple formulae for measuring their ultimate strength. A good agreement between their proposed formulae and the FE results was achieved with a mean value with the scatter of 3.2 %, based on the FE results. Wang *et al.* (2010) compared various buckling and ultimate strength assessment criteria of stiffened panels under combined longitudinal compression and lateral pressure. The ultimate strength predictions from these various methodologies were found to be generally close to the test data in most cases. They also found differences in the predicted ultimate strength's sensitivity with respect to lateral pressure in some of the rules.

Cho *et al.* (2011) derived formulae for stiffened panels that were subject to combined axial and transverse compression, shear forces, and lateral pressure. Residual stresses were included similar to those provided by the ISSC2000 committee VI.2 (ISSC, 2000) and shape imperfections were modeled using sinusoidal variations where a half wave was assumed for the axial direction to better represent reality – closer to the hungry-horse mode than the elastic buckling mode. The formulations were verified against FE-analyses using the DnV software PULS.

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Gordo and Guedes Soares (2011) performed axial collapse tests for three-bay stiffened panels with associated plate made of very high tensile steel, namely S690. The use of this high strength steel led to the use of U stiffeners as an unconventional solution. Four different configurations were considered for the stiffeners, which were made of mild or high tensile steel for bar stiffeners and mild steel for 'L' and 'U' stiffeners. The results showed that the hybrid panels performed better than the fully S690 panels for similar squash loads due to their lower column slenderness relative to the fully S690 panels, which had large cross-section areas. The 'U' stiffeners were $2\,mm$ thick and the large slenderness of the flange plating showed signs of early-stage buckling and unstable load shedding after ultimate strength had been reached. The buckling collapse behaviour of these stiffened panels was investigated numerically by Xu and Guedes Soares (2011c) using FEA, with special attention paid to the influence of the stiffener geometries and the appropriate boundary conditions for numerical models.

The stiffened plate structures in ships and ship-shaped offshore installations often display nonuniform plate thicknesses. Seo *et al.* (2011) checked the validity of the equivalent plate thickness method against the ultimate strength analysis of stiffened panels with nonuniform plate thicknesses using nonlinear finite element method computations. This method was based on the weighted average approach and showed that the equivalent plate thickness method can be successfully used with finite element models.

In addition to ultimate strength, the correct formulation of the post-buckling, stress-strain relationships between stiffened panel elements subject to various loads acting on their edges is another key aspect for evaluating the ultimate capacity of ship structures. Benson *et al.* (2010) presented a semi-analytical approach to predict the load shortening curves of stiffened panels under uniaxial compression. Their method considered local and overall failure modes, including gross panel collapse, interframe collapse, and local component buckling. The results revealed that their method predicted the effects of gross panel buckling on the pre- and post-collapse behaviour of the panels. Brubak *et al.* (2009) presented another semi-analytical method for the analysis of stiffened plates in the pre- and post-buckling range. Load-deflection curves were computed using this method in combination with a strength criterion that allowed the ultimate strength limit to be predicted. In particular, stiffened plates with a free edge or with an edge stiffener were considered. Taczala (2009) developed an approximate method for the evaluation of the stress-strain relationship of stiffened panels under tension, compression, and shear.

Amlashi *et al.* (2010) developed a probabilistic tool to assess the capacity distribution of stiffened panels. A Monte Carlo simulation scheme was applied using PROBAN (DNV), which interactively utilizes PULS method as an efficient ultimate strength prediction tool for plated panels. The suitability of the assumed distribution for the strength was demonstrated with relatively little computational time and the yield stress and imperfection sizes were treated as random variables.

There has been an increased interest in the buckling/plastic collapse behaviour of aluminium structures in recent years. Although a large number of ultimate strength prediction methods are available for steel stiffened panels, they cannot be directly applied to aluminium structures for various reasons, including softening effects in the heat-affected zones (HAZs) near fusion weld lines, a more rounded stress-strain relationship than steel, and more varieties of the cross-sectional geometries produced by extrusion.

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The post-buckling behaviour and strength of multi-stiffened aluminium panels subjected to combined axial compression and lateral pressure were studied by Khedmati *et al.* (2010b), including the effect of HAZs at the longitudinal (axial) and/or transverse weld lines. The model without HAZs and model B (see Figure 1), which had longitudinal weld lines at the intersections of extruded elements, exhibited maximum ultimate strength in general, while model A+C, which had longitudinal weld lines at the junction lines between the plate and the stiffeners and the transverse weld lines exhibited minimum ultimate strength for any value of lateral pressure. This is partly due to the softening effect in HAZs and partly due to the location of the effective width of the plate after buckling. Chen and Moan (2010) investigated the effects of material softening and residual stresses on the ultimate strength of stiffened aluminium panels under axial and transverse compression. Their results were similar to those observed by Khedmati *et al.* (2010b). Chen and Moan also found that the softening effect of transverse welds on the axial strength of stiffened panels is greater for sturdy panels with smaller panel slenderness.

Khedmati *et al.* (2009b) investigated the elastic buckling and ultimate strength of continuous stiffened aluminium panels under combined axial compression and lateral pressure using a nonlinear finite element approach. The influence of initial deflections and the effect of the heat affected zone on the buckling/plastic collapse behaviour were investigated to discover the different lateral pressure values. Based on the results, Khedmati *et al.* (2010b) developed empirical formulae for predicting ultimate strength through a regression analysis that considered the effect of the weld on initial imperfections and heat affected zones.

Collette (2011) developed a series of rapid semi-analytical methods for predicting the compressive and tensile response of aluminium plates and stiffened panels. These models allowed Smith-type progressive collapse approaches to be implemented for aluminium vessels. Particular attention was paid to capturing aluminium-specific response features, such as round material stress-strain curves and the weakening effect of fusion welds. The methods were validated against finite element analysis and experimental results.

Paik *et al.* (2012b) carried out an experimental and nonlinear FEA-based numerical study on buckling collapse of a fusion-welded aluminium stiffened plate structure. A set of aluminium stiffened plate structures fabricated via gas metal arc welding in which the test structure is equivalent to a full scale deck of an $80\,m$ long high speed vessel. The plate part of the test structure is made of 5383-H116 aluminium alloy and extruded stiffeners are made of 5083-H112 aluminium alloy. It is concluded that the nonlinear FEM computations significantly depend on the structural modelling technique applied. In particular, the welding-induced initial imperfections in terms of initial distortions, residual stresses, and softening in the heat-affected zone need to be modelled as appropriate for the nonlinear FEA of welded aluminium structures.

The text book titled *Ship Structural Analysis and Design* (Hughes and Paik, 2010) presents the most recent theories for buckling and ultimate strength calculations of stiffened panels.

5.1.3 Shells

Most offshore floating platform components are made as stiffened cylinders, and an improved model for the design process could affect their total construction costs and schedule to a great extent. A reliability-based design approach is considered advantageous over the deterministic type of structural designing process because the former

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addresses uncertainties in the design variables, which leads to a more consistent level of safety. A reliability-based approach still needs a robust strength model to predict the capacity with respect to random design variables.

Das *et al.* (2011) proposed a strength model for ring, stringer, and orthogonally stiffened cylindrical shells that is a modified version of a previously proposed strength model. This model showed better agreement with the experimental results compared to the practicing DNV and API design codes. The model uncertainty factor and the strength model can be utilised in the reliability analysis of similar structures. It was also noted that the experimental data available for the radial pressure load cases for ring-stringer stiffened cylinders are very low and further investigation would be required to acquire more data.

An overview of current design practices for submarine pressure hulls was presented by MacKay *et al.* (2011), along with the results from a survey of the literature that was conducted to determine standard nonlinear numerical modeling practices for those structures. The accuracies of the conventional submarine design formulae (SDF) and nonlinear numerical analyses for predicting pressure hull collapse were estimated by comparing predicted and experimental collapse loads from the literature. The conventional SDF were found to be accurate within approximately 20 %, with 95 % confidence, for intact pressure hulls. The accuracy of a wide range of nonlinear numerical methods, including axisymmetric finite difference and general shell finite element models, was found to be within approximately 16 % with 95 % confidence. The accuracy was found to be within 9 % when only higher fidelity general shell FE models were considered.

A way for the incorporation of nonlinear numerical methods into the design procedure to move forward has also been discussed. Because real imperfections cannot be precisely anticipated, characteristic values must be used in partial safety factor approaches. The existing codes normally use the most pessimistic geometric imperfections that meet the specified design tolerances. One concept of an alternative approach that considers more realistic geometric imperfections for a given method of manufacture based on imperfection databanks was proposed. This would lead to less conservative design than the use of worst-case imperfection assumptions. Although a consensus with respect to the most appropriate modeling of imperfection is needed, this is an important topic that requires future research if it is to be successfully applied to any structural components.

Thick, truncated cones are primarily used in the offshore industries as transition elements between two cylinders of different diameters and as piles for holding jackets when driven into the sea bed. These conical shells undergo buckling within the elastic-plastic range. There are few results within this range compared to the thinner shells used in aeronautical applications where the load-carrying capacity is usually limited by elastic buckling. Błachut and Ifayefunmi (2010) conducted experimental and numerical examinations of the static stability of truncated metallic conical shells subjected to axial compression and/or external hydrostatic pressure. The FE predictions of the collapse pressures overestimated the experimental values by about 5 % and those of axial collapse loads by about 13 % to 30 %. Possible sources of discrepancy were discussed, including uncertainties in geometry, wall thickness, and welding residual stresses. Numerical studies were also performed by Ifayefunmi and Błachut (2011) on truncated cones under axial compression and/or external hydrostatic pressure to examine the sensitivity of their ultimate strength in relation to the following types of imperfections: (i) initial geometric imperfections, (i.e., deviations from perfect geometry), (ii) variations in wall thickness distribution, and (iii) imperfect boundary conditions.

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Pan *et al.* (2010) performed nonlinear finite element analyses of a series of titanium alloy spherical pressure hulls that included structural imperfections. Based on their numerical results, the sensitivity of the ultimate strength to critical arch length, thickness to radius ratio, and structural imperfections were studied. The empirical formulae for the ultimate strength of titanium alloy spherical pressure hulls of deep manned submersibles were proposed based on the numerical studies.

5.1.4 Composite and Sandwich Panels

Failure Theory of Composite Material

In order to increase confidence in the use of fibre-reinforced composites, an international activity called the World-Wide Failure Exercise (WWFE) has been organized. The aim of this exercise is primarily to benchmark and validate failure theories and design methodologies. The first WWFE-I originates from a meeting held at St Albans, UK in 1991. From that 19 failure theories were compared with experimental results for the failure of a unidirectional fibre reinforced lamina, initial and final failure of multi-directional laminates, and the large deformation of laminates under biaxial loads (Hinton *et al.*, 2004).

Some of the theories demonstrate good agreement with experimental results and others have limited capabilities. Some of the typical results are as follows.

- On a lamina level, Tsai was the highest scorer but Cuntze and Puck also did well and further experiments are required to confirm Tsai's predictions of increased lamina strength under biaxial compression.
- On final strength predictions for multi-directional laminates under biaxial loads; Puck, Cuntze, Tsai, and Zinoviev achieved the highest scores. The importance of a good post initial failure analysis method in the prediction of final failure was demonstrated.
- It has proven necessary to handle multiple nonlinearities arising from damage, nonlinear shear behaviour, and change in fibre orientation to accurately predict the stress-strain behaviour up to the failure of laminates under load conditions that result in matrix dominated behaviour.

There were many important outcomes from WWFE-I, and it also highlighted the significant shortfalls in predicting the strength and deformation response of polymer composite structures under biaxial stress states. To bridge some of the gaps that were identified, additional exercises were organized: (a) the Second World Wide Failure Exercise (WWFE-II) (Kaddour and Hinton, 2005), which considered triaxial failure and associated theories; and (b) the Third World Wide Failure Exercise (WWFE-III) (Kaddour *et al.*, 2007), which dealt with damage and associated modelling techniques.

There are many criteria that are used to predict the failure of composite materials. Several recently published methods are presented here. Daniel (2007) gave a concise overview of theories and procedures for predicting and analysing failure in composite materials. The validity and applicability of the various theories were evaluated based on convenience of application and agreement with experimental results. In the case of ultimate laminate failure, a progressive damage scheme coupled with a failure mode-discriminating criterion was discussed with special attention paid to textile composites.

Las *et al.* (2008) focused on the prediction of composite material failure using modern failure criteria for composites, namely LaRC04 and Puck. Three types of specimens were analysed and the the process of failure propagation was monitored using a method known as progressive failure analysis, which uses a material degradation approach.

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Liu *et al.* (2010) focused on developing a model to predict the failure of notched cross-ply laminates with the influence of matrix failure. To estimate the local stress concentration in the critical damage zones, a method was developed to decompose the local stress concentration into several parts: the geometrical contribution of the notch, the damage contribution, and the stacking-ratio contribution. The damage-dependent stress concentration of the laminate was established for different notches and it was then utilised to predict the ultimate strength of the notched laminates.

WWFE-I indicated that the bridging micromechanics model exhibited a unique feature for calculating internal thermal stresses in the constituent fibre and resin materials of a laminated composite. Once applied to laminate strength prediction, however, the model only produced a moderate correlation with the experiments. Zhou and Huang (2008) incorporated a material degradation scheme and a modified ultimate failure criterion for laminates into the bridging model to improve its predictive capacity. Pure resin inter-layers were also introduced to simulate the effect of interfaces between the lamina plies. With these modifications, much more accurate predictions were obtained for the majority of the exercise problems, especially for the ultimate strengths and deformations of the multi-directional laminates.

Many different kinds of degradation schemes have been proposed in the literature, and none of them have proven accurate enough to describe the degradation behaviour of various materials.

Zhou and Huang (2008) multiplied the modulus of the resin by a factor of 0.01 to deteriorate the stiffness of the failed lamina. This deterioration scheme was motivated to be reasonable because the resin had undergone a significant plastic deformation before failure and the hardening modulus, which was defined as a tangent to the resin stress–strain curve, of the resin at failure had to be significantly smaller than its elastic modulus.

In the original problem (Huang, 2004), an ultimate failure of the laminate was considered to occur when all of the laminate had failed regardless of whether the failures were caused by the failure of the fibres or the resin, which gave poor ultimate strength predictions for the laminates subjected to some of the loading conditions. Thus, the ultimate failure of the laminate was considered to occur if and only if any single ply failure was due to that of the fibres or due to the compressive failure of the resin. In other words, even if all of the lamina plies failed due to the tensile failure of the resin, it could not be stated that the laminate had attained an ultimate failure.

Sandwich Panels

Sandwich constructions are commonly used in automotive, aerospace, wind energy, and marine applications due to their high strength-to-weight and stiffness-to-weight ratios. Sandwich elements consist of two strong, stiff face skins that are separated by a thick, flexible core. The skins provide flexural stiffness while the core provides shear resistance and composite interaction between the skins. Common skin materials include thin metal sheets or fibre reinforced polymer (FRP) composites. Core materials include balsa wood, polymeric foams, FRP reinforced foam cores, metallic foams, honeycomb constructions, and lattice structures.

Reany and Grenestedt (2009) presented a technique for analysing sandwich panels with one flat and one corrugated skin. Corrugated skins can significantly increase the wrinkling strength of uniaxially compression loaded lightweight sandwich structures. The corrugations can also be used to carry some of the shear load of a sandwich

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panel. Such panels could, for example, be used as bottom panels in ship hulls. The structural improvements that result from skin corrugation were studied numerically for the buckling of simply supported panels subjected to uniaxial compression or shear loading. The numerical analysis predicted the corrugated panel to be 25 % stronger than its flat counterpart despite being 15 % lighter.

Dawood *et al.* (2010) conducted research that evaluated the two-way bending behaviour of 3D glass fibre reinforced polymer (GFRP) sandwich panels. The panels consisted of GFRP skins with a foam core and through-thickness fibre insertions. The experimental results were compared to those from a nonlinear, finite element model. The measured and predicted responses indicated that at lower deflections the panel behaviour was dominated by plate bending action while membrane action dominates at higher deflections. Yoon and Lee (2011) discussed sandwich panels composed of glass fibre epoxy composite faces and foam cores. The flexural bending strength and deformation of these panels were evaluated using FE analysis and compared to the experimental test results. It was found that the weight efficiency of the asymmetric sandwich panel was higher than that of the symmetric sandwich panel.

Polymer foam-cored sandwich composites are widely used in the load-bearing components of naval structures. One of the prominent characteristics of polymers is their viscoelasticity. Temperature changes and humid environmental conditions can significantly degrade the stiffness and strength of the polymer foam core, which in turn affects the performance of the entire sandwich structure. Joshi and Muliana (2010) analysed the effect of moisture diffusion on the deformation of viscoelastic sandwich composites. The time-dependent responses of the sandwich composites subject to moisture diffusion were analysed using a finite element method. FE analyses of the delamination between skins and core under combined moisture diffusion and mechanical loading were also performed.

Frank *et al.* (2011) discussed the structural design of a laser-welded, steel-sandwich structure. They introduced a design system to design the steel sandwich panel structure with a minimum weight that still satisfied yield and buckling criteria. To decrease the calculation time, a homogenization of the panel was carried out based on the Reissner-Mindlin plate theory. To validate and illustrate the optimization system, two case studies were presented featuring corrugated core sandwich panels.

Web-core sandwich panels have a uni-directional core that causes their high orthotropic to shear stiffness. Romanoff *et al.* (2009) investigated the influence of filling material on the shear characteristics of web-core sandwich structures. Beams with spans that are opposite the web plate direction, were tested and simulated under four point bending. The results showed that the decrease in shear deflection and shear-induced normal stress in the face plates was 3 and 7 times, respectively, in the linear elastic regime with an increase in weight of only 6 % and 15 %, respectively. The increase in ultimate strength was not as large as the increase in stiffness or the decrease in stresses. The beams failed by the shear failure of the filling material, followed by the formation of plastic hinges at the laser-welds.

Romanoff *et al.* (2011) studied the interaction between the web-core sandwich deck, including the joints, and the hull girder of a modern passenger ship. The investigation was carried out using FEM. In the analysis the sandwich decks were modelled as equivalent orthotropic shell elements that included the influence of out-of plane bending and shear deformations. A case study of a post-Panamax passenger ship was presented where the ship was subjected to vertical bending loading. In that case, the

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traditional deck, made from stiffened plates, was replaced by sandwich decks that had equal cross-sectional areas and symmetrical or nonsymmetrical joints. Both deflection and normal stresses were considered as the response.

Sandwich panels constructed from metallic face sheets with cores composed of an energy-absorbing material have shown potential as effective blast resistant structures. The energy-absorbing crushed cellular material can form a stable configuration post-collapse that further contributes to blast resistance. Two commonly studied cellular materials are aluminium foams and honeycomb. Theobald *et al.* (2010) conducted air-blast tests on sandwich panels composed of steel face sheets with unbonded aluminium foam or hexagonal honeycomb cores. The test results showed that face sheet thickness has a significant effect on the performance of the panels relative to an equivalent monolithic plate. Ruan *et al.* (2010) experimentally investigated the mechanical response and energy absorption of aluminium foam sandwich panels subjected to quasi-static indentation loads. Quasi-static indentation tests were conducted with sandwich panels either simply supported, or fully fixed. Force-displacement curves were recorded and the total energy absorbed by the sandwich panels was calculated accordingly. The effects of face-sheet thickness, core thickness, boundary conditions, and the adhesive and surface conditions of face-sheets on the mechanical response and energy absorption of sandwich panels were discussed.

The stability of a sandwich structure is characterized by its buckling failure. This behaviour can be explained by several mechanisms such as fibre breaking, the debonding of the face-skin from the core, and delamination in the faces. These mechanisms reduce the structure's capacity to bear loads, leading to premature failure. Henao *et al.* (2010) presented a study about the influence of through-thickness tufted fibres on the compression and bending properties of sandwich structures.

5.1.5 Tubular Members and Joints

Pipelines operating in arctic and seismically active regions may be subjected to large ground movement that can lead to large plastic deformation in the pipelines. Deepwater flowline can also experience large lateral displacement in start-up and shut-down operations. The traditional allowable stress design methods may not be sufficient for design of pipelines that may experience large strains, and there is a need for developing the design method for pipelines beyond yield, commonly termed strain-based design. Extensive works on the strain-based design have been performed from several aspects, such as material, strain capacity both in tension and compression, testing, macro and microscopic FE modelling and pipeline system modelling (e.g., Newbury, 2010). Gresnigt and Karamanos (2009) gave an overview of the available test results and differences in various design standards concerning the local buckling strength and deformation capacity of pipes in bending. Tsuru *et al.* (2010) investigated the effect of the possible variation of the pipe geometries and the material strengths on the strain limit of girth-welded line pipes in bending through full-scale tests and FE analyses.

Offshore pipelines often carry hot hydrocarbons at a certain internal pressure. When such a line is trenched, buried or anchored, it is simultaneously subjected to axial compression due to the axial constraint. When these load effects are high enough to produce plasticity, the line buckles into an axisymmetric wrinkling mode. The subsequent cyclic load actions during lifetime may cause a gradual increase of plastic strain, called ratcheting, which may eventually leads to the collapse by localization of the wrinkling. Jiao and Kyriakides (2009, 2011a, 2011b) made detailed investigation of the ratcheting and wrinkling behaviour of tubes subjected to axial cycling with and

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without internal pressure, both experimentally and numerically. One of the major founding is that the collapse under cyclic loading occurs when the net shortening of, or average strain in, the tube reached a level that corresponds to the average strain at the load maximum under monotonic loading. This provides a practical way of estimating the life expectancy of a wrinkled tube that is experiencing cyclic loading.

Limam *et al.* (2010) investigated the bending capacity of long cylinders under different values of internal pressure and the factors that affect it using both experiments and analyses. It was shown that internal pressure can significantly stabilize the structure by delaying localization and collapse, provided that the material exhibits sufficient ductility and the tube is relatively free of imperfections. The onset of wrinkling and the associated wrinkle wave length were well simulated by the bifurcation buckling formulation, and also the evolution of wrinkling and its eventual localization by the FE shell model in which the inelastic material response including yield anisotropies and the initial geometric imperfections are accurately considered.

Current design practice to assess the collapse resistance of corroded pipelines is based on the conservative approaches such as those in which thickness losses at corrosion defects are extended to the entire circumference. The typical corrosion defects, however, have more localized features, such as corrosion pits, small patches, axial or circumferential grooves. Chen *et al.* (2011) investigated the effect of corrosion defects on the collapse capacity of corroded pipelines under external pressure using finite element method. The numerical results were validated with the full-scale collapse tests. A reliability-based practical assessment method to determine the remaining collapse capacity was developed through extensive sensitivity and probabilistic studies. The selected example showed that when the proposed criteria were applied, the remaining capacity was considerably higher than assumed in current practice.

Li *et al.* (2011) investigated the burst capacity of steel pipeline with a colony of corrosion defects under internal pressure, i.e. longitudinal and circumferential aligned double corrosion defects. A basic combination of a pair of defects called as compound aligned defects was proposed with the concepts of effective corrosion width and effective corrosion length. Considering the interacting between adjacent defects and all possible combinations of defects, an assessment method of the burst capacity were presented. The predicted failure pressure was compared with the measured failure pressure from burst tests and the improved agreement with experimental results was obtained compared to the prediction by the existing methods.

A promising possibility to reduce costs in pipelines that require corrosion resistant alloys (CRA) is the use of lined pipe, consisting of a carbon steel load-bearing outer pipe that provides the structural capacity and a corrosion-resistant alloy (CRA) liner, protecting the carbon steel outer pipe from the transported corrosive product. Hilberink *et al.* (2010, 2011) performed a series of numerical and experimental studies on the mechanical behaviour, including a liner wrinkling, of Tight Fit Pipe (TFP) under axial compression and also that under bending. TFP is a type of lined pipe, where the CRA liner is fitted inside the carbon steel outer pipe through a thermo-hydraulic manufacturing process. The effect of mechanical parameters, such as the friction between liner and outer pipe, initial hoop and axial stresses, initial imperfections on the deformation and load carrying capacity was investigated. Vasilikis and Karamanos (2011) investigated the buckling of clad pipes under bending and external pressure including the difference in the mechanical behaviours between TFP and Snug Fit Pipes (i.e., stress free liner initially in contact with the outer pipe).

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Some other concepts for submarine pipelines have been studied. Recent advances have been made for the better understanding of the strength of pipe-in-pipe and sandwich pipe systems. Goplen *et al.* (2011) made an analytical estimate of the global buckling of pipe-in-pipe systems under axial loads generated by differential pressure and thermal change. They concluded that the recommendations of DNV OS F101 and DNV RP F110 can be used to design and estimate the global bucking of such structures.

In view of the large application of flexible pipes and hoses on offshore industry, many researchers have dedicated their studies to the comprehension of such structures. The layers strength of flexible pipes was studied individually by several authors. Neto *et al.* (2010) has obtained the burst pressure of the pressure armor layer comparing the results of three different FE models and an analytical approach. Pesce *et al.* (2010) proposed a numerical-analytical-experimental study to get the crushing capacity of the interlocked carcass layer. Nogueira and Netto (2010) developed a simple FE model of the same layer to obtain its collapse pressure. Although these recent works are relevant for the complete understanding of the ultimate strength of such structures, much more must be done to have conclusive results.

The behavior of a flexible pipe under axial compression was studied by Sousa *et al.* (2010) through a numerical-experimental approach. The nonlinear FE model representing all the structural layers of the flexible pipe is theoretically coherent and seems to represent the axial stiffness of the structure, but the onset of the collapse cannot be detected precisely, when compared with the experimental results. The same FE model was employed by Merino *et al.* (2010) to conduct the strength study of a flexible pipe under torsion. The results showed that the correct characterization of friction between layers plays an important role in this case.

The ultimate limit state of composite hoses for fluid transferring operation (offloading) was obtained by Lassen *et al.* (2010) from experimental tests of combined bending and tension loads. Therefore, in view of the reduced number of samples employed (two) it is difficult to have conclusive results. The complex structure of a cryogenic flexible hose to LNG transferring operations was studied by Bardi *et al.* (2011). The ultimate strength of the corrugated layers was determined with the aid of a FE model under loadings of tension, compression, bending, torsion and internal pressure.

Concerning the ultimate strength of tubular joints, Lie and Yan (2011) developed a method of plastic collapse loads of cracked square hollow sections (SHSs) T-, Y- and K-joints. The concept of a reduction factor F_{AR}, which has been adopted in BS7910 but validated only for cracked circular hollow sections (CHSs) T-, K- and DK-joints, was applied to SHS T-, Y- and K-joints. The numerical plastic collapse strength was also calculated by the nonlinear finite element method using the twice elastic compliance method. It was found that the plastic collapse loads predicted by the reduction factor were on the 10–15 % conservative side compared to the numerical results, and that the numerical plastic collapse loads were in good agreement with the full-scale experimental tests results.

Advanced methods of well completion and enhance oil recovery are increasingly implemented in many existing offshore oil & gas fields to continue production. Structural Integrity Management (SIM), or Platform Re-assessment and Rehabilitation (RRR), is a key to extending the useful life of offshore platforms that support the infrastructure. Puskar *et al.* (2006) summarised background details on the development of the API Recommended Practice (RP) 2SIM to offer in-depth guidance on risk-based inspection, assessment, upgrades and repairs, and platform decommissioning. Marshall

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and Choo (2009) provided an overview of the SIM research at National University of Singapore and re-assessments conducted to support the case for renewed drilling offshore California.

The International Institute of Welding (IIW) sub-commission XV-E members have conducted extensive research in recent years on tubular (also referred as circular hollow section, CHS) connections or joints. Zhao *et al.* (2010) summarised the IIW static design recommendations for welded tubular joints. These recommendations refer to the key technical contributions that included the investigations on effects of chord length and boundary conditions on CHS T- and X-joints (van der Vegte and Makino, 2010), strength of thick-walled joints (Qian *et al.*, 2009), moment capacity of CHS joints (van der Vegte *et al.*, 2010), and evaluation of the CHS strength formulae to design strengths (van der Vegte *et al.*, 2009). Detailed comparisons of the new IIW strength formulae to those of API RP2A were provided by Wardenier *et al.* (2009).

5.1.6 Influence of Fabrication-related Initial Imperfections

The primary load for which ship hull girders are designed is wave-induced longitudinal bending. The bending stresses are resisted by longitudinally stiffened plates that can also contain residual stresses caused by the fabrication of the structure. The welding process has a significant influence on the fabrication factors associated with distortion and the residual stress of the steel stiffened panels that are representative of ship and offshore structures. The shape of the residual stress field can often be approximated for a butt welded panel or a panel's fillet welded stiffener if a single pass weld is performed. In the longitudinal direction, a high tensile value in the weld region (often close to the yield stress value) is balanced by a lower compressive value away from the weld region. However, the shape of the weld residual stress field may be more complicated if more weld passes are needed to complete a weld joint, or if the panel or structure to be welded is restrained during the welding process, as is the case when fabricating larger structures. Moreover, depending on the location of the panels in the ship's structure, the residual stresses in welds may be partly or fully redistributed or relaxed during the elastic shakedown caused by overloads during the operation of the ship's hull structure. In addition to residual stresses, the welding process also forms residual deformations in the panel, particularly out-of-plane deformations or so called fabrication imperfections which in most cases are detrimental to the ultimate strength.

Focusing on welded stiffened panels that are mainly subject to axial compression, the welding deformations are normally difficult to obtain from numerical FE-analyses because the complete assembly and fabrication process and possibly the change in shape during overload under operation must be simulated. One option is to measure out-of plane deformations during the fabrication and during service. When measured distortions are not available, there are three possible methods to account for the initial imperfection in FE-analyses (Amlashi and Moan, 2008):

1. Use the lowest buckling modes obtained from an eigen mode analysis.
2. Use Fourier displacement function (sinusoidal variation in the plane of the panel) for the deformation modes of interest. The generated coordinates are given directly to the nodes.
3. Use the initial imperfections resulting from a pseudo-static analysis.

A disadvantage of method (1) is that it may be difficult to extract the buckling modes of interest from the eigenvalue analysis for large-scale or complicated structures. An enhanced technique changes the geometry properties, such as plate and stiffener thickness, to decouple the local deformations of interest from the lower eigen modes, fol-

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lowing Amlashi and Moan (2008) and Xu and Guedes Soares (2011a, 2011b). The modes of interest are the local plate panel deflection, the column-type initial deflection of stiffeners, the pure torsional deflection of stiffeners, and the sideways initial deflection of stiffeners. Method (2) contains there two typical approaches for the initial deflection of a local plate panel. The first is to consider the lowest elastic buckling mode, and the second is to consider the more realistic shape of initial deflection from the thin-horse mode expressed by the sum of several sinusoidal deflection components. When the same maximum amplitude is assumed, the ultimate strength obtained by the former approach normally falls on the conservative side. Method (3) has a less rational background.

The imperfection amplitudes to be used are often determined according to design codes and based on statistical data from actual panels, however, in practice the amplitude may vary from case to case. The common proposal for steels is that the amplitude $w \sim \beta$ or β^2, where β is the plate slenderness ratio, $\beta = (b/t)\sqrt{\sigma_Y/E}$, where b = breadth of panel, t = thickness of panel, σ_Y = yield stress, and E = Young's modulus for the plate material. The value of the proportionality factor depends on the severity of the fabrication imperfection. One may also put $w \sim a,b$ (length or breadth of the panel, respectively).

Gannon *et al.* (2009) developed a finite element model capable of simulating thermo-mechanical welding process and examined the distortion and residual stresses generated during welding for different welding sequences. The distribution pattern of the longitudinal residual stress was not significantly influenced by the welding sequence; however, it did affect the peak values. The welding-induced distortions were influenced by the welding sequences and the predicted magnitude of the distortions was of a lower magnitude than the typical values suggested in the literature.

Gannon *et al.* (2011) studied the influence of welding residual stresses and deformation on the strength of tee-stiffened panels under axial compression. Residual stresses were obtained from a full thermo-mechanic simulation. Prior to the strength analysis, the panel was subject to axial shakedown loads that reduced both the tensile welding stress peaks and the amplitudes of the welding deformations. A partial relief of welding stresses was found to increase the ultimate strength somewhat, neglecting residual stresses and only considering fabrication imperfections to produce what was seen as an overly optimistic hull girder strength.

Paik and Sohn (2012) investigated the effect of welding residual stresses in a butt welded plate subject to axial compression. The welding stresses were introduced as a simplified, uniaxial initial stress field. Welding deformations were modeled as a sinusoidal field in two directions and the results revealed that longitudinal residual stresses influenced the maximum load level for thicker plates. Transverse residual stresses were also less important before buckling for the axial load situation.

Loose (2008) analyzed the stability of cylindrical shells and the influence of residual stresses and deformations introduced by a single pass circumferential weld using FEA. The influence of the different weld sequences on the radial deformation and shell stability was quantified.

Several papers investigate the influence of fabrication-induced imperfections on the ultimate strength of stiffened plates (panels) under axial compression or combined axial and transverse compression and lateral pressure. In these cases the fabrication residual stress field was not considered. Chaithanya *et al.* (2010) compared two different shapes, namely a sinusoidal variation and a cusp-shaped variation, for plate, stiffener

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bowing, and stiffener warping imperfections. Khedmati *et al.* (2009a, 2009b) studied the influence of three different fillet welding procedures for stiffener to plate junction lines in stiffened plates subject to axial and transverse compression. The methods were continuous welding, chained intermittent welding, and staggered intermittent welding – all of which were considered through the modeling of the weld stiffness. Intermittent welding was found to reduce the ultimate strength.

Different methodologies for determining the ultimate strength of stiffened panels have been compared by Zhang and Khan (2009), Paik and Seo (2009b), Paik *et al.* (2011b), Frieze *et al.* (2011), and Wang *et al.* (2010) using sinusoidal variations or linearized buckling modes as fabrication imperfections and with imperfection amplitudes taken from recommendations based on experience. While typical shapes of initial deflection found in actual ship plates are summarized in textbooks (e.g., Paik and Thayamballi, 2003), some studies such as Ueda and Yao (1985), Paik and Pedersen (1996), Fujikubo *et al.* (2005), and Cho *et al.* (2011) used the initial deflection that resembles the thin-horse mode. The influence of the shape of initial plate deflection on the ultimate strength of stiffened panels has also been studied by this committee.

For welded aluminium panels, there is a special complication caused by the softening of HAZs during fusion welding, presumably caused by the annealing of the HAZs during the temperature cycle experienced during welding. This results in a lower yield strength in the HAZs, which normally reduces the ultimate strength.

Yoon *et al.* (2009) studied the buckling of a stiffened square Aluminium panel where Friction Stir Welding was used for the fabrication. Two or three stiffener cases were studied. Welding residual stresses were not included and fabrication imperfections were introduced using a buckling mode. The presence of the FSW (with a resulting lower yield strength) reduced the ultimate strength for the panel by 3 %–10 %.

Benson *et al.* (2011) studied the ultimate strength of aluminium plates subject to axial and compressive loading. Welding residual stresses were modelled using a simplified, uniaxial stress field (initial stress) and fabrication imperfections using sinusoidal variations. The softening of the HAZ is seen top have a significant influence on the ultimate strength, whereas the residual stress filed has a moderate effect except for the most stocky plates analyzed.

5.1.7 Influence of In-service Damage

Significant research has been conducted on the ultimate strength of plates and stiffened panels with in-service damage such as corrosion wastage, fatigue cracking, and mechanical damage.

Ahmmad and Sumi (2010) investigated the strength, deformability, and energy absorption capacity of steel plate specimens with pitting corrosion or general corrosion and subject to uniaxial tension, both experimentally and numerically. The pitted surface of the specimens was generated using a CAD/CAM technique and the same model was employed for nonlinear 3D-solid FE analysis. The strength reduction factor given by Paik *et al.* (2003) for the compressive strength of pitted plates was also applicable to the tensile strength reduction factor. The empirical formulae to estimate the reduction in deformability and energy absorption capacity due to pitting corrosion and general corrosion were proposed. Islam and Sumi (2011) studied the effects of pit shape (i.e., conical or ellipsoidal) and plate size on the strength and deformability of corroded steel plates. Strength and deformability increased along with the plate width and decreased along with an increasing length. In addition, while the size effect was

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not so significant for a plate wider than 500 mm, deformability was affected in a much wider range.

Silva *et al.* (2011) investigated the effect of randomly distributed nonuniform corrosion on the ultimate strength of rectangular plates under axial compression using shell FE models. Based on analyses of the surface geometry of 570 plates as generated by Monte Carlo simulation, empirical formulae for predicting strength reduction due to corrosion was developed. Jiang and Guedes Soares (2011) studied the ultimate strength of pitted mild steel plates under biaxial compression.

As for the effects of cracking damage, Paik (2009) analysed the residual ultimate strength of steel plates with longitudinal cracks under axial compression, by ANSYS nonlinear FEM. The effects of crack orientation, crack location, crack size, plate thickness and plate aspect ratio on the residual ultimate strength were discussed. It was found that either longitudinal-inside cracks or longitudinal-end cracks more significantly reduced a plate's ultimate strength under axial compression because the location of these cracks approached the plate's edge. The results were deemed to be a starting point for designing cracking damage-tolerant steel-plated structures and to assess and monitor the condition of aging steel-plated structures with cracking damage. A numerical study on the influence of crack location and crack length on the ultimate strength of a steel plate under longitudinal compression was also conducted by Bayatfar *et al.* (2011). The most critical type of cracks were transversally located in the longitudinal (unloaded) edges of an imperfect plate component.

Wang *et al.* (2009) discussed the residual ultimate strength of structural members with multiple crack damage in tension by employing nonlinear FE methods. The existence of small, disturbing cracks reduced the ultimate strength relative to a single-cracked plate, although such cracks in low-stress regions can be ignored in residual ultimate strength assessment. The obtained results provided an initial basis for considering the multi-crack problem, but further studies are needed, including crack propagation under combined loads.

Witkowska and Guedes Soares (2009) showed, numerically, that local damage to the stiffener could change the collapse mode of the plate and decrease its ultimate strength. The reduction of strength depended on the location of the dent and the initial global deflection. According to cases with more than one type of existing damage, the behaviour of a plate depends mostly on whichever type of damage is more dominant. Liu and Amdahl (2009) conducted a numerical simulation of the residual strength of a damaged double bottom. The initial damage was caused by a variety of indenters. A single stiffener model was proposed to predict the residual strength of the double bottom and an analytical equation was derived.

Amante and Estefen (2011) carried out the collapse test of six small-scale stiffened panels fabricated by special techniques to keep them in accordance with the usual full-scale tolerances related to initial geometric imperfections (Estefen *et al.*, 2007). The longitudinal length of the models was 178 mm, the transverse length was 268 mm, the plate thickness was 1.03 mm, and the stiffener space was 53.6 mm. tee-bar stiffeners ($21.6 \times 0.77 + 21.6 \times 1.03\, mm$) were TIG welded to the plate. The nonlinear finite element analysis considering the initial shape imperfections obtained by measurements showed good numerical experimental correlations in the collapse behaviour of both intact and damaged stiffened panels. The results indicated that damage located at the stiffener was potentially worse for the panel's overall ultimate strength than the damage to the plate.

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5.2 Systems

5.2.1 Ship-shaped Structures

An essential step of the safety check performed on ship-shaped structures is the assessment of the progressive collapse behaviour and ultimate strength of the hull girder. Simplified methods, such as the Smith method, ISUM (idealised structural unit method), ISFEM (intelligent supersize finite element method, Hughes and Paik, 2010), and empirical methods are usually employed in the ultimate strength analysis of hull girders. However, the continued growth of computer capabilities and an advance in robust nonlinear finite element methodologies have made it possible to carry out the nonlinear finite element analysis of ultimate hull girder strength with reasonable computational effort and proper modelling.

Amlashi and Moan (2008, 2009) developed a methodology for the nonlinear finite element modelling of holding tanks in a bulk carrier under different alternate hold loading conditions (i.e., fully loaded cargo and (partially) heavy cargo) that used the Abaqus program. A critical review of the external and internal design pressures for different alternate hold loading conditions was accomplished using both CSR-BC rules and DNV rules. The implications of using different design pressures on the hull girder strength were assessed. The FE results were then used to contribute to the development of simplified methods that are applicable to the practical design of ship hulls under combined global and local loads. Factors in the influence of double bottom bending such as initial imperfections, local loads, stress distribution, and failure modes on the hull girder strength were discussed. Simplified procedures for determining the hull girder strength of bulk carriers under alternate hold loading conditions were also discussed in light of the FE analyses.

Progress has been made in the reliability assessment of bulk carriers under alternate hold loading conditions based on the achievements of nonlinear finite element analyses. Amlashi and Moan (2011) proposed a reliability-based approach that fulfilled the semi-probabilistic design criteria for the ultimate hull girder strength of bulk carriers under alternate hold loading conditions with an emphasis on combined global and local loads. They found that the interaction formula proposed for bulk carriers under local pressures resulted in a consistent safety level. However, the model uncertainty in the prediction of the ultimate pressure should be more thoroughly assessed. The effect of correlations between global and local loads for both still-water and wave loads was found to be relatively important. Shu and Moan (2011) adopted an interaction equation based on the ultimate hull girder strength assessment obtained by nonlinear finite element analyses to consider the relationship between ultimate longitudinal bending capacity and average external sea pressure over the bottom. They showed that the local lateral pressure had a significant influence on the annual probability of bulk carrier failure in hogging and alternate hold loading conditions.

Okasha and Frangopol (2010) proposed a probabilistic approach to determine the strength of the ship hull where the ultimate strength of the hull girder was found using an optimization search algorithm modelling stiffened panels deterministically according to an IACS methodology. The best-fit probability distribution of the ultimate strength of the ship hull was provided. Vhanmane and Bhattacharya (2011) discussed the effect of randomness in yield strength and initial imperfections on ultimate hull girder strength. Different levels of statistical dependence between yield strength and the initial imperfection of stiffeners and the plating between stiffeners

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have been considered. The methodology was applied to a bulk carrier and a VLCC tanker.

Significant progress has also been noted in both empirical and simplified approaches for predicting ultimate hull girder strength. Paik *et al.* (2011a) extended the Paik-Mansour formula for the ultimate strength calculations of ship hulls subject to vertical bending moments. The original method did not allow for the expansion of the yielded part in the vertical members, but rather limited this part to the tension flange (i.e., the deck panel in hogging conditions and the outer bottom panel in sagging conditions). The modified method permitted the expansion of the yielded part, thereby allowing the pure vertical bending moment condition to be achieved regardless of the geometrical properties of the hull cross-sections or the vertical bending loading direction. The modified Paik-Mansour formula gave an improved estimate of the ultimate strength that was in good agreement with the ANSYS and ALPS/HULL method predictions.

Yao *et al.* (2009) developed a total system that included a capacity calculation and applied the most recent version of ISUM method developed by Fujikubo and Kaeding (2002), in addition to the load calculation for the progressive collapse analysis of a ship's hull girder under longitudinal bending. Pei *et al.* (2011) applied this ISUM system to the collapse analysis of a container ship model under combined bending and torsion, considering the initial deflection and welding residual stresses. Good agreement was reached with the results of the collapse test carried out by Tanaka *et al.* (2009). The ultimate strength of the hull girder under combined global and local loads depended on the accuracy of the collapse analysis of double hull structures. The ISUM code for the double hull structure, considering shear and lateral pressure along with thrust and welding residual stresses, was developed by Gao *et al.* (2011) and applied to the double bottom structures.

Wang *et al.* (2011) applied three different methodologies of hull girder ultimate strength assessment to the hull girder ultimate strength calculations of six different FPSO designs. The three methodologies were the incremental-iterative approach by Sun and Wang (2005b), the HULLST method developed by Yao and Nikolov (1991) based on Smith's method, and the ISUM of Fujikubo and Kaeding (2002). All three methods showed good agreement in terms of the hull girder ultimate strength calculation of selected FPSOs. In general, the prediction of HULLST and ISUM are almost identical for most cases, although Sun and Wang's method produced slightly conservative results.

An issue was raised by Lehman (2006) in his official discussion of the report from Committee III.1, ISSC2006; i.e., the calculation of the moment versus curvature curves beyond the maximum sustainable bending moment is far from realistic.The natural world is, however, not controlled by pathways, but by forces. The input of a curvature does not adequately represent the failure process. To determine the realistic failure process of a hull girder when it is subjected to external loads that exceed its ultimate capacity, the progressive collapse analysis – including the effects of inertia forces and the interaction between fluid forces and structural deformations – is needed. The consequence or the severity of the failure calculated by such advanced analyses may be utilised in the risk assessment of the hull girder collapse of ships.

Xu *et al.* (2011a) investigated the dynamic collapse behaviour of a ship's hull girder in waves. The ship's entire hull was modelled as a two-rigid-bodies system connected by a rotational spring, which represented the nonlinear relation between the displacement and the moment. Nonlinear strip theory was used to solve the force equilibrium

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of the two bodies. The approach was validated against tank tests, which showed that the collapse increased rapidly after the ultimate strength was reached, and the plastic deformation grew until unloading started and the bending rigidity recovered. Xu *et al.* (2011b) proposed a numerical analysis system to predict the collapse behaviour in waves, including the post-ultimate strength behaviour of ship hulls. An analytical solution to describe the post-ultimate strength behaviour was proposed. They found that the plastic deformation could be characterised by the magnitude of the load and the post-ultimate strength of the hull girder in addition to the load frequency. They also found that the plastic collapse under whipping loads after slamming is less significant.

Yang *et al.* (2011) investigated the structural dynamic buckling strength of containership bow structures subjected to impact force using a finite element method. A transient dynamic program was used in which the wave impact pressures were obtained by applying the semi-empirical formula established by Lloyd's Register. The results revealed that the impact force integration was the dominant factor in the structure buckling strength assessment.

The text book titled *Ship Structural Analysis and Design* (Hughes and Paik, 2010) presents the fundamental theories for ultimate strength of ship hulls.

5.2.2 Other Marine Structures

A variety of types of structures are used for offshore applications depending on the required functions and working conditions. Ye *et al.* (2011) investigated the ultimate strength of a typical drilling semisubmersible platform subjected to typical hydrodynamic loads using nonlinear finite element method. The final collapse mode of each case was found to have a close relationship to the corresponding wave load case. The initial yielding point due to split force is generally on the horizontal brace and that due to bending moment is at the regions of pontoon longitudinal centreline bulkhead around column. Pontoon and column connections are vulnerable regions to shear force and torsional moment.

Despite the efforts to reduce ship accidents, the collision between supply vessels and offshore platforms continues to happen. Amante *et al.* (2010) investigated the residual strength of a semisubmersible platform column damaged by a supply vessel collision. Finite element method simulations were performed considering material and geometric nonlinearities, initial fabrication imperfections, friction and contact formulations. The column damages due to the sideway and bow collisions of the conventional and bourbon types supply vessels with different collision energies were calculated and then the residual strength of the damaged columns under axial loading was studied to estimate the safety margin associated with the column structural capability after the collisions.

5.2.3 Influence of Fabrication-related Initial Imperfections

Kippenes *et al.* (2010) performed a nonlinear finite element (FE) analysis of a 170.000 DWT capsize bulk carrier. A three cargo hold FE model with a detailed representation of the geometry was developed. Different combinations of vertical bending moment, sea pressure, and cargo load were considered. Transverse stresses giving the long-waved buckling of the hopper plating were induced during the progressive collapse for an analysis of the initially perfect model in alternate hold loading. Two kinds of FE models with and without initial geometrical imperfections in the hopper, bilge, and side shell were analysed. Initial geometrical imperfections were seen to reduce the hull girder's ultimate strength in alternate hold loading by 5 %. The effect of geometrical imperfections for real welded structures is expected to be even less.

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Estefen *et al.* (2010) determined the ultimate strength of the middle section of a bulk carrier due to longitudinal bending moments using FEA. The influence of a repair weld in the upper wing tank was studied. The ship section was assumed to have sinusoidal variations of the fabrication-induced imperfections. For the plates in the upper wing area, imperfections after repair welding were measured in-locus using laser technology. The repair weld was also modelled using activating elements, hence the weld stiffness was included but the residual stresses were not. The analysis was able to identify panels and stiffeners that should be reworked to avoid damage during operation.

5.2.4 Influence of In-service Damage

The effect of corrosion on the ultimate strength of hull girders has been investigated by several research groups. Wang *et al.* (2008) performed a statistical study of the time-variant hull girders of tankers using a database of as-gauged hull structures. The expanded data set was collected from 2195 as-gauged girth belts (transverse sections) of 211 single-hull tankers that were 12–32 years old. The data set demonstrated a high variation of hull girder section moduli that changed over time. They showed that almost all previous studies estimated a much greater HG loss than what this database revealed.

Saad-Eldeen *et al.* (2011) performed an experimental assessment of the ultimate strength of a severely corroded box girder subjected to a uniform bending moment resulting from four-point loading. Three box girders capable of simulating the behaviour of midship sections were deteriorated in a corrosive seawater environment to simulate different levels of corrosion degradation in ageing ship structures. It was concluded that the load-carrying capacity and ultimate bending were highly affected by the corrosion deterioration of plating and material property changes. An interpretation of the latter should confirm that the effective elastic modulus and yield strength were reduced due to the local undulating material surface resulting from corrosion.

Notaro *et al.* (2010) performed comprehensive nonlinear analyses of a Bulk Carrier, a FPSO vessel, and a container vessel that were documented under different damage conditions. The damage size and shape were varied systematically, considering likely collision and grounding scenarios. Full ship width models were used to account for asymmetric damages. Other issues considered included FE model extension, the extension of the damages, boundary/transverse frame supports, and the model imperfection shape of the intact areas. It was found that the effect of the damage extent in the vertical and transversal directions was more critical than it was in the longitudinal direction, and the damage modified the location of the neutral axes, inducing higher stresses in proximity to the damaged areas.

6 BENCHMARK STUDIES

To validate some of the selected methods that are applicable in the ultimate strength calculations of ship and offshore structures, and also to investigate the ultimate strength characteristics, benchmark studies were undertaken on unstiffened plates, stiffened panels, and hull girders. Because of page limits, the benchmark study results are briefly summarized in this report, while details of the benchmark studies will be published in a separate article.

6.1 Candidate Methods

Table 2 – 4 indicates the candidate methods selected for the present benchmark studies.

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Table 2: Candidate methods for unstiffened plates

Method/Tool	Symbol	Working Organization
ALPS/ULSAP	ALPS/ULSAP (PNU)	Pusan National University
DNV/PULS	DNV/PULS (DNV)	Det Norske Veritas
ANSYS	ANSYS (ULG) ANSYS (IRS)	University of Liege Indian Register of Shipping
MSC/MARC	MSC/MARC (OU)	Osaka University

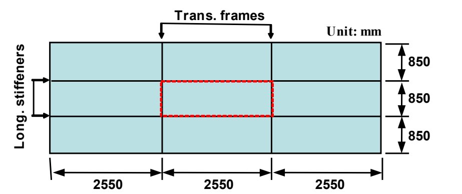
Table 3: Candidate methods for stiffened panels

Method/Tool	Symbol	Working Organization
ALPS/ULSAP	ALPS/ULSAP (PNU)	Pusan National University
BV Advanced Buckling	BV Advanced Buckling (BV)	Bureau Veritas
DNV/PULS	DNV/PULS (DNV)	Det Norske Veritas
Abaqus	ABAQUS (NTUA) ABAQUS (DNV)	National Technical University of Athens Det Norske Veritas
ANSYS	ANSYS (ULG) ANSYS (IRS) ANSYS (PNU)	University of Liege Indian Register of Shipping Pusan National University
MSC/MARC	MSC/MARC (OU)	Osaka University

Table 4: Candidate methods for hull girders

Method/Tool	Symbol	Working Organization/Reference
Test (1/3-scale frigate model)	Test result	Dow (1991)
Modified Paik-Mansour method	Modified P-M at ULS (PNU)	Pusan National University (Paik *et al.*, 2011a)
RINA Rules	RINA Rules (UoG)	University of Genova
Common Structural Rules	CSR (BV) CSR (CR) CSR (PNU)	Bureau Veritas China Corporation Register of Shipping Pusan National University
ALPS/HULL ISFEM	ALPS/HULL (PNU)	Pusan National University
Abaqus	ABAQUS (CR)	China Corporation Register of Shipping
ANSYS	ANSYS (IRS) ANSYS (PNU)	Indian Register of Shipping Pusan National University
ISSC 2000	ISSC 2000	ISSC (2000)

Table 5: Geometric and material properties of target plates

Geometric and material properties	Nomenclature
• Yield stress of plate, $\sigma_{Yp} = 313.6\,N/mm^2$ • Elastic modulus, $E = 205800\,N/mm^2$ • Poisson's ratio, $\nu = 0.3$ • Plate length, $a = 2550\,mm$ • Plate breath, $b = 850\,mm$ • Plate thickness, $t_p = 9.5,11,13,16,22,33\,mm$ • Under biaxial compressive loads	

6.2 Target Structures

6.2.1 Plates

Plates surrounded by longitudinal stiffeners and transverse frames are selected as the target structure of the benchmark studies. The geometric and material properties of target plates are defined as shown in Table 5.

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Table 6: Panel A and Panel C

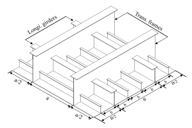
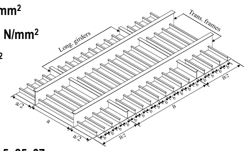
Panel A: Bottom of a bulk carrier	Panel C: Deck of a double hull tanker
• Yield stress of plate, σ_{Yp} = 313.6 N/mm^2 • Yield stress of stiffener, σ_{Ys} = 313.6 N/mm^2 • Elastic modulus, E = 205800 N/mm^2 • Poisson's ratio, v = 0.3 • Plate length, a = 2550 mm • Plate breath, b = 850 mm • Plate thickness, t_p = 9.5, 11, 13, 16, 22, 33 mm • Number of stiffeners: 2 stiffeners in a panel  	• Yield stress of plate, σ_{Yp} = 313.6 N/mm^2 • Yield stress of stiffener, σ_{Ys} = 313.6 N/mm^2 • Elastic modulus, E = 205800 N/mm^2 • Poisson's ratio, v = 0.3 • Plate length, a = 4750 mm • Plate breath, b = 950 mm • Plate thickness, t_p = 11, 12.5, 15, 18.5, 25, 37 mm • Number of stiffeners: 8 stiffeners in a panel 

Table 7: Geometry of stiffeners considered

Dimensions [mm]

	Flat bar (h_wxt_w)	Angle bar (h_wxb_fxt_w/t_f)	Tee bar (h_wxb_fxt_w/t_f)
Size 1	150x17	138x90x9/12	138x90x9/12
Size 2	250x25	235x90x10/15	235x90x10/15
Size 3	350x35	383x100x12/17	383x100x12/17
Size 4	550x35	580x150x15/20	580x150x15/20

Nomenclature

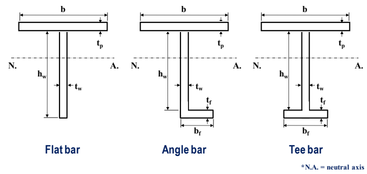


Table 8: Coefficients of the initial distortion equations

Methods	A_0	B_0	C_0
ALPS/ULSAP, ALPS/HULL, Abaqus, ANSYS, MSC/MARC	$0.1\beta^2\, t_p$	$0.0015\, a$	$0.0015\, a$
DNV/PULS	$b/200$	$0.001\, a$	$0.001\, a$

6.2.2 Stiffened Panels

Stiffened panels surrounded by longitudinal girders and transverse frames are selected as the target structure of the benchmark studies. Two types of stiffened panels are considered, namely Panel A and Panel C (see Table 6), which were taken from the bottom panels of a bulk carrier and the deck panels of a very large, double hull crude oil tanker, respectively.

Three types of stiffeners, namely flat bar, angle bar, and tee bar, were considered with varied dimensions as shown in Table 7.

Three types of initial distortions are considered, namely plate initial deflection, the column type initial distortion of the stiffener, and the sideways initial distortion of the stiffener, which can be expressed as follows (Hughes and Paik, 2010).

- Buckling mode initial deflection of plating: $w_{opl} = A_0 \sin \frac{m\pi x}{a} \sin \frac{\pi y}{b}$
- Column type distortion of stiffener: $w_{oc} = B_0 \sin \frac{\pi x}{a} \sin \frac{\pi y}{B}$
- Sideways initial distortion of stiffener: $w_{os} = C_0 \frac{z}{h_w} \sin \frac{\pi x}{a}$

where m = buckling mode of the plate which is defined as a minimum integer satisfying $a/b \leq \sqrt{m\,(m+1)}$. In the present benchmark studies, the coefficients of the abovementioned initial distortion equations are presumed for each of the following candidate methods as shown in Table 8.

6.2.3 Hull Girders

The six kinds of hull structures considered in the present benchmark studies are shown in Figure 4, 5, 6, 7, 8 and 9.

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Stif. No.	Dimensions	Type	σ_Y (MPa)	Stif. No.	Dimensions	Type	σ_Y (MPa)
All deck & shell Longitudinals	38.1×1.78+14×3.3	Tee-bar	245	No. 3 Longitudinal	162×2+51×2	Tee-bar	245
No. 2 Deck	292×6+120×10	Tee-bar	245	No. 7 Longitudinal	117.5×2+51×2	Tee-bar	245
No. 2 Deck bar	60×6	At-bar	245	No. 11 Longitudinal	111×2+51×2	Tee-bar	245
Vertical Keel	228.6×3+51×2	tee-bar	245	No. 3 & 4 Deck	114×5+44.5×9.5	Tee-bar	245

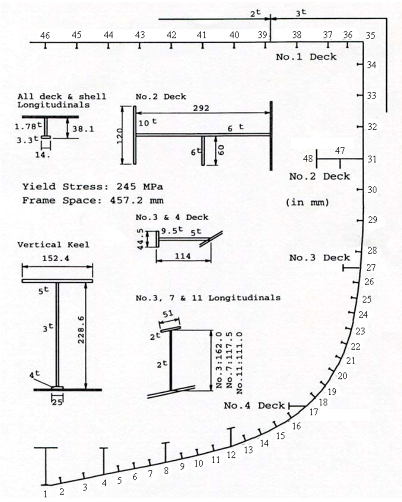

Figure 4: Dow's test hull – 1/3-scale frigate

Stif. No.	dimensions	type	σ_Y (MPa)	Stif. No.	dimensions	type	σ_Y (MPa)
1	300 × 38	at-bar	352.8	9	230 × 10	at-bar	313.6
2	300 × 28	at-bar	313.6	10	300 × 90 × 13/17 IA	angle-bar	313.6
3	250 × 90 × 10/15 IA	angle-bar	313.6	11	150 × 90 × 12/12 IA	angle-bar	313.6
4	250 × 90 × 12/16 IA	angle-bar	313.6	12	250 × 90 × 12/15 IA	angle-bar	313.6
5	300 × 90 × 11/16 IA	angle-bar	313.6	13	150 × 12	at-bar	313.6
6	300 × 90 × 13/17 IA	angle-bar	313.6	14	150 × 90 × 9/9 IA	angle-bar	313.6
7	350 × 100 × 12/17 IA	angle-bar	313.6	15	150 × 10	at-bar	313.6
8	400 × 100 × 11.5/16 IA	angle-bar	313.6	16	300 × 90 × 11/16 IA	angle-bar	313.6

(dimensions in mm)

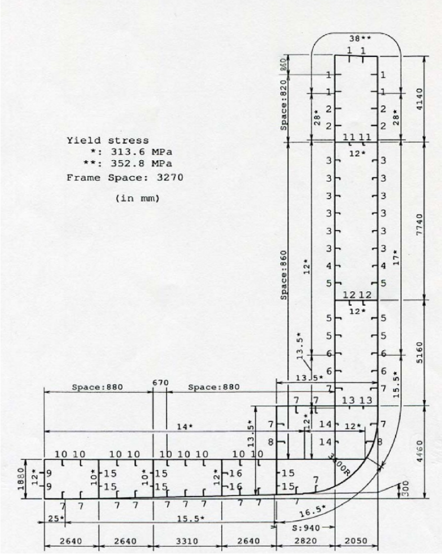

Figure 5: Container ship hull

Stif. No.	dimensions	type	σ_Y (MPa)	Stif. No.	dimensions	type	σ_Y (MPa)
1	390 x 27	at-bar	392.0	8	283 × 9 + 100 × 17	tee-bar*	352.8
2	333 × 9 + 100 × 16	tee-bar*	352.8	9	333 × 9 + 100 × 18	tee-bar*	352.8
3	283 × 9 + 100 × 14	tee-bar*	352.8	10	333 × 9 + 100 × 19	tee-bar*	352.8
4	283 × 9 + 100 × 18	tee-bar*	352.8	11	383 × 9 + 100 × 17	tee-bar*	352.8
5	333 × 9 + 100 × 17	tee-bar*	352.8	12	383 × 10 + 100 × 18	tee-bar*	352.8
6	283 × 9 + 100 × 16	tee-bar*	352.8	13	383 × 10 + 100 × 21	tee-bar*	352.8
7	180 × 32.5 × 9.5	bulb-bar	235.2	14	300 × 27	at-bar	392.0

(dimensions in mm)

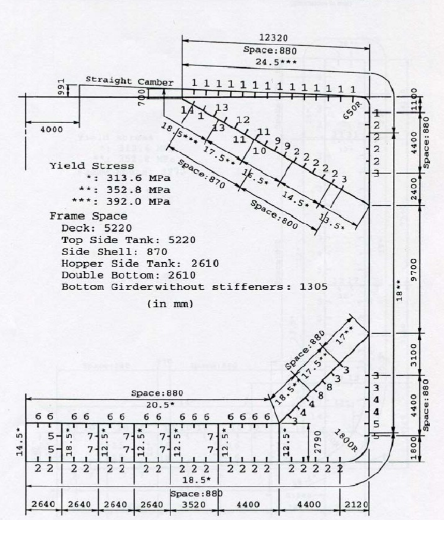

Figure 6: Bulk carrier hull

Stif.No.	Dimension	Type	σ_Y (MPa)	Stif.No.	Dimension	Type	σ_Y (MPa)
1	400×10+150×13	Tee-bar	315.0	20	750×14+200×13	Tee-bar	315.0
2	400×10+150×13	Tee-bar	315.0	21	385×10+125×13	Tee-bar	315.0
3	500×10+150×22.5	Tee-bar	355.0	22	480×10.25+150×24.75	Tee-bar	315.0
4	500×10+150×18.5	Tee-bar	355.0	23	440×10.25+150×20.75	Tee-bar	315.0
5	520×10+150×18.5	Tee-bar	315.0	24	400×10.25+150×16.75	Tee-bar	315.0
6	480×10+150×16.5	Tee-bar	315.0	25	400×10.25+150×14.75	Tee-bar	315.0
7	440×10+150×16.5	Tee-bar	315.0	26	385×10.25+125×13.75	Tee-bar	315.0
8	420×10+150×14.5	Tee-bar	315.0	27	340×10.25+125×13.75	Tee-bar	315.0
9	400×10+150×14.5	Tee-bar	315.0	28	750×14+200×13	Tee-bar	315.0
10	385×10+150×13.5	Tee-bar	315.0	29	385×10+150×13	Tee-bar	315.0
11	500×9.75+150×22.5	Tee-bar	355.0	30	350×100×10.5/15.5	Angle-bar	315.0
12	500×11.5+150×20	Tee-bar	355.0	31	250×13.5	At-bar	315.0
13	480×9.75+150×26.25	Tee-bar	315.0	32	150×13.5	At-bar	315.0
14	440×9.75+150×22.25	Tee-bar	315.0	33	150×10.75	At-bar	315.0
15	400×9.75+150×20.25	Tee-bar	315.0	34	400×100×11.5/16.5	Angle-bar	315.0
16	400×9.75+150×16.25	Tee-bar	315.0	35	385×9.5+150×13	Tee-bar	315.0
17	385×9.75+150×13.25	Tee-bar	315.0	36	385×10+125×13	Tee-bar	315.0
18	385×9.75+125×13.25	Tee-bar	315.0	37	340×9.5+125×13	Tee-bar	315.0
19	385×10.25+125×13.25	Tee-bar	315.0				

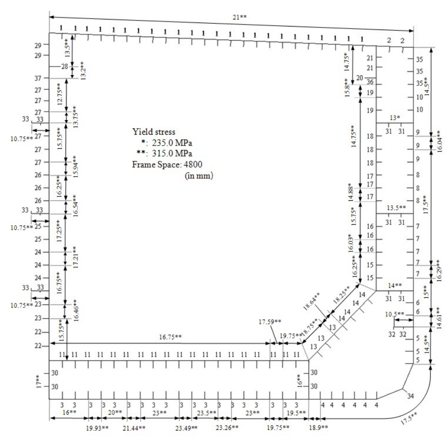

Figure 7: Suezmax class double hull oil tanker hull

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Stif. No.	dimensions	type	σ_Y (MPa)	Stif. No.	dimensions	type	σ_Y (MPa)
1	797 × 15 + 200 × 33	tee-bar*	313.6	17	747 × 12.7 + 180 × 25	angle-bar*	235.2
2	300 × 100 × 11.5/16	angle-bar	313.6	18	797 × 14 + 180 × 25	tee-bar*	235.2
3	370 × 16	at-bar	313.6	19	847 × 14 + 180 × 25	angle-bar*	313.6
4	425 × 25	at-bar	313.6	20	847 × 14 + 180 × 32	tee-bar*	235.2
5	480 × 32	at-bar	313.6	21	847 × 15 + 180 × 25	angle-bar*	313.6
6	300 × 100 × 11.5/16	angle-bar	313.6	22	847 × 15 + 180 × 32	angle-bar*	313.6
7	370 × 16	at-bar	313.6	23	897 × 15 + 200 × 25	angle-bar*	253.2
8	447 × 11.5 + 125 × 22	tee-bar*	313.6	24	945 × 16 + 200 × 25	angle-bar*	235.2
9	549 × 11.5 + 125 × 22	angle-bar*	235.2	25	897 × 15 + 200 × 25	angle-bar*	313.6
10	597 × 11.5 + 125 × 22	angle-bar*	235.2	26	797 × 15 + 180 × 25	angle-bar*	313.6
11	597 × 11.5 + 125 × 22	angle-bar*	235.2	27	347 × 11.5 + 125 × 22	angle-bar*	313.6
12	647 × 11.5 + 125 × 22	angle-bar*	235.2	28	397 × 25	at-bar	313.6
13	350 × 25.4	at-bar	235.2	29	300 × 25	at-bar	253.2
14	646 × 12.7 + 150 × 25	angle-bar*	235.2	30	230 × 12.7	at-bar	253.2
15	697 × 12.7 + 150 × 25	angle-bar*	235.2	31	230 × 12.7	at-bar	253.2
16	747 × 12.7 + 150 × 25	angle-bar*	313.6	32	397 × 11.5 + 100 × 25	tee-bar*	313.6

(*: fabricated by welding; dimensions in mm)

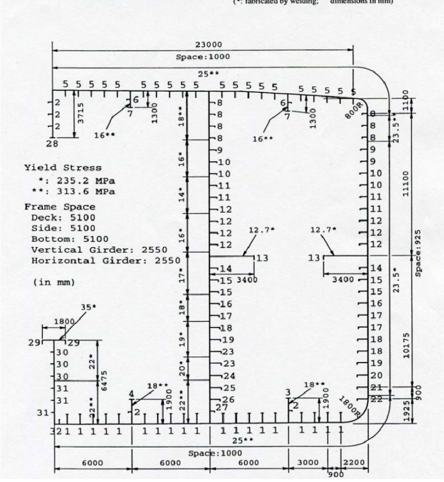

Figure 8: Single hull VLCC hull

Stif. No.	dimensions	type	σ_Y (MPa)	Stif. No.	dimensions	type	σ_Y (MPa)
1	300 × 90 × 13/17 IA	angle-bar	313.6	25	250 × 90 × 12/16 IA	angle-bar	313.6
2	350 × 100 × 12/17 IA	angle-bar	313.6	26	450 × 11 + 150 × 22	tee-bar*	352.8
3	400 × 100 × 11.5/17 IA	angle-bar	313.6	27	450 × 11 + 150 × 19	tee-bar*	352.8
4	400 × 11 + 150 × 12	tee-bar*	313.6	28	450 × 11 + 150 × 16	tee-bar*	352.8
5	400 × 11 + 150 × 14	tee-bar*	313.6	29	450 × 11 + 150 × 14	tee-bar*	352.8
6	450 × 11 + 150 × 12	tee-bar*	313.6	30	450 × 11 + 150 × 12	tee-bar*	352.8
7	450 × 11 + 150 × 14	tee-bar*	313.6	31	450 × 11 + 150 × 14	tee-bar*	352.8
8	450 × 11 + 150 × 16	tee-bar*	313.6	32	400 × 100 × 11.5/16 IA	angle-bar	352.8
9	450 × 11 + 150 × 19	tee-bar*	313.6	33	350 × 100 × 12/17 IA	angle-bar	352.8
10	450 × 11 + 150 × 22	tee-bar*	313.6	34	300 × 90 × 13/17 IA	angle-bar	352.8
11	450 × 11 + 150 × 25	tee-bar*	313.6	35	850 × 17 + 150 × 19	L-bar*	352.8
12	500 × 11 + 150 × 28	tee-bar*	313.6	36	250 × 90 × 12/16 IA	angle-bar	352.8
13	500 × 11 + 150 × 30	tee-bar*	313.6	37	300 × 90 × 12/16 IA	angle-bar	352.8
14	500 × 11 150 × 32	tee-bar*	313.6	38	400 × 11 + 150 × 14	tee-bar*	352.8
15	500 × 11 150 × 34	tee-bar*	313.6	39	450m × 11 + 150 × 12	tee-bar*	352.8
16	550 × 12 150 × 30	tee-bar*	313.6	40	450 × 11 + 150 × 14	tee-bar*	352.8
17	550 × 12 150 × 25	tee-bar*	313.6	41	450 × 11 + 150 × 16	tee-bar*	352.8
18	350 × 100 × 12/17 IA	angle-bar*	313.6	42	450 × 11 + 150 × 19	tee-bar*	352.8
19	550 × 12.5 150 × 32	tee-bar*	352.8	43	450 × 11 + 150 × 22	tee-bar*	352.8
20	500 × 11.5 150 × 30	tee-bar*	352.8	44	450 × 11 + 150 × 25	tee-bar*	352.8
21	500 × 11.5 150 × 28	tee-bar*	352.8	45	450 × 11 + 150 × 28	tee-bar*	352.8
22	500 × 11 150 × 25	tee-bar*	352.8	46	500 × 11 + 150 × 25	tee-bar*	352.8
23	450 × 11 150 × 28	tee-bar*	352.8	47	500 × 11 + 150 × 28	tee-bar*	352.8
24	250 × 12.5	at-bar	313.6	48	230 × 12.5	at-bar	313.6

(*: fabricated by welding; dimensions in mm)

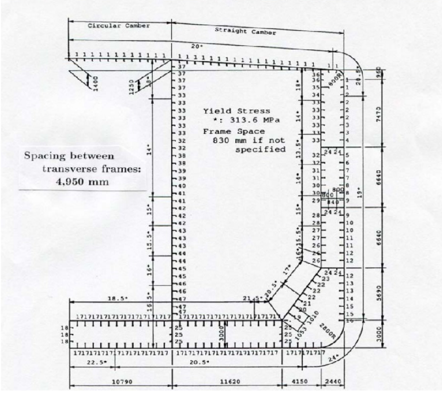

Figure 9: Double hull VLCC hull

6.3 Modelling Techniques

6.3.1 Plates

It is assumed that the four plate edges are simply supported for theoretical computations of ultimate strength. However, the nonlinear finite element methods take into account the effect of rotational restraints along the plate edges. The effects of fabrication-related initial imperfections on plate ultimate strength are also studied.

6.3.2 Stiffened Panels

It is assumed that the four panel edges are simply supported in theoretical methods, while the nonlinear finite element methods more realistically consider the effect of rotational restraints along the panel edges. Three types of finite element method modelling techniques are considered and the effect of initial distortions is also studied.

Figure 12 compares the ultimate strength behaviour of Panel C under longitudinal compressive loads between the one bay/one span model, Figure 10, and the two

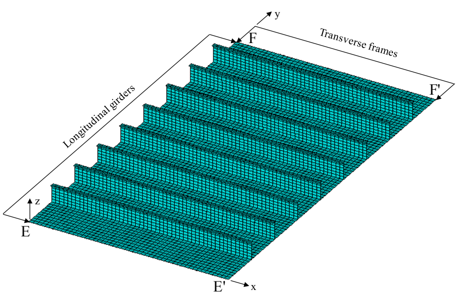

Figure 10: One bay/one span model

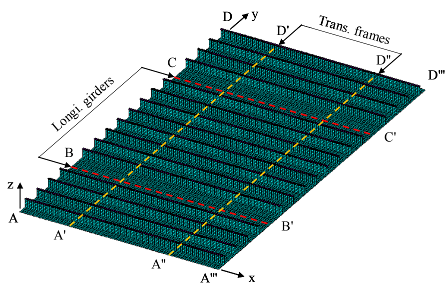

Figure 11: Two bay/two span model

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Table 9: Boundary condition for one bay/one span model

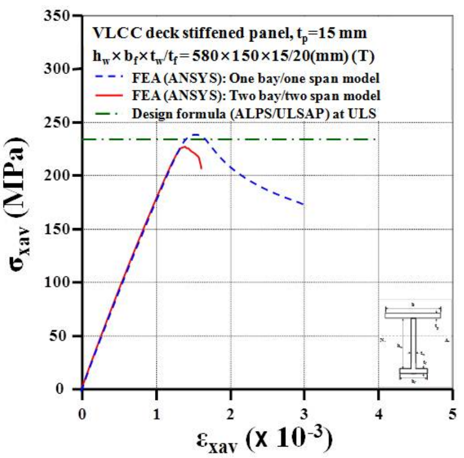
Boundary	Description
$E-E'$ and $F-F'$	Simply supported condition with $R_y = R_z = 0$ and $U_z = 0$, uniform displacement in the y direction (U_y=uniform), coupled with the plate part
$E-F$ and $E'-F'$	Simply supported condition with $R_x = R_z = 0$ and $U_z = 0$, uniform displacement in the x direction (U_x=uniform), coupled with the longitudinal stiffeners

Table 10: Boundary condition for two bay/two span model

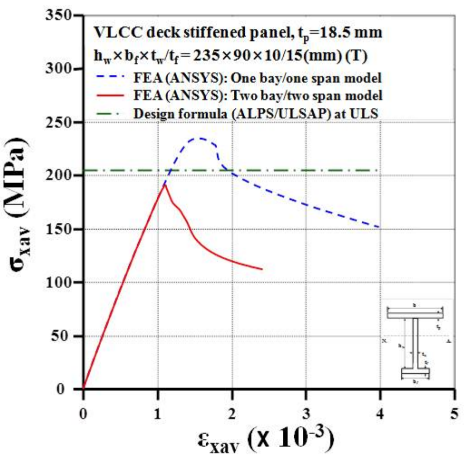
Boundary	Description
$A-A'''$ and $D-D'''$	Symmetric condition with $R_x = R_z = 0$ and uniform displacement in the y direction (U_y=uniform), coupled with the plate part
$A-D$ and $A'''-D'''$	Symmetric condition with $R_y = R_z = 0$ and uniform displacement in the x direction (U_x=uniform), coupled with the longitudinal stiffener
$A'-D'$, $A''-D''$, $B-B'$ and $C-C'$	$U_z = 0$

bay/two span model, Figure 11. The results of the one bay/one span model are usually in good agreement with those of the two bay/two span model, but it is cautioned that the former are significantly larger than the latter in the other case. This is due to the fact that in the former case, the sideways deformations of stiffeners located at the transverse frames are not allowed. It is desirable to apply the two bay/two span model in this regard when the transverse frames may distort before the panel reaches the ultimate strength.

An MSC/MARC nonlinear finite element method analysis was undertaken by Osaka University using two bay/two span models. The boundary condition of the models



(a) Panel C with tee bars (size 4)



(b) Panel C with tee bars (size 2)

Figure 12: Ultimate strength behaviour of Panel C under longitudinal compressive loads

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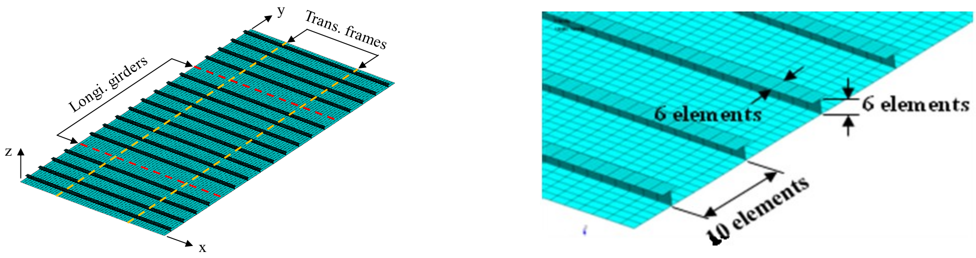

Figure 13: 6,480 elements for Panel A and 37,200 elements for Panel C

for in-plane displacements are as indicated in Table 10, while that for out-of-plane displacements is the periodically symmetric boundary condition. The same mesh sizes were applied regardless of the different sized stiffeners in the stiffened panels, as shown in Figure 13.

An Abaqus nonlinear finite element method analysis was carried out by DNV using a three bay (1/2+1+1+1/2)/one span model, in which only a longitudinal compressive load case was studied (i.e., without transverse compressive loads). The same mesh sizes were applied regardless of the different sized stiffeners in the stiffened panels, see Figure 14. Table 11 indicates the mesh sizes applied for the Abaqus nonlinear FEA by DNV.

The Abaqus nonlinear finite element method analysis was also undertaken by NTUA

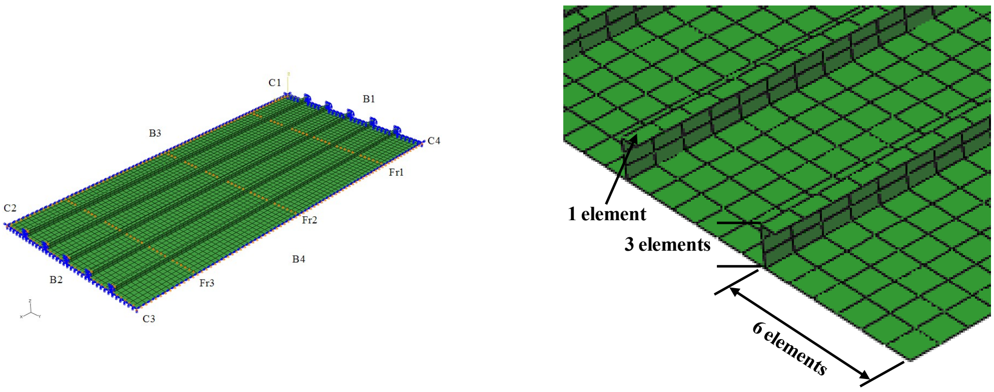

Figure 14: 7,740 elements for Panel C

Table 11: Boundary condition for three bay/one span model applied for Abaqus nonlinear FEA

Boundary	Description
B1 and B2	All fixed condition with $R_x = R_y = R_z = U_y = U_z = 0$, uniform displacement in the x direction (U_x=uniform), coupled with the longitudinal stiffeners
B3 and B4	Simply supported condition with $R_y = R_z = 0$ and $U_z = 0$, uniform displacement in the y direction (U_y=uniform), coupled with the plate part
Fr1, Fr2 and Fr3	$U_z = 0$

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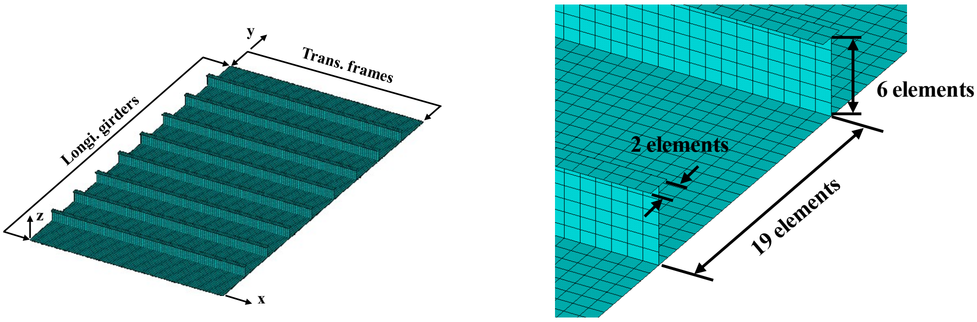


Figure 15: 22,325 elements for Panel C

using a one bay/one span model. The same mesh sizes were applied regardless of the different sized stiffeners in the stiffened panels, as shown in Figure 15.

6.3.3 Hull Girders

The hull structures between two adjacent transverse frames at midship are taken as the extent of the analysis.

6.4 Results and Observations

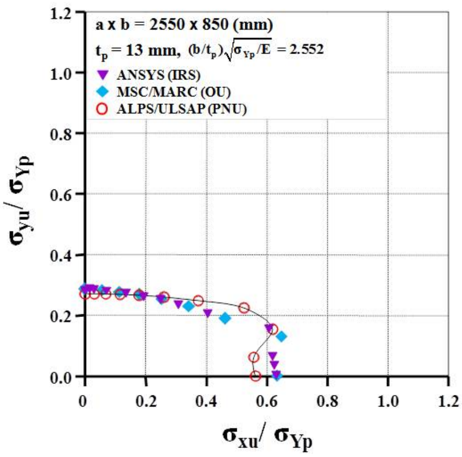
6.4.1 Plates

Under Biaxial Compression

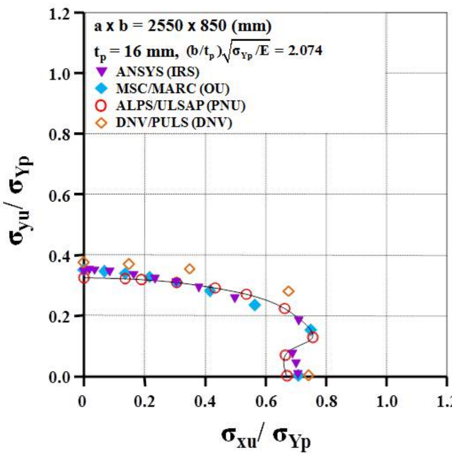
Figure 16 represents the results of the benchmark studies on unstiffened plates under biaxial compressive loads.

Effect of Initial Deflection

The effects of plate initial deflection in terms of magnitude and shape are studied considering two types of initial deflection shapes, namely buckling mode shape and hungry-horse mode shape, as shown in Figure 17. It is found that the ultimate strength of plates with the hungry-horse initial deflection shape is greater than that of plates



(a) Plate with $t_p = 13\,mm$



(b) Plate with $t_p = 16\,mm$

Figure 16: Results of benchmark on unstiffened plates under biaxial compressive loads

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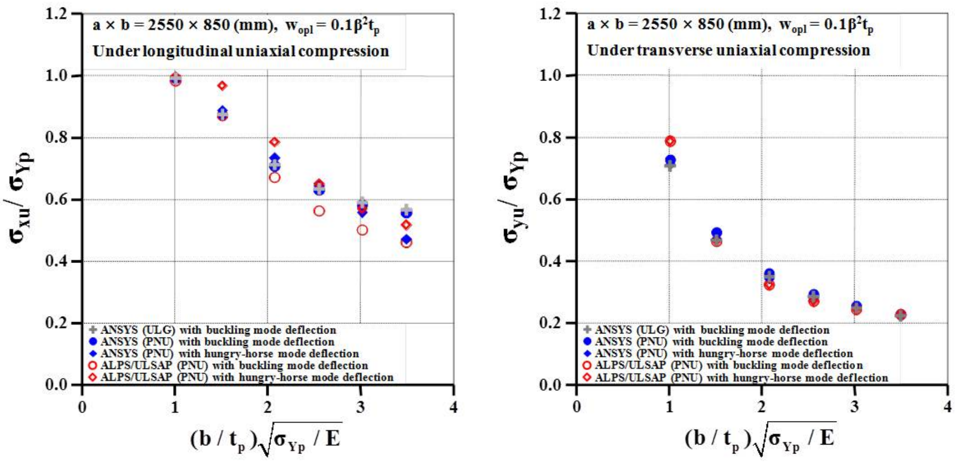

(a) Under longitudinal compression (b) Under transverse compression

Figure 17: Effect of Initial Deflection

with buckling mode initial deflection when longitudinal compressive loads are predominant, but the effect of the initial deflection shape is small when predominantly transverse compressive loads are applied.

6.4.2 Stiffened Panels

In the following, the benchmark study results for stiffened panels are presented. ALPS/ULSAP method calculations provide the information for panel collapse modes, which are classified into six types, namely (Hughes and Paik, 2010)

- Mode I: overall collapse
- Mode II: plate collapse without distinct failure of stiffeners
- Mode III: beam-column type collapse of stiffeners with attached plating
- Mode IV: local buckling of stiffener web
- Mode V: torsional-flexural buckling (tripping) of stiffeners
- Mode VI: gross yielding

Panel A

Figure 18 represent the results of the benchmark studies on Panel A under longitudinal or transverse compressive loads, respectively, in which the types and dimensions of stiffeners are varied. Figures 19 show the ultimate strength of stiffened panels under longitudinal or transverse compressive loads, respectively, as a function of the column slenderness ratio. Figures 20–22 represent the results for Panel A under biaxial compressive loads with varied stiffener types and dimensions, where σ_{Yeq} is the equivalent yield stress and r = radius of gyration for the stiffener with attached plating.

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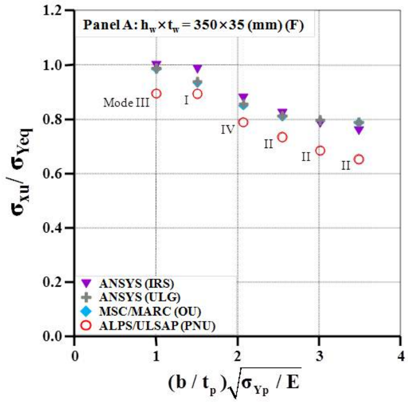
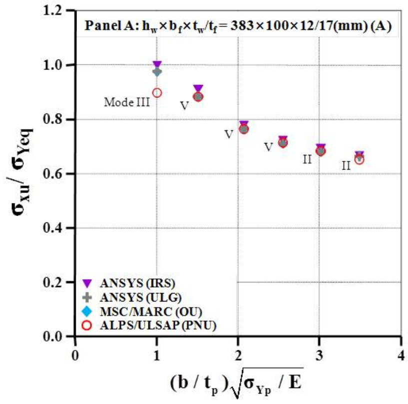
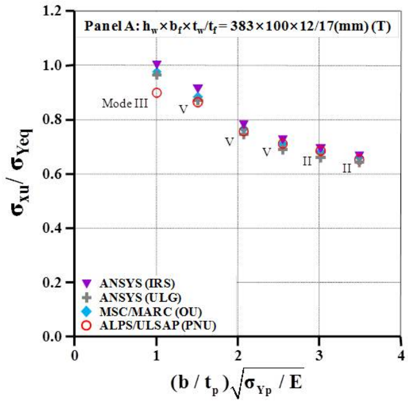


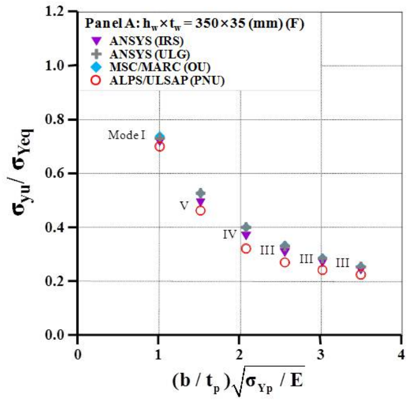
(a) Panel A with flat bars (size 3)



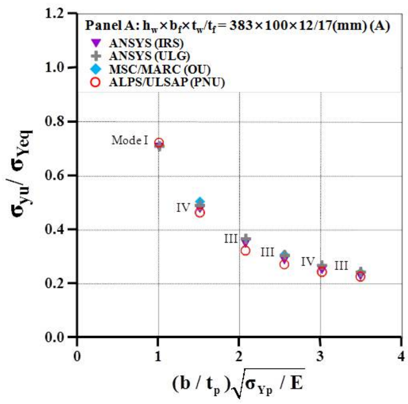
(b) Panel A with angle bars (size 3)



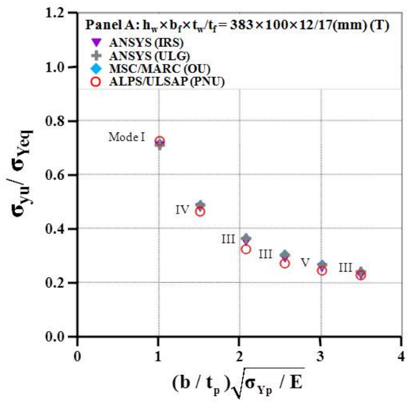
(c) Panel A with tee bars (size 3)



(d) Panel A with flat bars (size 3)



(e) Panel A with angle bars (size 3)



(f) Panel A with tee bars (size 3)

Figure 18: Results of Panel A under longitudinal or transverse compressive loads

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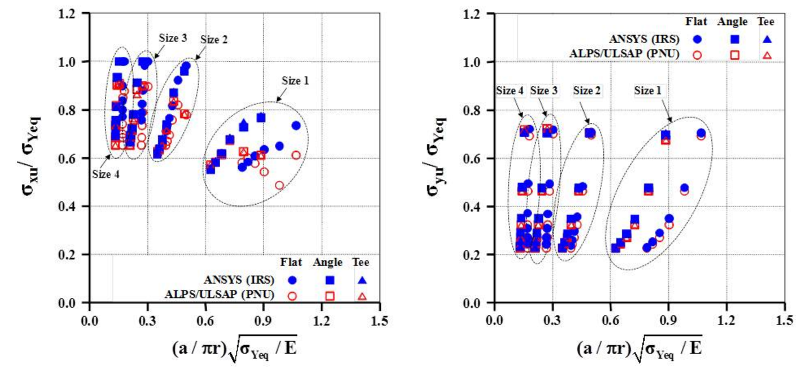
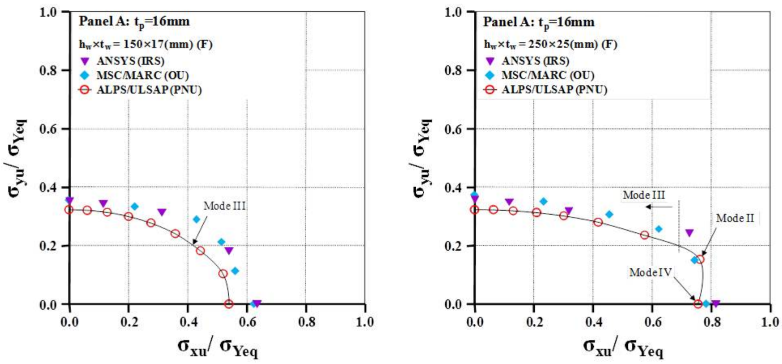


(a) Panel A under longitudinal compression

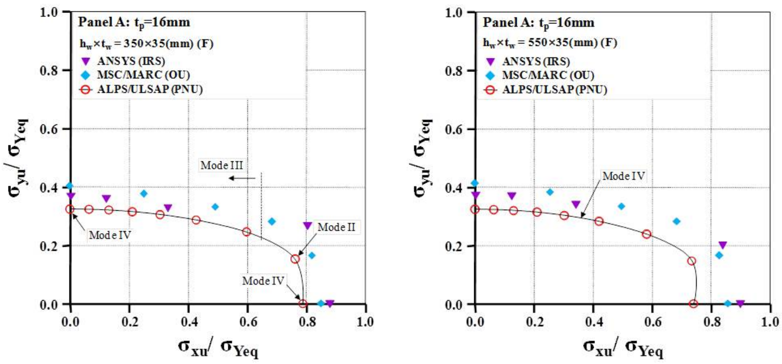
(b) Panel A under transverse compression

Figure 19: Ultimate strength of stiffened panels under longitudinal or transverse compressive loads



(a) Panel A with flat bars (size 1), $t_p = 16\,mm$

(b) Panel A with flat bars (size 2), $t_p = 16\,mm$



(c) Panel A with flat bars (size 3), $t_p = 16\,mm$

(d) Panel A with flat bars (size 4), $t_p = 16\,mm$

Figure 20: Results for Panel A under biaxial compressive loads with varied stiffener types and dimensions

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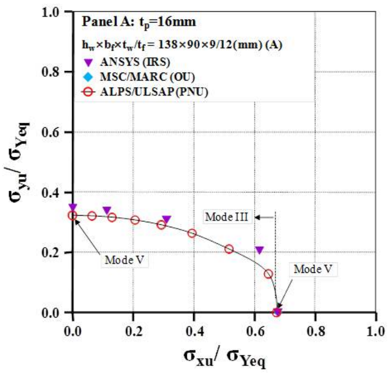
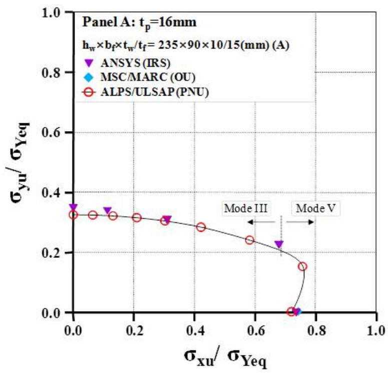
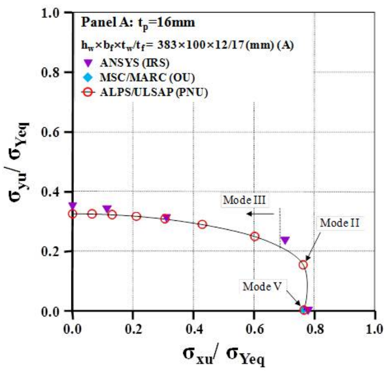


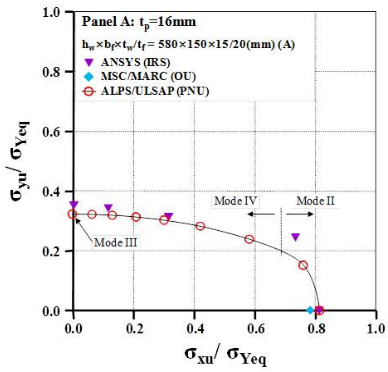
(a) Panel A with angle bars (size 1), $t_p = 16\,mm$



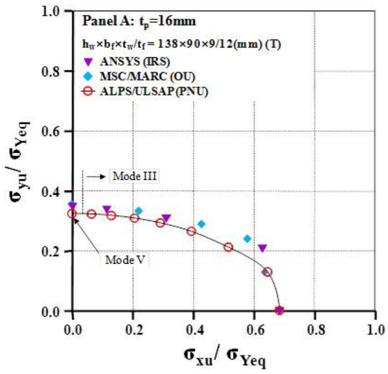
(b) Panel A with angle bars (size 2), $t_p = 16\,mm$



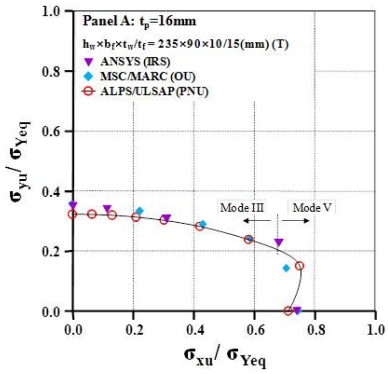
(c) Panel A with angle bars (size 3), $t_p = 16\,mm$



(d) Panel A with angle bars (size 4), $t_p = 16\,mm$



(e) Panel A with Tee bars (size 1), $t_p = 16\,mm$



(f) Panel A with Tee bars (size 2), $t_p = 16\,mm$

Figure 21: Results for Panel A under biaxial compressive loads with varied stiffener types and dimensions – continued

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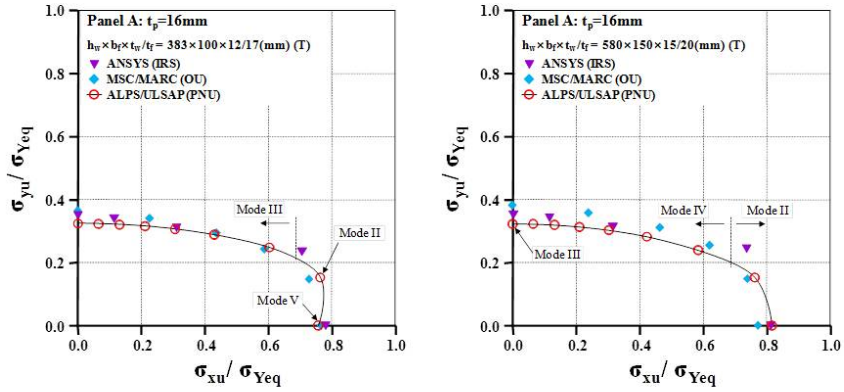


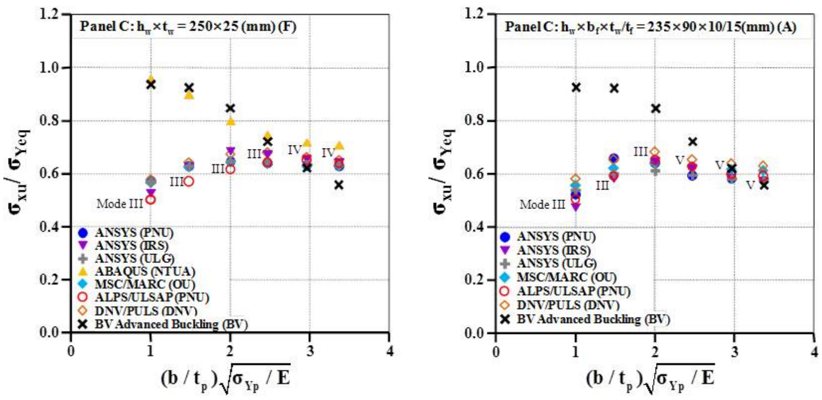
(a) Panel A with Tee bars (size 3), $t_p = 16\,mm$

(b) Panel A with Tee bars (size 4), $t_p = 16\,mm$

Figure 22: Results for Panel A under biaxial compressive loads with varied stiffener types and dimensions – continued

Panel C

Figures 23 and 24 represent the results of the benchmark studies on Panel C under longitudinal or transverse compressive loads, respectively, in which the types and dimensions of stiffeners are varied. Figure 25 show the ultimate strength of stiffened panels under longitudinal or transverse compressive loads, respectively, as a function of the column slenderness ratio. Figures 26 and 27 represent the results of benchmark studies for Panel A under biaxial compressive loads with varied stiffener types and dimensions, where σ_{Yeq} is the equivalent yield stress. It is found that the BV method is not applicable for some ranges of stiffener dimensions. Also, the Abaqus method applied by NTUA significantly overestimates the ultimate strength in some cases. This is due to the fact that the Abaqus models by NTUA adopted the one bay/one span model where the sideways distortions of stiffeners at the locations of transverse frames are not allowed, and subsequently the panel ultimate strength can be overestimated as discussed with Figure 12.



(a) Panel C with flat bars (size 2)

(b) Panel C with angle bars (size 2)

Figure 23: Results of studies on Panel C under longitudinal compressive loads

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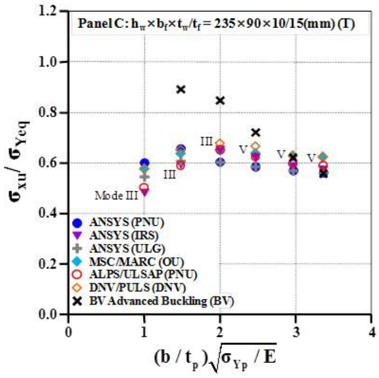
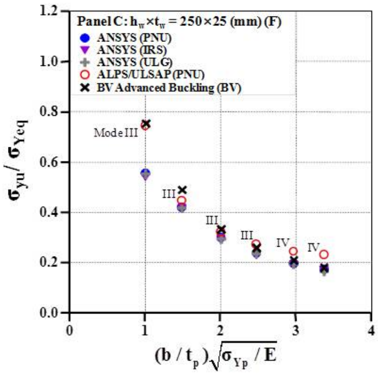
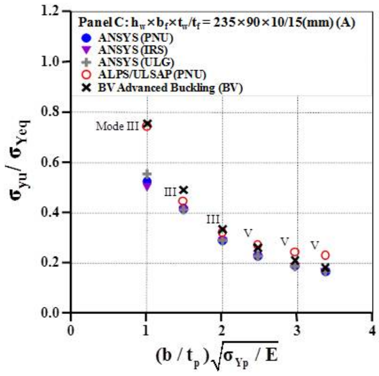


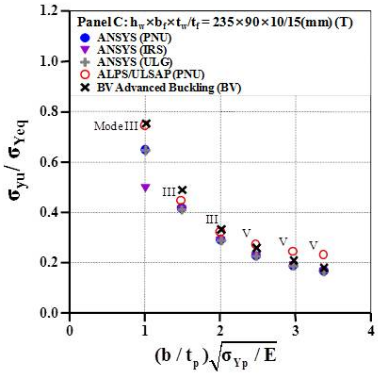
(a) Panel C with Tee bars (size 2)



(b) Panel C with flat bars (size 2)

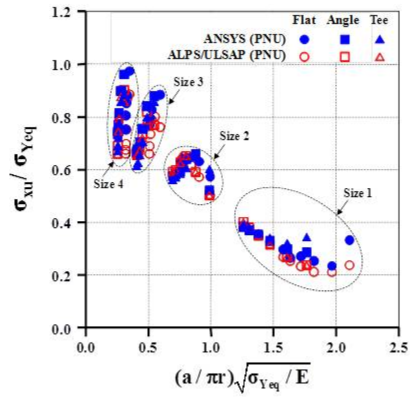


(c) Panel C with angle bars (size 2)

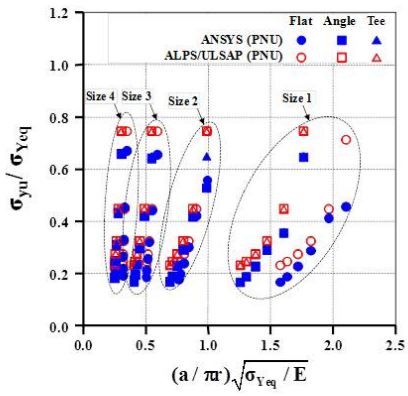


(d) Panel C with Tee bars (size 2)

Figure 24: Results of studies on Panel C under longitudinal or transverse compressive loads



(a) Panel C under longitudinal compression as a function of column slenderness ratio



(b) Panel C under transverse compression as a function of column slenderness ratio

Figure 25: Ultimate strength of stiffened panels under longitudinal or transverse compressive loads

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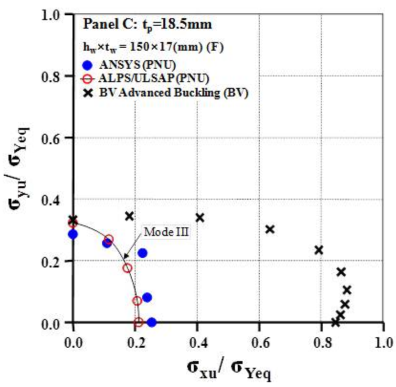
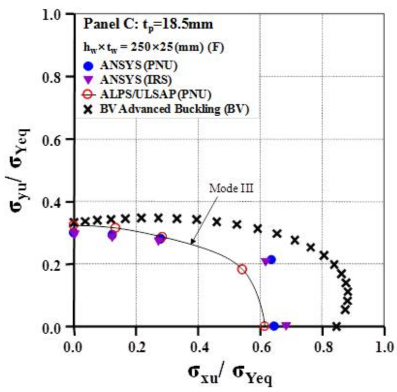
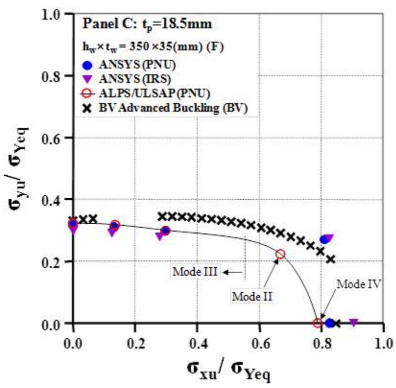


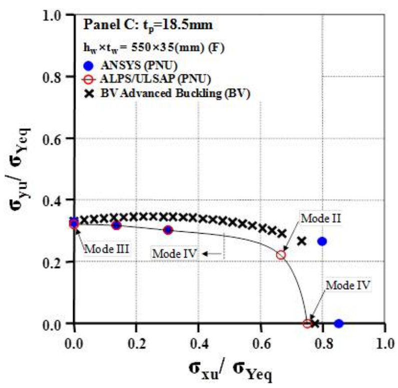
(a) Panel C with flat bars (size 1), $t_p = 18.5\,mm$



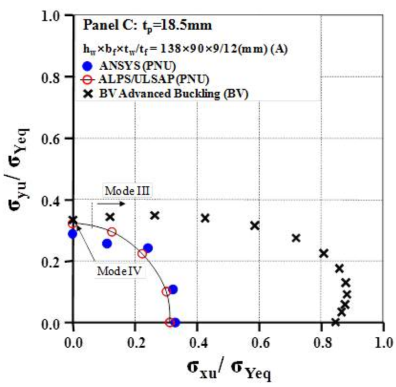
(b) Panel C with flat bars (size 2), $t_p = 18.5\,mm$



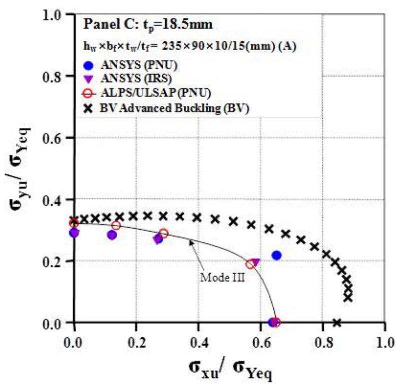
(c) Panel C with flat bars (size 3), $t_p = 18.5\,mm$



(d) Panel C with flat bars (size 4), $t_p = 18.5\,mm$



(e) Panel C with angle bars (size 1), $t_p = 18.5\,mm$



(f) Panel C with angle bars (size 2), $t_p = 18.5\,mm$

Figure 26: Results of studies for Panel C under biaxial compressive loads

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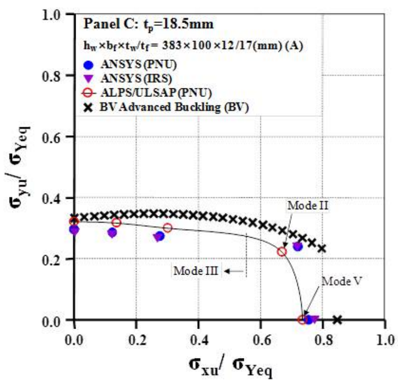
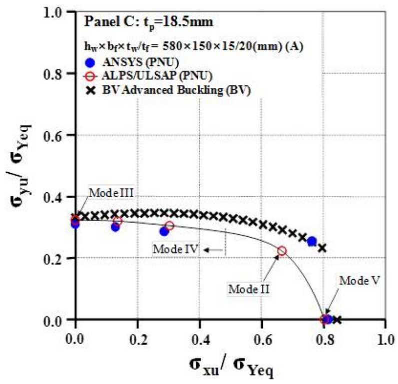
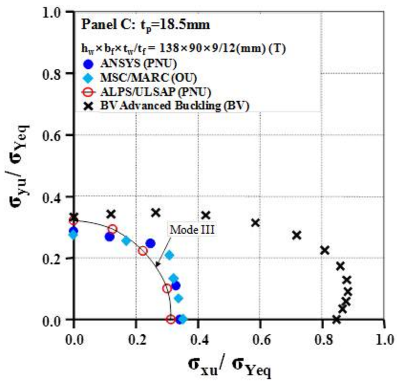


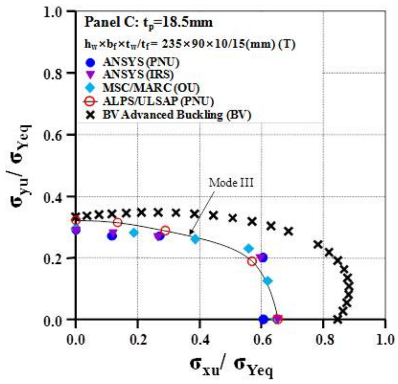
(a) Panel C with angle bars (size 3), $t_p = 18.5\,mm$



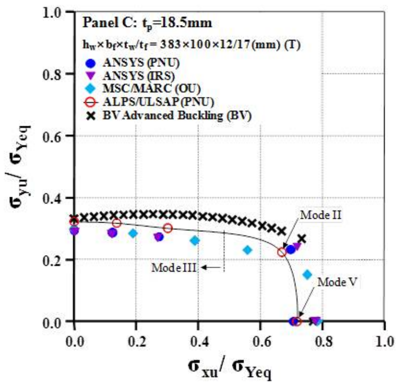
(b) Panel C with angle bars (size 4), $t_p = 18.5\,mm$



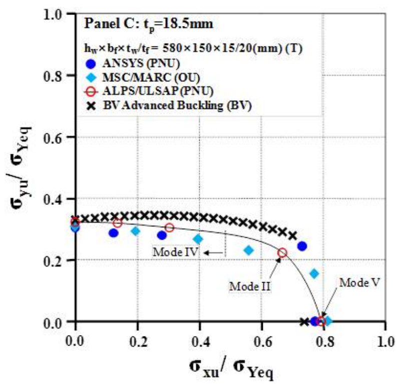
(c) Panel C with Tee bars (size 1), $t_p = 18.5\,mm$



(d) Panel C with Tee bars (size 2), $t_p = 18.5\,mm$



(e) Panel C with Tee bars (size 1), $t_p = 18.5\,mm$



(f) Panel C with Tee bars (size 2), $t_p = 18.5\,mm$

Figure 27: Results of studies for Panel C under biaxial compressive loads – continued

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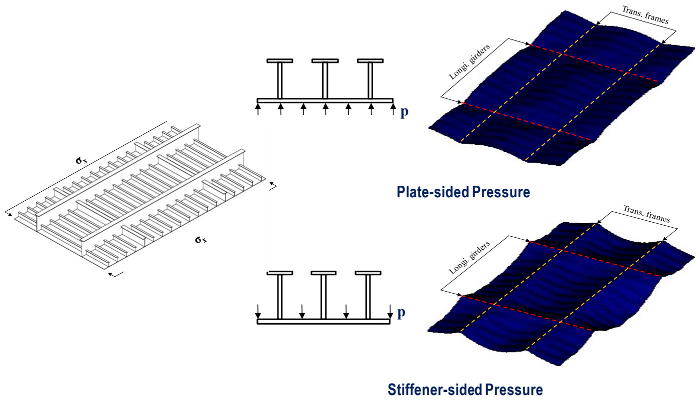


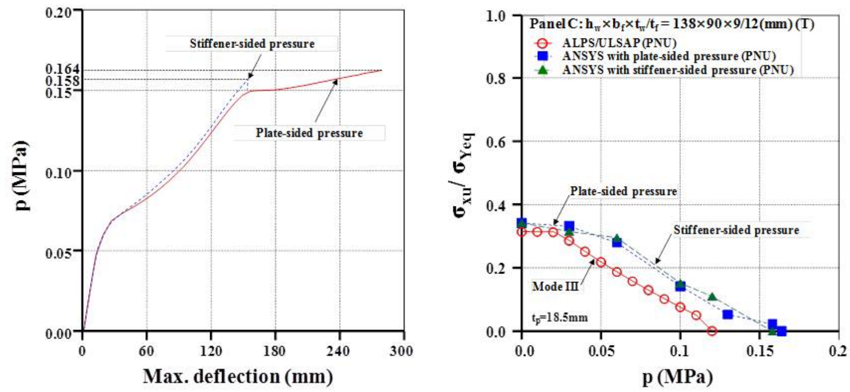
Figure 28: Plate-sided pressure and stiffener-sided pressure

Effect of Lateral Pressure Loads

Two types of pressure loads are considered in terms of loading direction, namely plate-sided pressure and stiffener-sided pressure (see Figure 28). Figure 29 shows the effect of lateral pressure on the ultimate strength of Panel C under longitudinal compressive loads with varied stiffener types and dimensions.

Effect of Plate Initial Deflection

To investigate the effect of initial distortions on panel ultimate strength, the magnitude and shape of initial distortions for plates and stiffeners are varied. Figure 31 shows the effect of initial distortions. In Figure 31, Case A is with the buckling mode initial deflection; Case B with a hungry-horse mode initial deflection and with the magnitude as referred in Japanese shipyards with the fabrication tolerance of Japanese Shipbuilding Quality Standards in plate thickness of 6 mm; and Case C with a hungry horse-mode initial deflection whose magnitude is same to Case A with the buckling mode. It is found from Figure 31 that the initial deflection of Case A, widely used in the literature, significantly underestimate the ultimate strength of the stiffened panel



(a) Under lateral pressure alone (Tee bars with size 1, $t_p = 18.5\,mm$)

(b) Under combined compression and pressure (Tee bars with size 1, $t_p = 18.5\,mm$)

Figure 29: Effect of lateral pressure on the ultimate strength of Panel C under longitudinal compressive loads

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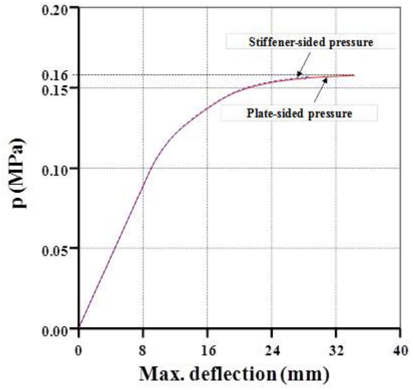
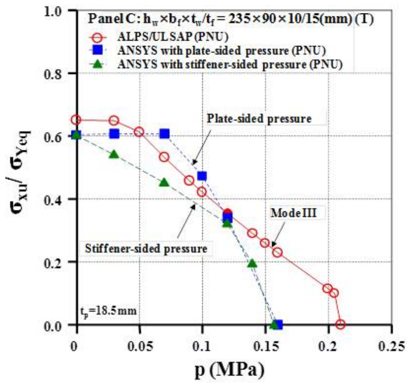
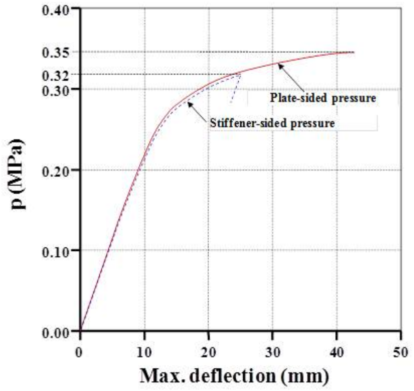


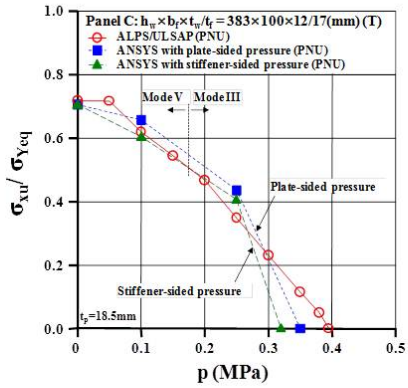
(a) Under lateral pressure alone (Tee bars with size 2, $t_p = 18.5\,mm$)



(b) Under combined compression and pressure (Tee bars with size 2, $t_p = 18.5\,mm$)



(c) Under lateral pressure alone (Tee bars with size 3, $t_p = 18.5\,mm$)



(d) Under combined compression and pressure (Tee bars with size 3, $t_p = 18.5\,mm$)

Figure 30: Effect of lateral pressure on the ultimate strength of Panel C under longitudinal compressive loads – continued

with the initial deflection of Case B, which has more realistic shape and magnitude. In this regard, a systematic analysis of modeling uncertainty is highly required when Case A is going to be applied.

Effect of Welding Residual Stresses

To investigate the effect of welding residual stresses, the following residual stresses were considered.

- Welding residual stress in plating:

$$\sigma_{rcx} = \begin{cases} -0.05\sigma_{Yp} & \text{for slight level} \\ -0.15\sigma_{Yp} & \text{for average level} \\ -0.3\sigma_{Yp} & \text{for severe level} \end{cases} \quad \text{where } \sigma_{Yp} = 313.6\,MPa$$

- Welding residual stress in stiffeners:

$$\sigma_{rcx} = -0.15\sigma_{Ys}, \text{ where } \sigma_{Yp} = 313.6\,MPa$$

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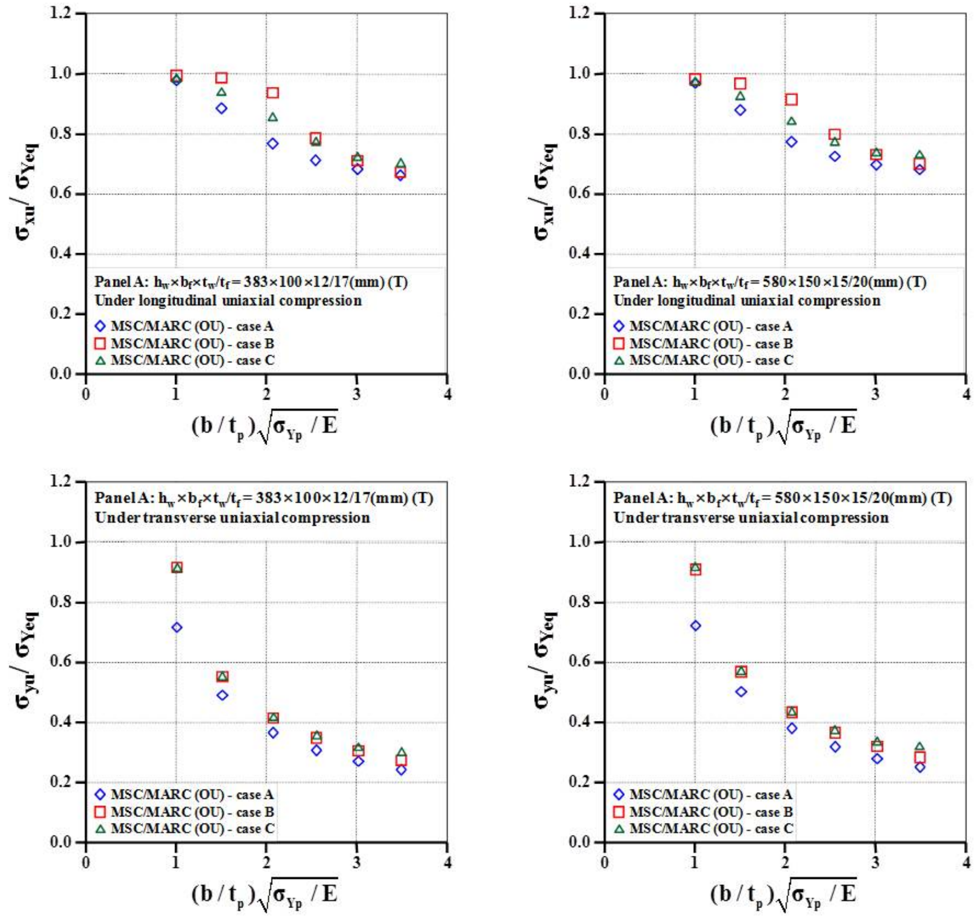

Figure 31: Ultimate strength of Tee-stiffened panels (Panel A) on the effect of initial deflection under longitudinal or transverse compression

- Initial deflection: buckling mode initial deflection with an average level

Figure 32 represents the effect of welding residual stresses on the ultimate strength of Panel A or C under biaxial compressive loads, respectively, showing that the effect of residual stresses is small under predominantly transverse compressive loads. This is because the welding residual stresses in the transverse direction were not presumed in the present study. However, support members are attached by welding in the transverse direction as well as in the longitudinal direction, and thus the effect of welding residual stresses on a panel's ultimate strength even under predominantly transverse compressive loads can also be significant (Paik and Thayamballi, 2003; Paik and Sohn, 2012).

6.4.3 Hull Girders

Under Vertical Bending Moments

Figures 33 and 34 shows the progressive collapse behaviour of various ship hulls under vertical bending moments. Table 12 summarizes ultimate hull girder strengths obtained by each candidate method for six types of ship hulls under hogging and sagging moments. It is found that the CSR method results differ by different working organizations. This may be due to the different modelling techniques including hard corner

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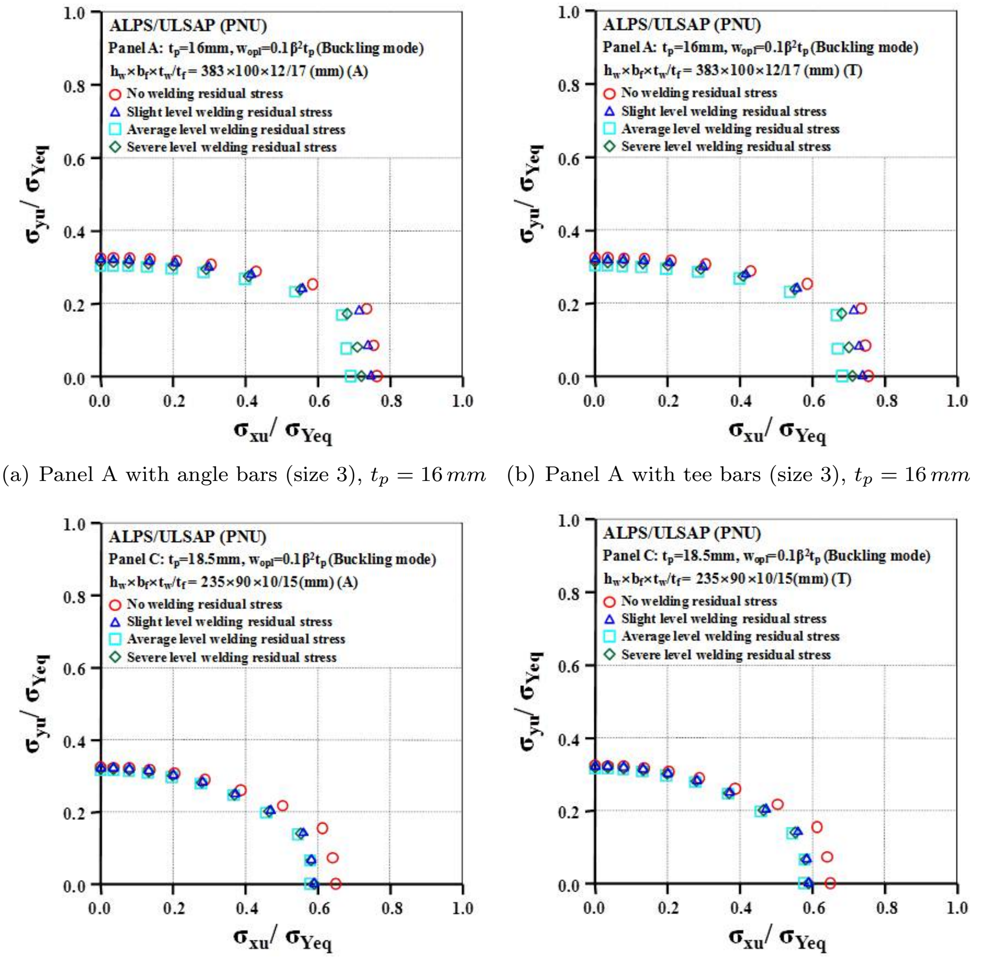

(a) Panel A with angle bars (size 3), $t_p = 16\,mm$ (b) Panel A with tee bars (size 3), $t_p = 16\,mm$

(c) Panel C with angle bars (size 2), $t_p = 18.5\,mm$ (d) Panel C with tee bars (size 2), $t_p = 18.5\,mm$

Figure 32: Effect of welding residual stresses on the ultimate strength of Panel A or C under biaxial compressive loads

elements adopted by the different working organizations, among others. However, it is important to realize that the modelling techniques can significantly affect the resulting computations. If the modelling techniques are inadequate, then the results could be totally wrong. Furthermore, it is recognized that there are still a lot of uncertainties in terms of predicting hull girder's ultimate strength.

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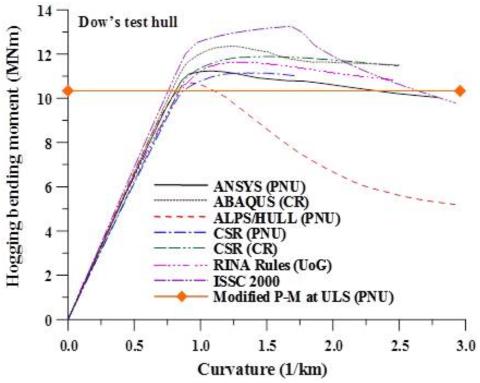
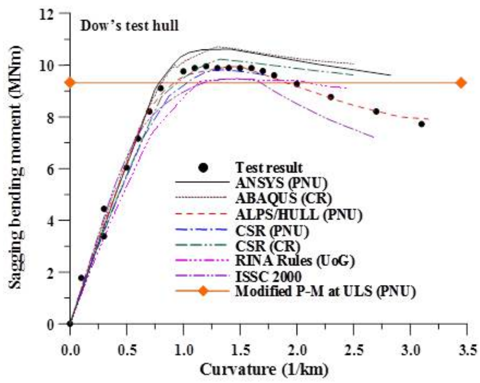
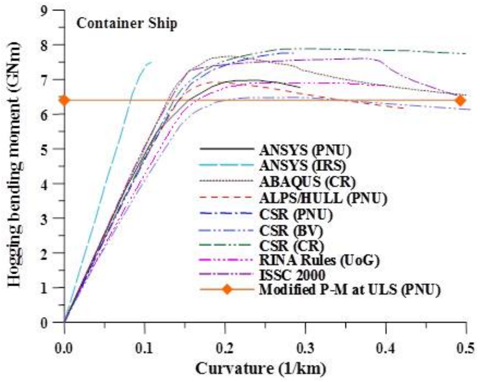


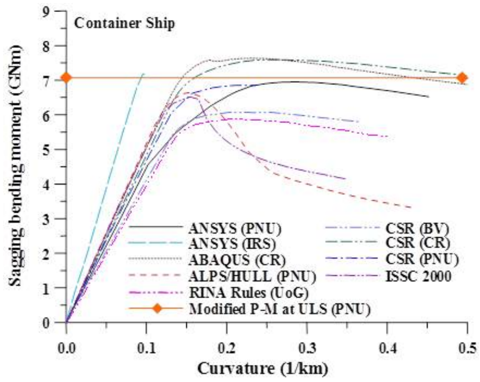
(a) Progressive collapse behaviour of Dow's test hull under hogging moment



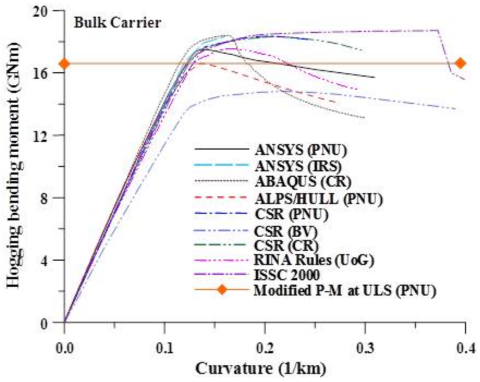
(b) Progressive collapse behaviour of Dow's test hull under sagging moment



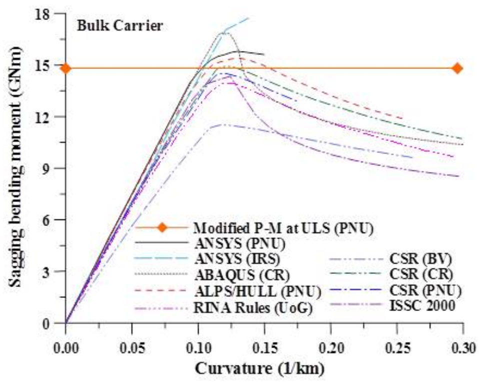
(c) Progressive collapse behaviour of container ship hull under hogging moment



(d) Progressive collapse behaviour of container ship hull under sagging moment



(e) Progressive collapse behaviour of bulk carrier hull under hogging moment



(f) Progressive collapse behaviour of bulk carrier hull under sagging moment

Figure 33: Progressive collapse behaviour of various ship hulls under vertical bending moments

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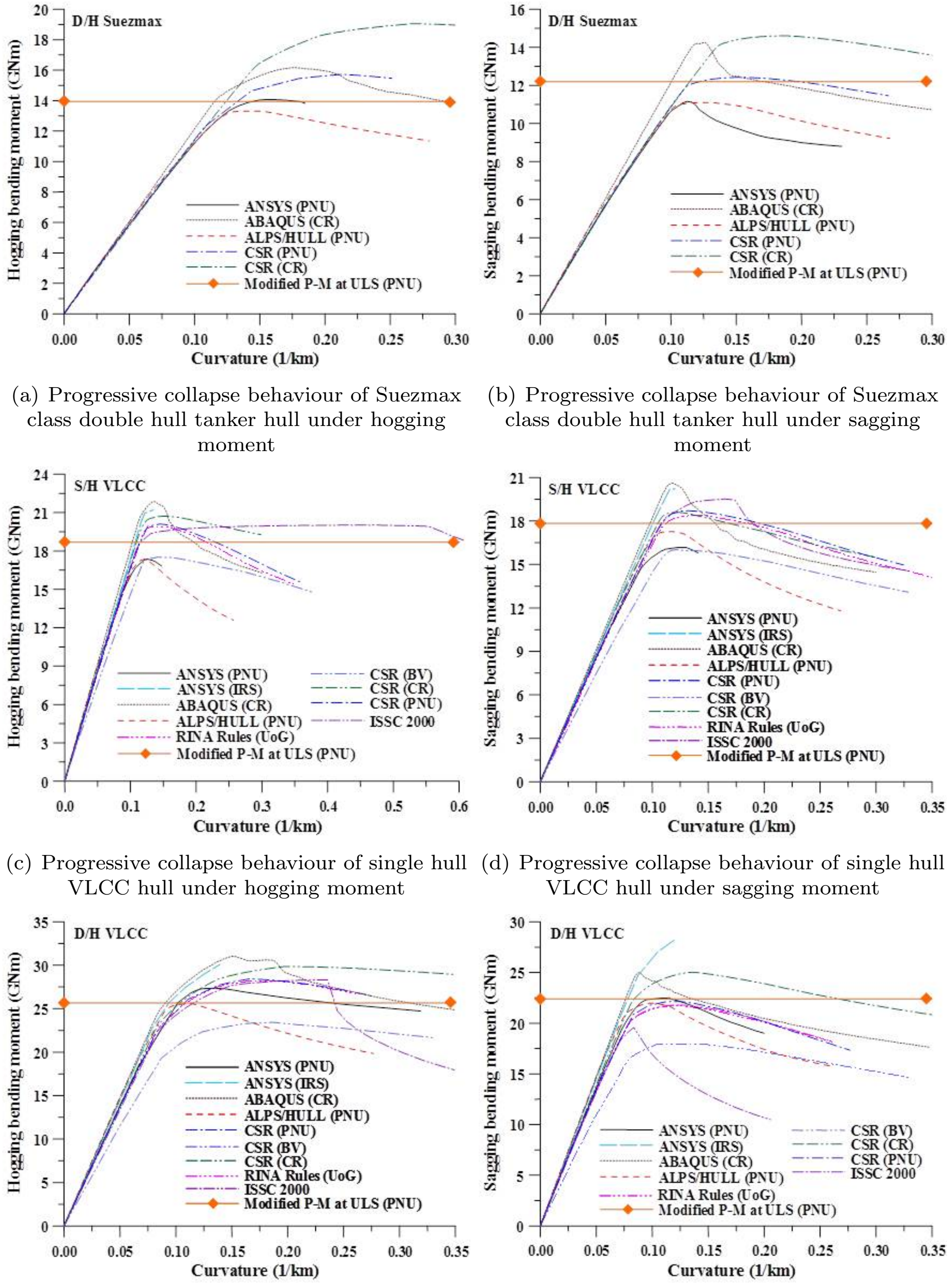

(a) Progressive collapse behaviour of Suezmax class double hull tanker hull under hogging moment

(b) Progressive collapse behaviour of Suezmax class double hull tanker hull under sagging moment

(c) Progressive collapse behaviour of single hull VLCC hull under hogging moment

(d) Progressive collapse behaviour of single hull VLCC hull under sagging moment

(e) Progressive collapse behaviour of double hull VLCC hull under hogging moment

(f) Progressive collapse behaviour of double hull VLCC hull under sagging moment

Figure 34: Progressive collapse behaviour of various ship hulls under vertical bending moments

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Table 12: Summary of ultimate hull girder strengths obtained by each candidate method for six types of ship hulls under hogging and sagging moments

Method	Dow's test hull (MNm)		Container (GNm)		Bulk carrier (GNm)		D/H Suezmax (GNm)		S/H VLCC (GNm)		D/H VLCC (GNm)	
	Hog.	Sag.	Hog.	Sag.	Hog.	Sag.	Hog.	Sag.	Hog.	Sag.	Hog.	Sag.
ANSYS (PNU)	11.235	10.618	6.969	6.951	17.500	15.800	14.066	11.151	17.355	16.179	27.335	22.495
ANSYS (ISR)	-	-	7.490	7.176	18.326	17.726	-	-	21.200	20.210	30.106	28.175
ABAQUS (CR)	12.357	10.708	7.664	7.631	18.396	16.855	16.160	14.258	21.860	20.625	31.006	24.995
ALPS/-HULL (PNU)	10.698	9.940	6.916	6.635	16.602	15.380	13.308	11.097	17.335	17.263	25.594	21.967
CSR(BV)	-	-	6.476	6.068	14.822	11.521	-	-	17.500	16.029	23.431	17.941
CSR (CR)	11.890	10.220	7.879	7.589	18.338	14.921	19.045	14.605	20.708	18.593	29.847	25.014
CSR (PNU)	11.149	9.825	7.758	6.851	18.360	14.500	15.714	12.420	20.102	18.712	28.423	22.130
RINA Rules(UoG)	11.624	9.454	6.859	5.898	17.482	13.952	-	-	19.836	18.468	28.202	21.696
ISSC (2000) Rigo(1)	13.261	9.475	7.600	6.513	18.714	14.340	-	-	18.460	17.900	28.312	19.573
Modified P-M(PNU)	10.338	9.329	6.400	7.077	16.576	14.798	13.965	12.213	18.701	17.825	25.667	22.390
Test (Dow, 1991)	-	9.64	-	-	-	-	-	-	-	-	-	-

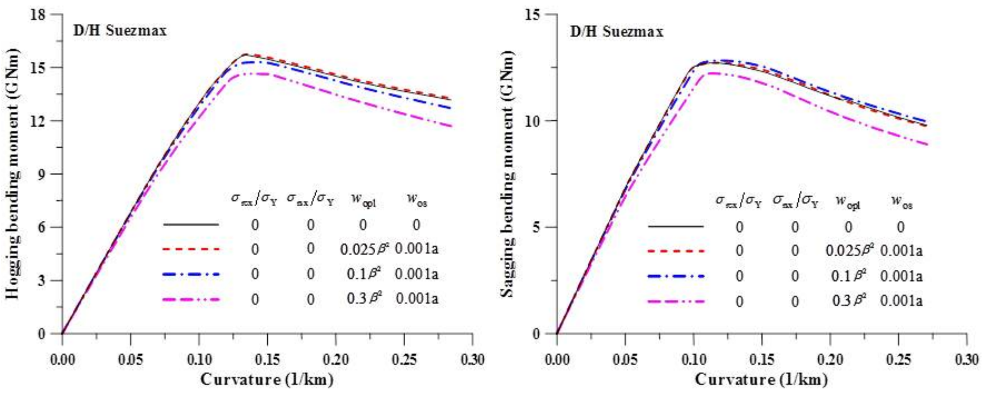
Note: Estimated applied bending moment of S/H VLCC at collapse in hogging = 17.94GNm (ISSC, 2000)

Effect of Initial Distortions

Figure 35 and 36 shows the effect of plate initial deflection on the progressive collapse behaviour of a Suezmax class double hull tanker hull or a double hull VLCC hull. It is found that the effect of initial distortions on the ultimate hull girder strength is small as long as the magnitude of initial distortions is less than an average level.

Effect of Residual Stresses

Figure 37 shows the effect of welding residual stresses on the progressive collapse behaviour of a Suezmax class double hull tanker hull or a double hull VLCC hull. It is found that the effect of welding residual stresses of plates on ultimate hull girder strength is small.



(a) Suezmax double hull oil tanker hull under hogging moment

(b) Suezmax double hull oil tanker hull under sagging moment

Figure 35: Effect of plate initial deflection on the progressive collapse behaviour

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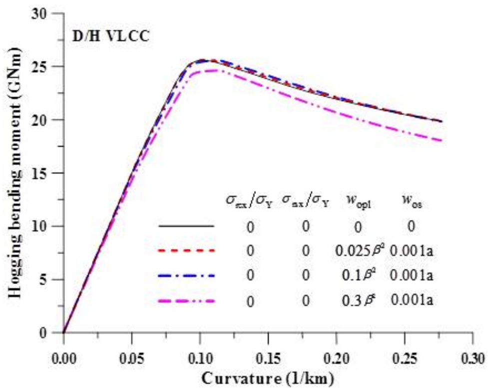
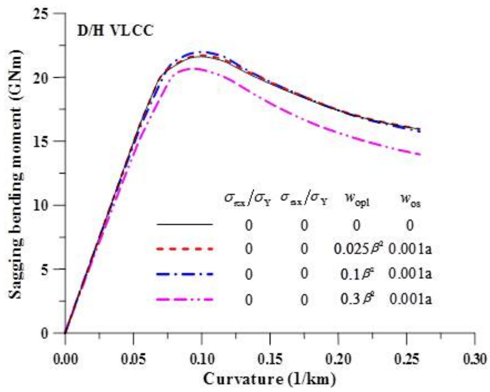
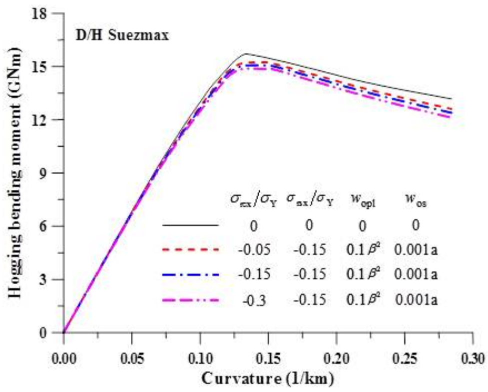


(a) Double hull VLCC hull under hogging moment

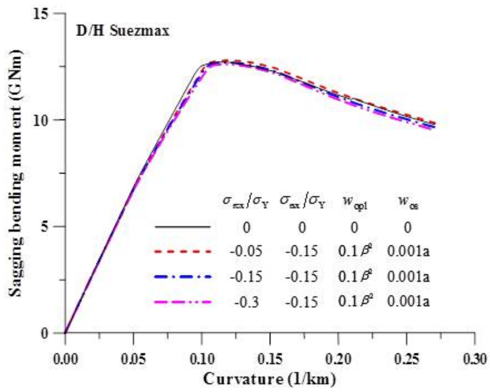


(b) Double hull VLCC hull under sagging moment

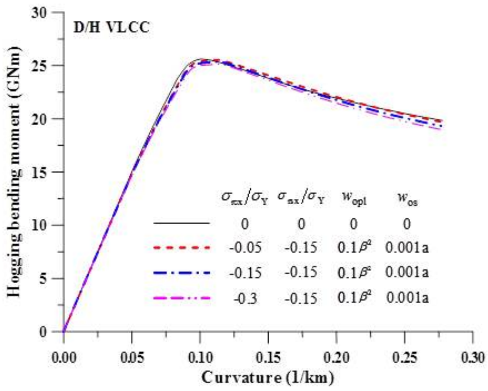
Figure 36: Effect of plate initial deflection on the progressive collapse behaviour – continued



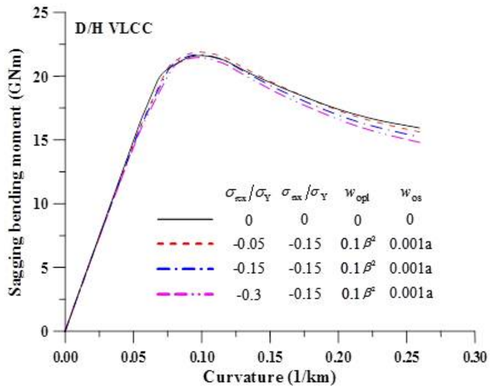
(a) Suezmax double hull oil tanker hull under hogging moment



(b) Suezmax double hull oil tanker hull under sagging moment



(c) Double hull VLCC hull under hogging moment



(d) Double hull VLCC hull under sagging moment

Figure 37: Effect of welding residual stresses on the progressive collapse behaviour

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7 CONCLUSION AND RECOMMENDATIONS

It is now well recognized that ultimate strength is a much better basis for structural design and safety assessment than the traditional allowable working stress. This is because the realistic safety margin of a structure can not be determined as long as the ultimate strength remains unknown. It is therefore required to calculate the ultimate strength of both structural members and system structures accurately and efficiently. In recent years, useful methods have been developed for this purpose. However, it is realized that there are still a lot of technical challenges associated with various factors affecting the ultimate strength behaviour as discussed in Section 2.2. A comprehensive benchmark study with various candidate methods has been undertaken in the Committee, observing that some methods are considered to be mature enough to apply in daily practice of structural design and safety assessment but a great attention should be paid in conjunction with possible uncertainties due to modelling techniques as well as inherent aspects.

Despite significant recent advancements in ultimate strength evaluation procedures and the availability of increasingly more powerful computation means, final results can still be affected by large uncertainties that must at least be identified and then possibly estimated. Indeed, the description of the practical aspects of calculations in Section 4 is aimed at identifying uncertainties and highlighting the difficulties that prevent correct and consistent analyses.

Physical aspects, i.e., uncertainties affecting input variables, such as material properties, definition of geometries, etc., have been widely studied in recent years, and reliability analyses account for such aspects by properly considering the statistical analysis of involved variables. Even if reliability analyses cannot be applied in daily design practice, useful results can be obtained for rules calibration. While the process is not fully completed, it is believed that the trend is clear and that the harmonization process of classifying society rules confirms it.

The estimation of model uncertainties is much more difficult because the comparative (and trustworthy) term is not always clear and defined enough to obtain information about the approximation in ultimate strength calculations. In fact, this estimate involves engineering judgment in the definition of the structures' limit states and abilities to properly idealize them according to the available theoretical and numerical structural models (i.e., beam theory, plate theory, FEM, etc.). Quantitative estimates of model uncertainties are also complex because interactions among various aspects often cannot be considered by current calculation procedures.

Ageing effects have recently been noted in a more explicit and transparent way by classification societies' rules, and again the trend is towards a deeper and wider analysis of such aspects in ships' structural designs. Even if the implementation of ageing effects in the calculations is still in progress, as several effects and relevant interactions with other effects are still empirically accounted for (e.g., local and global corrosion), statistical and reliability analyses are of great help.

In addition, actual data about ageing effects are rather hard to collect and sometimes not available. However, a few of the numerical studies conducted recently are starting to analyse ageing effects and their interactions (e.g., the effect of local corrosion and pitting on the ultimate strength of misaligned components).

In short, the abovementioned limitations can be defined as "technology transfer" problems and it should be recognized that if not correctly faced, important research achievements cannot be successfully implemented in ship design and technical management.

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18th INTERNATIONAL SHIP AND
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VOLUME 1

COMMITTEE III.2

FATIGUE AND FRACTURE

COMMITTEE MANDATE

Concern for crack initiation and growth under cyclic loading as well as unstable crack propagation and tearing in ship and offshore structures. Due attention shall be paid to practical application and statistical description of fracture control methods in design, fabrication and service. Consideration is to be given to the suitability and uncertainty of physical models.

COMMITTEE MEMBERS

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KEYWORDS

Fatigue, fracture mechanics, unstable crack propagation, multiaxinal fatigue, materials, rules and guidelines, damage control, inspection and life extension

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CONTENTS

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1 INTRODUCTION

Most of our knowledge on fatigue is either based on experience from structural or component failures, or from fatigue experiments. For more than 150 years, the fatigue and fracture engineering disciplines have been investigated but they are still developing and of large contemporary interest, not only for ship and offshore structures, but virtually for all engineering structures. Recent advances in computational mechanics together with the rapid increase in computer capacity have enabled the possibility to utilize more advanced, highly detailed fatigue and fracture analyses within the offshore and shipping industries. Consequently, today, there are several commercial tools available that are suitable for thorough structural integrity analysis of large-scale structures; see Figure 1 for an example of different state-of-the-art methods (accuracy versus complexity) for fatigue assessment of offshore and ship structures. However, despite the fast development of new commercial software, that can assist engineers in their daily work to design safer, lighter and more reliable structures, it is of outmost importance to continue striving for further improvement of existing fatigue design methods and development of new methodologies.

In the planning of the current report, the committee members decided to have new focus in the reporting on fatigue and fracture in contrast to previous reports. It was found of great value to pay attention to in particular unstable crack propagation, new materials, damage control and risk-based assessment, and update of latest changes in design methods for ships and offshore structures. Section 2 presents a brief overview of the recent developments in fatigue assessment methods. This was a significant part of the ISSC2009 report, and hence, it was decided to give it less attention in the current report; multiaxial fatigue analysis procedures is an exception here since a lot of work has been presented lately. Section 3 continues to present findings on unstable crack propagation. Methods for the analysis and experimental measurements of nucleation and propagation of brittle fracture are presented along with an example of how brittle crack propagation can be prevented in container ships.

Some advances in materials and structural details are presented in Section 4. Examples of investigations that present new findings on most commonly used materials today are presented, followed by extra high-strength steel, steel with improved crack growth properties, materials for cold climate, honeycomb structures, etc. In Section 5, methods suitable for damage control and risk-based assessment are reviewed, considering factors such as effect of workmanship, internal defects, welding procedure, etc. Attention is paid to the suitability and uncertainty of physical models, uncertainty in

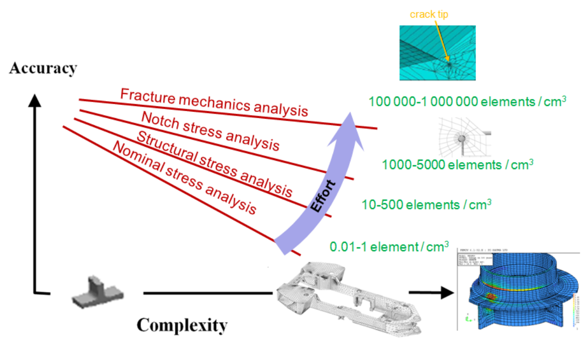

Figure 1: Illustration of different techniques that can be used to solve fatigue-related issues, Marquis (2009).

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fatigue assessment diagrams and fatigue life assessments, and finally, the analysis of ageing and aged ships and offshore structures is discussed.

Section 6 is a review of update and comparison of design methods for ships and offshore structures, such as the Common Structural Rules (CSR) for oil tankers and bulk carriers, the Harmonized Common Structural Rules (CSR-H) for oil tankers and bulk carriers, rules for offshore installations, Arctic design codes. Some of the procedures reviewed in Section 6 are challenged in a comparison presented as a benchmark study in Section 7. The intention of the benchmark study is to show how uncertainties in fatigue assessment of welded structures are treated when unconventional loading pattern is to be applied on a simple welded joint. Finally, in Section 8, recommendations for further research are presented followed by a summary of the conclusions in Section 9.

2 RECENT DEVELOPMENTS IN FATIGUE ASSESSMENT METHODS

Fatigue has become a critical limit state for engineers in designing a new structure or in assessing an existing structure. The next-generation offshore structures require an optimal fatigue design based on improved fatigue assessment methods supported by continuous research efforts. In contrast to the fracture mechanics, which are supported by substantial development in the theoretical and analytical solutions to engineering boundary value problems, the engineering assessment of fatigue failures has largely relied on formulations and procedures developed from empirical evidences. The development in the fatigue theories based on the classical continuum mechanics faces two critical challenges. Fatigue as an engineering phenomenon often involves material damage in a microscopic scale, which involves non-homogeneity of the material properties at these length scales. In addition, the fatigue damage entails continuous separation of the materials, which impinges on the fundamental assumption in the continuum mechanics. Despite the primitive theoretical development in the fatigue theory, engineering approaches developed from empirical database proves satisfactory assessments for realistic welded structural details. This chapter summarizes the developments in the fatigue assessment methods for the ship and offshore structural details over the last three to four years.

2.1 Low Cycle, High Cycle and Ultra-High Cycle Fatigue Approaches

Fatigue assessment methods separate into three broad categories based on the type of cyclic loading experienced by the structure, namely the strain-based low-cycle, stress-based high-cycle and ultra-high cycle fatigue. Low-cycle fatigue refers to the condition where fatigue failure occurs at a relatively low number of cycles (often less than 10^4 cycles) due to material damage incurred by macroscopic plastic deformations under cyclic actions, as illustrated in Figure 2. The high-cycle fatigue damage, on the other hand, occurs as an elastic phenomenon on a macro scale of the material, with the number of cycles ranging approximately from 10^4 to 10^7 cycles, with the latter often defining the fatigue endurance limit for structures under constant amplitude loading. This fatigue endurance limit does not exist for structures under variable amplitude loading. The fatigue behaviour beyond 10^7 is of particular significance for design against variable amplitude loading. The latest IIW design code (2009) includes a decay in the S-N curve for very high cycle applications beyond the fatigue limit.

Lotsberg (2010a) summarizes the latest improvement made in the revised DNV's design guide line for fatigue design of offshore steel structures, and highlights that the assessment of low-cycle fatigue has become a recommended practice in association

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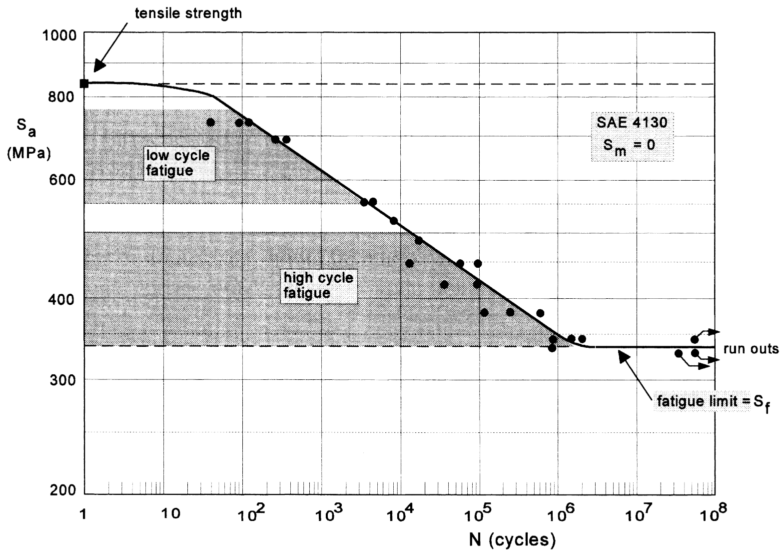

Figure 2: Low-cycle and high-cycle fatigue for structural details (Schijve, 2009).

with the assessment for an ultimate limit state, for example, for an offshore structure under a storm condition. He also points out that low-cycle fatigue is a more critical concern for details in ship structures than those in offshore structures, since the utilization ratios for ship structural details remain much higher than the utilization ratios in offshore structures under ultimate limit states.

Crupi *et al.* (2009, 2010) present a thermographic method to determine the entire S-N curve, covering high-cycle fatigue behaviour, the low-cycle fatigue behaviour and fatigue limit for welded details. The thermographic method operates on the temperature change caused by the applied cyclic stress. The maximum stress range that creates no temperature change becomes the theoretical fatigue limit for the structural material. The unique relationship between the stress range and the temperature change forms the basis to determine the S-N curve for the material. The thermographic method provides a rapid approach to determine the fatigue limit and the S-N curve based on very limited experimental data, and proves to be consistent with the conventional S-N approach in the IIW code. The behaviour of the structural components under very high cycle fatigue loading has recently become an important research topic. Marines-Garcia *et al.* (2007) report an important failure phenomenon for structural components loaded between 10^6 to 10^8 cycles. The location of the failure initiation may switch from the specimen surface to an interior "fish-eye". Liu *et al.* (2010) discuss the material effects on the probabilistic assessment of fatigue failure for high-strength steels under high-cycle fatigue or very high-cycle fatigue. They propose a modified Basquin's equation to predict the S-N curves for the high-strength steel specimens. Sosino (2007b) discusses the endurance limit of the S-N curves that most codes specify. He point out that in the high-cycle regime a decrease of fatigue strength with increased number of cycles is seen, hence assuming an endurance limit can be unconservative. He recommends that a decrease of the slope of the S-N curve for steels, cast irons and magnesium alloys should be 5 % per decade if no large tensile residual stresses are present.

Some different approaches for the high cycles area have been discussed by Rother

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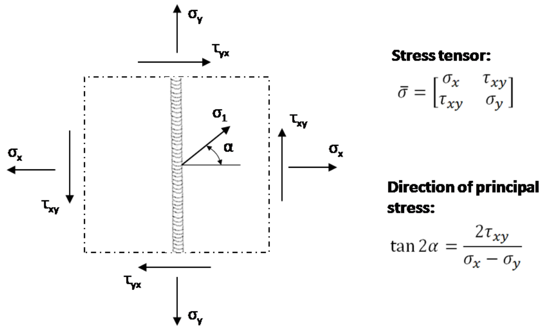

Figure 3: Multiaxial stress state on welded plate

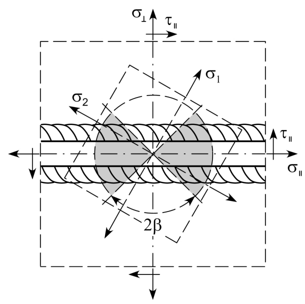

Figure 4: Biaxial oblique loading

and Rudolph (2011) who compared the hot-spot stress approach and the notch stress approach in the fatigue assessment of realistic welded structures, and recommended a hierarchical two-step approach for the critical structural components. The structural stress approach proves to be efficient in identifying the critical highly stressed locations for a subsequent detailed notch stress assessment. Erny *et al.* (2010) presented an approach to estimate the fatigue life of welded assemblies in ship structures, combining the finite element analysis results and the experimental investigation on the fatigue response of the material in the heat-affected zone. Radaj *et al.* (2009) reviewed the local approaches in the fatigue assessment of the welded connections. They concluded that all local concepts in predicting the fatigue life may possibly involve an unlimited number of variants in the modelling and estimation procedure. The local concepts do not separate the fatigue life into the crack initiation and the crack propagation. The crack initiation life may include an initiation life at the microstructural scale and a short-crack propagation life. Pujol and Pinto (2011) reported a novel approach based on the neural network method to predict the fatigue life. The neural network approach provides consistent predictions compared to other statistical models.

2.2 Multiaxial Fatigue

A multiaxial stress state refers to a loading condition where two or more stress components are acting on a critical plane of a structural detail, see Figure 3 and 4. This is especially important, when shear stress range is more than 15 % of the normal stress range or the direction of maximum principal stress α is changed significantly,e.g. more than 20°, during the cyclic loading, Hobbacher (2009). The individual stress components of multiaxial stress state should be considered. The stress components caused by complex loading may be occurring either in-phase or out-of-phase, i.e. be proportional or non-proportional. Non-proportionality means that the direction of the principal stress or strain is changing. The multiaxial fatigue behaviour is influenced both by the proportionality/non-proportionality as well as by the ductility of the material Sonsino (2009, 2011).

Failure mechanisms are controlled by shear stresses or strains in case of ductile materials, Sonsino (2009, 2011) and Wiebesiek *et al.* (2011). The normal stresses are dominating in case of brittle materials. For semi-ductile materials, failure mechanisms are controlled by the combination of shear and normal stresses. Consequently, the influence of multiaxial stress states differs according to the level of ductility. As shown in Figure 5, the change of the principal stress direction lowers the fatigue life of ductile materials noticeably. This effect does not occur in fatigue of semi-ductile materials

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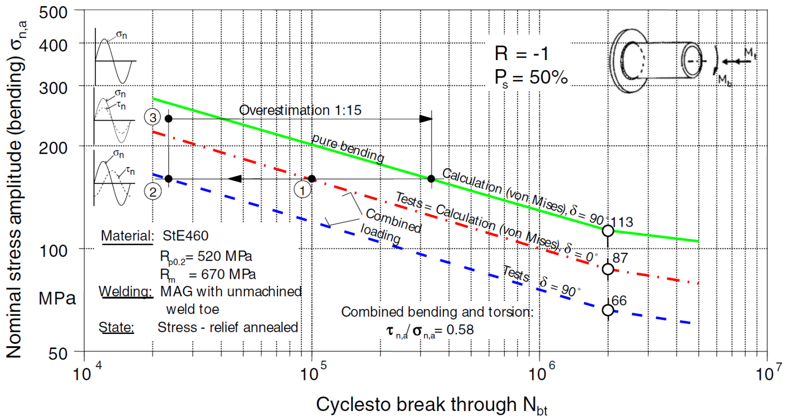

Figure 5: Fatigue strength of flange-tube welded connection under uniaxial and multiaxial loading. Number of cycles N_{bt} correspond to the crack depth of the tube thickness, Sonsino (2009).

and the change of principal stress direction may even increase the fatigue life of brittle materials. This is noticed for both constant amplitude and variable amplitude i.e. multiaxial spectrum loading. During the last decade, the problem of failure mechanisms in multiaxial fatigue has been investigated and several multiaxial fatigue criteria have been developed. Papuga (2011), Gómez *et al.* (2011) and Li *et al.* (2009) show overview and comparisons of different multiaxial fatigue criteria. The most common approaches are critical plane approaches, effective equivalent stress (integral plane) approaches and stress invariant based approaches.

A new effective stress method based on the resultant stress has been proposed by Kurinjivelan *et al.* (2010). This method can be used in conjunction with the normal stress S-N curve. The effectiveness of the method has been verified by comparing with the already existing methods for combined normal and shear stress cycles applied in phase. It is observed that by proposed method, the percentage of error is lesser when compared to the existing methods.

Some new critical plane approaches are trying to take the material properties also into account in addition to the stress state, Carpinteri *et al.* (2009). Reis *et al.* (2009) assess the applicability of the different critical plane criteria while considering the different cyclic plasticity behaviour, e.g. hardening effect, and sensitivity to non-proportionality of different materials. Susmel (2008, 2009, 2010 and 2011) suggest that the crack will initiate on the plane, which contains the direction along which the variance of the resolved shear stress reaches the maximum value.

Integral plane hypothesis, e.g. effective equivalent stress (EESH) or simpler modified Gough-Pollard for practical applications, are first mentioned by Sonsino (1995). For EESH local stresses or strains need to be known. The hypothesis states that the crack initiation is caused by the interaction of local shear stresses acting on different surface planes of the material considering the influence of non-proportional loading. These methods, unlike critical plane methods, are able to consider the phase difference in the loading. EESH is applied together with 0.05 mm fictitious weld root radius for laser beam welded thin steel structures under multiaxial in- and out-of-phase loading (Sonsino *et al.*, 2006) and together with 1 mm fictitious notch radius, Sonsino and Łagoda (2004). There, the EESH is compared with some of the other criteria and

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it seems to be the most suitable, giving the results on the safe side. However, the integral plane methods are even more time consuming than critical plane approaches.

Stress invariant based methods, see e.g. Vu *et al.* (2010), make use of the stress invariants, mostly the first invariant of the stress tensor and the second invariant of the stress deviator, and the maximum hydrostatic pressure. Stress invariant based methods aim at reducing the computation time. Recent papers discussing stress invariant based multiaxial fatigue criteria take the non-proportional loading into account. Both critical plane and integral stress or strain approaches use time-independent variables in the fatigue life assessment, while the idea behind Stress Space Curve Hypothesis (SSCH), presented by Wiebesiek *et al.* (2011), takes the complete time evolution of the very complicated multiaxial stress history into account. The method does not consider arbitrary stress signal, but rather the simplified shapes (ellipsoids). The EESH is a special case of SSCH. Castro *et al.* (2009) discuss the multiaxial fatigue criteria based on the equivalent shear stress amplitudes. They applied the maximum scalar measure of the different hypersurfaces enclosing the deviatoric stress history. Using the same method, Mamiya *et al.* (2011) have developed a multiaxial fatigue life estimation procedure based on a piecewise ruled S-N surface. Cristofori *et al.* (2008) discuss stress invariant based method which decouples the loading path by projecting it along the directions which are defined by the loading path itself. Brighenti and Carpinteri (2011) propose a method for fatigue assessment of structural components under complex multiaxial loading, which uses the damage accumulation expression with an appropriate endurance function containing stress invariants and the deviatoric stress invariants. The method does not require the evaluation of the critical plane nor any conventional loading cycle counting algorithm.

Although in the last two decades significant progress in the knowledge and theoretical modelling has been achieved, a generally applicable multiaxial fatigue criterion does not exist. No solid proof has been obtained to confirm the validity of the hypotheses for the constant amplitude loading in case of variable amplitude loading. Sonsino (2009) uses relatively low allowable stresses so as to cover most of the experimentally obtained results under multiaxial loading. However, this approach does not consider the physics behind the complex multiaxial fatigue damage behaviour. Recommendation of IIW, Hobbacher (2009) includes the modified Gough-Pollard algorithm for both constant amplitude and variable amplitude loading. The IIW recommendations suggest Palmgren-Miner damage sum $D = 0.5$ for steel under variable amplitude loading, when the load spectrum is narrow banded, i.e. the mean stresses are constant. If the load spectrum is wide banded, IIW recommendations suggest damage sum $D = 0.2$ according to Sonsino (2007a) to capture the mean stress effect. These damage sum values include the positive influence of the variable amplitude loading on the fatigue life and thus they are slightly higher than the real damage sums. For further information regarding multiaxial fatigue see Section 7.

2.3 Factors Influencing Fatigue

The fatigue damage and degradation of a material is affected by a large number of factors such as mean stresses and their redistribution, residual stresses, loading of the structure including load sequences, structural dimensions and plate thickness, corrosive environments and temperature of the surroundings, the design criterion, fabrication technology and methods for improving fatigue performance, and sensitivity of the material. This section focuses on recent developments with this topic and should be read in conjunction with the ISSC 2009 – Fatigue and Fractures committee report, where the topics have been described comprehensively.

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2.3.1 Thickness and size effect

A commonly used approach to estimate the reduction in fatigue strength of welded structures is to multiply the stress range by a factor $k_s = (t_{ref}/t)^k$ where t is the relevant plate thickness, t_{ref} is a reference thickness and k is an empirical constant, Hobbacher (2009). Kim *et al.* (2009) report the fatigue tests on butt-welded steel plates with thicknesses varying from $20\,mm$ to $80\,mm$ under three different applied stress ranges. The specimens demonstrate a decreasing fatigue life as the thickness increased. Most experimental work has been devoted to joints with plate thicknesses typically larger than $25\,mm$. In Gustafsson (2006), experimental data from constant amplitude fatigue testing of non-load carrying welded joints in high strength steel of thickness $3 - 12\,mm$ are presented. The results show an increase in fatigue strength with decreasing sheet thickness down to $3\,mm$. Similar findings were obtained by Ringsberg *et al.* (2008) in their fatigue testing of nuts welded to thin sheets

2.3.2 Corrosive environment and temperature

Many experimental investigations have contributed to significant findings in the area of corrosion fatigue for offshore applications. A few research groups; Eslami *et al.* (2010) and Ishikawa *et al.* (2008) investigate the stress corrosion crack initiation of pipeline steels in a near-neutral pH environment. Schroeder and Müller (2009) report the fatigue and corrosion fatigue behaviour of a typical alloy used in the riser construction of offshore platforms. Pargeter *et al.* (2008) report the corrosion fatigue investigation on steel catenary risers in sweet production. Vennemann *et al.* (2008) present the bending fatigue tests of large diameter steel wire rope for subsea deployment. Yang *et al.* (2009) report the fracture toughness testing of SE(T) specimens in a sour environment to simulate the corrosion on offshore pipelines and risers. Holtam *et al.* (2009) report an investigation into fatigue crack growth test methods in a sour environment. Thierry *et al.* (2010) report a series of experimental investigation on steel materials used in the offshore platforms tested under very high cycle regime with three different ambient environments: 1) laboratory air, 2) laboratory air after pre-corrosion and 3) real-time artificial sea-water flow. The fatigue strength of the specimens tested in real-time sea-water environment at 10^8 cycles decreases significantly by a factor of 74 % compared to the specimens tested in the laboratory air and 71 % compared to the pre-corroded specimens. These results can be compared to "an offshore design practice" where S-N curves for subsea installed items in free corrosion are reduced by a factor 3 relative to S-N curves in air.

2.3.3 CA and VA loading, residual and mean stress effects

In service, the great majority of marine structures are subjected to variable amplitude loading while the design of the structures generally is based on fatigue data for constant amplitude loading combined with e.g. a Miner's linear cumulative damage model and an adequate safety factor. The validity of the above approach was investigated by Zhang and Maddox (2009) conducting experiments for Variable Amplitude (VA) loading based on two types of welded specimens. In some cases, VA loading is significantly more damaging than Constant Amplitude (CA) loading. The experiment indicates that the influence of mean stress is less significant compared to possible sequence effects. In addition, they documented that some shakedown can occur during the life time of the structure due to external loading and the above approach might therefore be too conservative. Based on tests including part of a full-scale driven foundation pile, which formed part of the support for the Edda Tripod for 30 years, Lotsberg *et al.* (2010b) show that only minor shakedown of residual stresses occurred

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during installation and service. It was therefore recommended still to use S-N curves allowing for residual stresses up to the yield stress.

2.4 Fatigue Crack Initiation

The fatigue damage process and crack initiation in steel material starts with dislocation movements forming slip bands, which nucleate, causing micro cracks inside grains in the microstructure. When the density of micro cracks is high enough, they coalesce together causing a short crack, which grows under cyclic loading. This crack initiation process is significantly affected by the material microstructure since the crack forming is controlled by the largest grain size, McDowell and Dunne (2010). In addition, the microstructure barriers i.e. grain boundaries affect the short crack growth until the crack size is more than 8 times averaged grain size Kawagoishi *et al.* (2000). Lautrou *et al.* (2009) proposed an approach to estimate the fatigue crack initiation life for welded steel joint by implementing a two-scale damage model in the finite element analysis. When the the geometry of the crack starts to control the crack growth rate, a long crack is initiated. The theoretical models for fatigue crack initiation can be divided into two groups: microstructure-sensitive mesoscale models and continuum based models.

The mesoscale models are based on the crystal plasticity, and thus they can capture the main feature of the microstructure; the size, direction and location of the individual grain. Roters *et al.* (2011) and McDowell and Dunne (2010) provide a good overview about the mesoscale modelling and the microstructure-sensitive computational methods for the fatigue crack forming. The mesoscale model is applied by Guilhem *et al.* (2010) investigating the effect of the grain clusters on fatigue crack initiation, while Romanova *et al.* (2011) investigated the influence of the grain boundaries on the plastic strains in different weld zones under static loading. Cyclic plasticity under variable loading has been tackled by Li *et al.* (2011). Luo and Chattopadhyay (2011) introduce multiscale damage criteria for the crack forming, and Owolabi *et al.* (2010, 2011) apply a probabilistic mesoscale model to the damage process zone and notch effect. All these studies aim at increasing the physical understanding about the crack forming and the influence of the different property of the microstructure. However, the special challenges still exist to model the short crack growth between grains, and to define reliable material parameters required for the quantitative fatigue analysis.

The continuum based approaches, e.g. the strain-based approach, are the most traditional way to model the crack initiation. These approaches include the effect of microstructure implicitly through the cyclic stress-strain curve and the fatigue strength coefficient i.e. Coffin-Manson equation, see e.g. Radaj *et al.* (2009). There the notch effect is typically captured using Neuber's rule. The strain-based approach is successfully applied by Lassen and Recho (2009) to derive more accurate physically based S-N curve for welded steel joints. Pakandam and Varvani-Farahani (2011) study the applicability of different strain-based energy approaches for welded joints, and they conclude that the critical plane based approach gave the best agreement with the fatigue test results of different welded joints. However, as noted by Beretta *et al.* (2009), the strain-based approach can fail particularly for sharp notch and variable amplitude loading. The main limitation of the strain-based approach is that the analysis is based on the initial geometrical shape of the weld notch, and thus, the effect of crack growth on the stress-strain state and gradient is not considered. The fracture mechanics corrects this weakness, but it requires the initial crack. Fracture mechanics based approach to marine structures has been developed by Cui *et al.* (2011). Alternative interesting approach has been presented by Mikheevskiy *et al.* (2009, 2011)

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and Wang *et al.* (2011), when they applied the strain-based approach to determine the fracture mechanics parameters i.e. fatigue crack growth rate. However, the further investigation of the limits of the fracture mechanics based approaches is required, since they neglect the period of the crack forming and micro crack coalesce to the short crack. In general, the application of the different continuum-based approach for practise is also challenged the lack of the material data. Although the material data is available for different parent material, see Basan *et al.* (2011) and Wang and Cui (2009), the material data for welded joints is very limited.

2.5 Fracture Mechanics Approach (Propagation Phase; Toe and Root Cracking)

The S-N approach often covers the total fatigue life of a structural component's fatigue life from the crack initiation to a through-propagation of the fatigue crack. Coupled with a Paris-type law to determine the fatigue life consumed during the crack propagation, the S-N approach then enables an approximate estimation on the fatigue life corresponding to the fatigue crack initiation. The empirical Paris Law has become a widely recognized approach to estimate the propagation life of a fatigue-induced crack in ship and offshore structures. The Paris Law dictates that the rate of the fatigue crack growth depends on the range of the stress-intensity factors, which uniquely determines the stress-strain fields near the crack tip for a small-scale yielding condition. The practical application of Paris law requires an assumption on the initial fatigue crack size, since the fatigue driving force for tiny cracks often fall below the Paris' threshold.

2.5.1 Crack Growth Rate Models

The Paris Law, when applied to estimate the crack propagation life for components or structures, often shows dependence not only on the loading range, but also on the maximum or minimum load level. Noroozi *et al.* (2007) propose a two-parameter fatigue crack growth driving force to include the effect of the load ratios. Recent research efforts lead to the fatigue crack growth models based on the energy principles, Bian and Taheri (2008), which include the effect of elastic-plastic deformation near the crack tip and the mixed mode loading, Liu and Mahadevan (2007). Shahani *et al.* (2009) compare the fatigue crack growth rate model expressed in the cyclic range of stress-intensity factors (ΔK), the range of crack mouth opening displacement ($\Delta CMOD$), the range of crack-tip opening displacement ($\Delta CTOD$) and the range of energy release rate (ΔJ). The comparison with the experimental data reveals that the crack growth rate expressed in terms of $\Delta CTOD$ and $\Delta J$is independent of the loading ratio, while the crack propagation rate expressed in ΔK and $\Delta CMOD$ exhibits strong dependence on the loading ratio. To illuminate the need for the analytically intractable stress-intensity factor solutions for most 3-D structural geometries, Pugno *et al.* (2006) propose a generalized Paris law to estimate the fatigue crack growth. This generalized Paris law replaces the stress intensity factor range by the stress range,

$$da/dN = B\Delta\sigma^n a^m \tag{1}$$

where B, n and m are material constants. The generalized fatigue crack propagation rule removes the requirement to compute the stress-intensity factors for complicated geometries and different crack sizes. Li *et al.* (2008) propose an improved, normalized Paris law to estimate the fatigue crack propagation,

$$db^*/dN = Cf^m\left(b^*\right)\Delta\sigma^m a^{m/2-1} \tag{2}$$

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where $f(b^*)$ refers to the normalized stress-intensity factor range. This improved model predicts closer agreement for the propagation of surface cracks in rectangular plates.

2.5.2 Fatigue Crack Growth Assessment

The crack propagation in structural materials imposes strong effects on the fatigue life assessment of offshore structures. The effect of crack initiation and propagation at multiple crack sites has attracted some research efforts in recent years, since realistic fatigue cracks often initiate from multiple locations around the hot-spot region as observed in many experimental research. Mkaddem and El Mansori (2010) proposed an equivalent ellipse method to analyse the fatigue behaviour at multi-surface initiations. Bozic *et al.* (2010) investigated the growth of multiple fatigue cracks in plates under cyclic tension. Their experimental investigations revealed that three collinear fatigue cracks in a plate lead to higher crack growth and a 40 % shorter fatigue life than a single crack in a plate.

The estimation of the crack growth life under fatigue loading predicates essentially by the Paris law, which has been widely applied to the assessment of many structural components in ship and offshore structures, Niu *et al.* (2009) and Larrainzar *et al.* (2010). Saxena *et al.* (2009) showed an examples of the fatigue life prediction for surface cracked straight pipes. They concluded that the Paris law provides a reasonable estimation of the fatigue propagation life compared to the experimental data. Their study also demonstrated that the SIF computed from semi-elliptical surface cracks should not be used to assess the fatigue life if the pipe has a constant depth crack. Hachi *et al.* (2010) proposed a hybrid weight-function approach to predict the fatigue crack growth for elliptical cracks in welded joint structure. Their approach assumes that the elliptical crack evolves into a circular crack under fatigue loading. Nykanen *et al.* (2009) developed a simplified fatigue assessment method for high quality welded cruciform joints. Their approach utilizes the linear-elastic fracture mechanics theory to develop an equation between the geometric parameters and the fatigue strength of the welded joint. They compared their method with 152 experimental fatigue data points.

Darcis *et al.* (2009) report the experimental investigation of fatigue crack growth rates in pipeline steels. Combined with the compliance method obtained from the FEA approach, the Paris law leads to accurate predictions of fatigue crack growth data and true crack lengths. Herrera *et al.* (2010) report the experimental study in seam welded API 5L X42 pipeline steels with fatigue crack growth in three separate zones, where the base metal shows the strongest resistance against fatigue crack growth among the three materials, while the weld metal exhibits the least resistance. The fatigue crack growth in the weld metal and in the heat-affected zone follows closely the prediction of the Paris's law while the fatigue crack growth in the base metal demonstrates more scatter.

Feltz *et al.* (2010) and Fischer *et al.* (2011) worked on a reliable and practical fatigue assessment of the partial penetration welds, which can be found in many ship structures. Depending on the throat thickness of the weld, the crack can initiate at either the toe or the root of the weld. The preferable approach should be able to distinguish between these two modes. The work carried out by the authors includes experiments, mixed mode crack propagation analyses using FRANC2D, results from notch stress approach and results from a newly developed Notch Stress Intensity Factor (N-SIF) approach. All three approaches were found to provide relatively reliable

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prediction of failure mode, but the estimate fatigue lives were found to be conservative. Fricke (2009) addresses the notch stress approach in the IIW guideline for the Fatigue Assessment by Notch Stress Analysis for Welded Structures which reviews different proposals for reference radii together with associated S-N curves.

Zacke *et al.* (2010) investigated the safety against fracture of block joints welded with weaving and string-bead techniques with large gaps in shipbuilding by use of fracture mechanics evaluation based on the FITNET procedure. They carried out CTOD testing of the two techniques, and they concluded that it was beneficial for the fracture behaviour of the weld to have wider welds (e.g. 30 mm) with sufficient strength properties for the welds carried out by the weaving techniques; this was not seen for the string-bead technique where also critical crack lengths were much smaller than for the weaving technique.

In addition, there have been some new developments in estimating the fatigue damage of fatigue cracks in recent years. Lassen and Recho (2009) proposed a more accurate nonlinear S-N curve to estimate the fatigue life for welded steel joints. The proposed method separates the fatigue life into a two-phase procedure: the crack initiation phase and the crack propagation phase. The crack initiation life depends on the local notch stress while the crack propagation life derives from the integration of the Paris law. In parallel, Makkonen (2009) also presented a new method to estimate the total fatigue life of a structural component, consisting of the estimation of the crack initiation life and that for the crack growth life. The estimation of the crack initiation life utilizes a statistical approach while the estimation of the crack growth life employs the fracture mechanics based Paris law. Rozumek (2010) compares three empirical formulae based on the J-integral values to estimate the fatigue crack growth rate in the stage II fatigue crack growth. The three formulae include the fundamental Paris equation expressed in ΔJ; the Paris equation expressed in ΔJ and including the stress ratio effect and the crack growth model including the stress ratio and the fracture toughness of the material. The empirical formula including the both stress ratio and the fracture toughness demonstrate the best agreement among the three formulae.

2.5.3 Overload Retardation

Overloading incurred in a cyclic fatigue loading event creates a large compressive residual stress near the crack tip, causing the fatigue crack growth rate to decrease. Numerous experimental evidences; Bichler and Pippan (2007), Le Roux *et al.* (2009), Duan *et al.* (2008), Jacobsson *et al.* (2010) and Chen *et al.* (2008) reveal that overloading condition can cause significant retardation in fatigue crack growth rate of standard laboratory-scale compact tension specimens. Codrington (2009) investigate the effect of plate thickness on the retardation of fatigue crack growth caused by an overload. The effect of retardation caused by the overload generally decreases with plate thickness, due to the reduced plastic residual stress field in the thick, highly constrained crack fronts. Harmain (2010) propose a model to include the effect of overload retardation on the fatigue crack growth by a retardation factor, F_R;

$$\frac{da}{dN} = CF_R(K_{max} - K_{op})^m \tag{3}$$

where K_{op} refers to the stress intensity factor at the closure of the crack surface, K_{max} denotes the maximum stress intensity factor in cyclic load, C and m are material constants. The retardation factor depends on the size of the plastic zone caused by the overload in relation to the plastic zone caused by the constant amplitude loading. The

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retardation in fatigue crack growth due to plasticity-induced crack closure has been examined by Osawa and Sumi (2008) on ship structural details through a numerical investigation. They concluded that the load interaction effects slow down significantly the fatigue crack growth rate and the prediction rendered by the conventional Paris law provides a conservative estimation of the fatigue life.

2.5.4 Fracture Toughness and Stress Triaxiality

The final stage of the fatigue crack propagation often involves rapid and unstable crack growth, which leads to a complete separation of the material over the remaining ligament. Al-Mukhtar *et al.* (2010) demonstrate in their estimation of the fatigue crack propagation life that the crack size at which unstable crack propagation takes place does not impose a significant effect on the fatigue life estimation for different plate-type welded joints. Their calculation, therefore, assumes the crack size corresponding to the unstable crack propagation as half of the plate thickness, for weld toe cracks with the crack propagation path perpendicular to the applied load. Troshchenko (2009) investigated the fracture resistance of metals at the end of cyclic fatigue loads and concluded that for fatigue crack-tips under plane strain conditions, the material exhibits much lower fracture toughness values at the final fracture at the end of the fatigue load cycles than the material fracture toughness measured in fracture specimens under predominantly static loading.

The stress triaxiality affects ductile failure even in a microscopic level. Ohata *et al.* (2010) developed a meso-scale 3D simulation model to predict the effect of microstructural morphology in ferrite-pearlite steel on ductile failure resistance, incorporating the damage mechanism to control ductile cracking by strain localization between different microstructural phases. Ductile crack nucleation and subsequent growth and linking were simulated by damage evolution model including plastic potential to nucleate micro-void. Effect of applied triaxial stress state on critical macro-strain for ductile cracking was predicted, Figure 6.

Regarding unstable ductile crack propagation and arrest in high-pressure gas pipelines, the Battelle two curve (BTC) method has been widely used. The method compares gas decompression curve and crack driving force curve, both of which are expressed in terms of pressure, and predicts whether an axial crack propagates unstably or not. Japanese HLP approach also compares the two curves but can simulate a history of crack propagation and arrest. It has long been pointed out that the BTC needs correction for high-pressure, high-strength pipelines. A new model is proposed, which takes account of the interaction between gas decompression and crack propagation, Misawa *et al.* (2010). More accurate evaluation of the gas decompression and crack

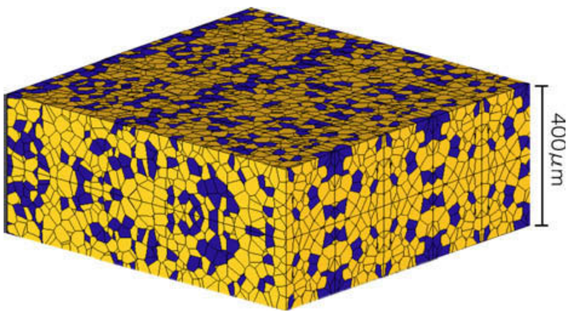

Figure 6: Meso-scale 3D numerical simulation of ductile fracture, Ohata *et al.* (2010).

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resistance curves are of crucial importance for better prediction of the unstable ductile fracture, Botros *et al.* (2010) and Duan *et al.* (2008).

2.5.5 Fracture Mechanics for Strain > 0.5 %

There is a general agreement in the industry that stresses above 0.5 % strain constitute strain based design. Currently, pipelines are designed for strains above 0.5 % due to reeling or environmental loads such as e.g. grounding, ice scouring and gouging, seismic loading and bottom snaking. Most research within this topic looks at the effect of internal pressure, the strain hardening characteristics of the pipe body material, degree of weld strength overmatch and the location of flaws. The topic was discussed in detail by the previous member of the ISSC fatigue and fracture committee, and hence the following section will focus on the latest research within this topic.

Extensive studies have been made for the strain-based design of linepipes, including full-scale tests; Mannucci *et al.* (2011), Tajika *et al.* (2011), Chen and Ji (2011), numerical simulations by Sandvik *et al.* (2011) and design methodology by Bjerke *et al.* (2011). Fairchild *et al.* (2011) provided a methodology of strain-based engineering critical assessment (SBECA) for ductile fracture. The methodology is based on the comparison of the tangency of the ductile tearing resistance curve (R-curve) and crack driving force and can be used to determine tolerable girth weld flaw sizes. A plot of about 150 weld metal and HAZ SENT R-curves was used to select three characteristic R-curves, Figure 7. The methodology has been calibrated and validated using about 50 full-scale tests covering a wide range of pipe geometries, material properties, degrees of girth weld misalignment, girth welding methods, and degrees of internal pipe pressure.

Stephens *et al.* (2009) present results of a large scale strain-based testing program of welded tubes where a range of parameters known to have significant impact on axial strain capacity of girth welds were examined, see Figure 8. A challenge is to estimate the strain from the deformation in full scale pipes and curved wide plate tests and they showed that axial strain could differ by more than 30 % depending on the location of the strain gauges. Hence, they recommend using a gauge length that bridges the girth weld and flaw location and also CMOD (crack mouth opening displacements) is contracted from the total elongation in order to be conservative. Wang *et al.* (2009) study the correlation between small-scale specimen material properties with large scale

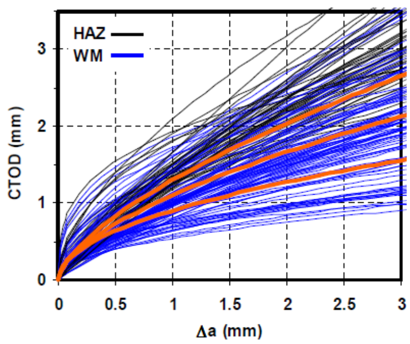

Figure 7: Ductile crack resistance curves of pipe girth weld metals for engineering critical assessment methodology, Fairchild *et al.* (2011).

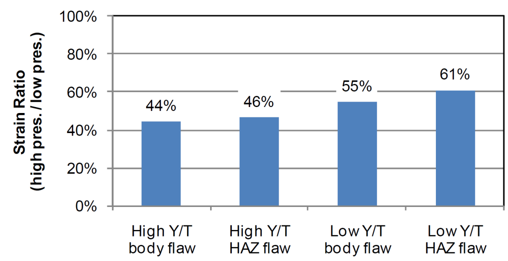

Figure 8: Effect of pressure on strain capacity (all flaws 3 x 50 mm with HAZ flaws adjacent to over-matched welds) Stephens *et al.* (2009)

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experimental test results including curved wide plate and full-scale pipes. Results presented showed uncertainties in the strain level in the range of 25 % when comparing FEM and full scale data. They conclude that understanding the true material response is important for all cases involving strain based design, and further work is still needed.

3 UNSTABLE CRACK PROPAGATION

Unstable crack propagation is of a type of fracture event in which a crack propagates at high velocity and long distance without increasing applied load, displacement or pressure. There are two types of unstable crack propagation; brittle and ductile crack propagation. Microscopic mechanism of brittle crack propagation in steel is predominantly cleavage fracture at high speed. The crack velocity of unstable ductile crack propagation is lower than that of brittle fracture, because energy consumption of this type of fracture is much larger than that of brittle fracture, large amount of stored energy is necessary for driving the crack. Prevention of unstable crack propagation is crucially important because it can lead to sudden catastrophic failure of the structures. Brittle crack propagation accidents can be prevented by applying steel plates with increased crack propagation resistance, or crack arrestability of base metal, together with proper crack arrest design. The crack arrestability of steel plates has been improved by applying e.g. thermo-mechanical control process (TMCP), see Section 4.

Unstable crack propagation has gained increased attention as design of offshore structures moves into artic regions where low design temperatures increase risk of brittle fracture. Furthermore, recent trend of adopting very thick steel plates in the design of large containerships and offshore structures has raised a concern regarding the reconsideration into brittle crack propagation because the brittle crack is more liable to propagate in heavier section steels due to the constrain effect (see Section 3.1.2). Recent developments of the research in this field are extensive, like standardization of crack arrest toughness testing and crack arrest design.

3.1 Nucleation of Brittle Fracture

The term used to describe a materials failure resistance to brittle fracture is fracture toughness; low toughness indicates a low resistance to brittle fracture and it is a functional of material properties such as microstructure and yield strength but also strongly dependent on the temperature, see Figure 9 where an upper and a lower shelf for toughness is defined. Fracture toughness is measured using highly constrained specimens, as represented by SENB specimens.

The Crack-Tip Opening Displacement has been widely used as fracture toughness parameters. The recent ASTM E 1290-08 employs a CTOD evaluation formula based on J-integral, which is different from the conventional formula based on the plastic hinge deformation model adopted in BS 7448. Tagawa *et al.* (2010) found that ASTM E 1290-08 based CTOD tends to give a smaller value than that of BS 7448 based CTOD. Ratio of the CTODs was about 60 % for low yield-to-tensile ratio steels. From direct measurement of CTOD of the SENB specimens, they found that ASTM E 1290-08 based CTOD corresponded to the CTOD of the thickness average, whereas BS 7448 based CTOD gave the CTOD at mid-thickness position. Considering the fact that most of the cleavage fractures are initiated at or near the mid-thickness positions, they presumed that the conventional BS 7448 based CTOD is more preferable for describing cleavage fracture initiation toughness, Figure 10.

A case study of the low temperature CTOD toughness for welded joints of the module stool of an FPSO is presented by Miao *et al.* (2010). Based on the international

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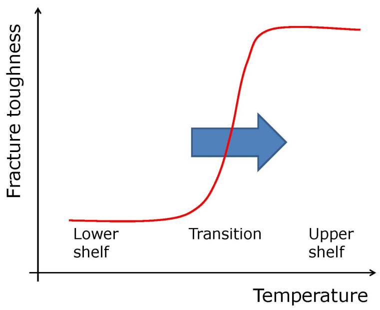

Figure 9: Fracture toughness as function of temperature

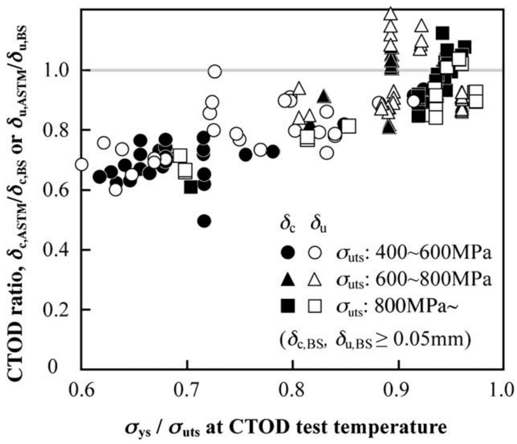

Figure 10: Comparison of E1290-08 and BS 7448 CTOD evaluation formula, Tagawa *et al.* (2009).

standard BS 7448 and DNV-OS-C401, a low temperature (-18° C) crack tip opening displacement (CTOD) test was conducted in the weld centre and the fusion line of the module stool. The results show that the CTOD values meet the requirements of DNV-OS-C401 (not less than 0.15 mm). Therefore, the preliminary welding procedure specification test can be used to weld the module stool for *et al.* which no further heat treatment is needed. Validation test like full scale and curved wide plate test (CWPT) is most often carried out at room temperature, however the integrity of the pipe needs to be proven for the lowest anticipated service temperature (LAST). Pari *et al.* (2010) investigate the use of Charpy V-notch testing in order to ensure upper-shelf fracture toughness. The goal was to provide guidance as to what CVN requirements are needed to ensure an upper-shelf performance, see Figure 10, and several models were investigated. They concluded that further work was needed, like the thickness effect, develop an upper-shelf temperature shift relation, finally the correlation to CTOD and SENT testing would be useful.

3.1.1 Influence of Constraint Effects

Fracture toughness is strongly dependent of the geometry and loading conditions. The standardized fracture toughness testing procedures such as those provided in ASTM and British Standards are intended to define a lower bound toughness value for the material or weld in question. These conventional toughness specimens like e.g. Compact Tension (CT) and Single Edge Notch Bend (SENB) have high constraint at the crack-tip and will provide lower bound fracture toughness with respect to the local geometry. Size criteria can be applied to prove that the test result is representative (conservative) when testing of these small scale test specimens are applied to large structures. Constraint corrections can be carried out either by correcting a higher constraint specimen or by using specimen with more similar constraint level found in the component in question. For both approaches there is a need to estimate the constraint level in the structure.

The constraint effects can be discussed based on the Weibull stress analysed, where determination of Weibull shape parameter, m, is an important issue. Handa *et al.* (2008) examined the values of m for a number of structural steels. No clear correlation could be observed between m and other parameters, including tensile properties, microstruc-

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tures, test temperatures, test specimen configurations and other parameters. However, they observed a mild dependence of lower bound value of m on critical CTOD, δ_{cr}; roughly 10 for δ_{cr} smaller than $0.05\,mm$ and 20 for δ_{cr} larger than $0.05\,mm$. Tagawa *et al.* (2010) evaluated the scatter in fracture toughness in the ductile-brittle transition temperature region for $500\,MPa$ class low carbon steel. They found that at -60° C the toughness showed a single modal Weibull distribution with $m = 4$, while in the temperature range from -20° C to -10° C, the distribution had a bilinear distribution with elbow points, beyond which the value of m did approach 2. The cause of bilinear toughness distribution was discussed taking account of subcritical crack growth, similar tendency was also seen by Wsposito *et al.* (2007). See also Østby *et al.* (2011) who investigated the fracture toughness scatter and the effect of constraint in weld thermal simulated HAZ microstructures at -60° C.

3.1.2 Cleavage and Brittle Bracture Nucleation in Welded Components

Welded joints are liable to brittle fracture initiation due to many reasons. One of the most influential factors is welding residual stress. Although the influence of the welding residual stress on brittle fracture initiation is well conceived and most of the fitness-for-service methods take its account, quantitative analyses have not yet been well undertaken. Yamashita *et al.* (2010) conducted a series of experiments using $780\,MPa$ class high-strength steel welds and numerical analyses based on the Weibull stress criterion. They found that critical CTOD of wide plates with residual stress can be simulated using the critical Weibull stress distribution which was determined by deep-cracked three-point bend specimens by considering the effects of both the increase in the crack-tip stress due to welding residual stress and the stress decrease due to plastic constraint loss in the wide plates. They further applied the concept of equivalent CTOD ratio, β, under the welding residual stress field and conducted fracture assessments for “After Weld Notch” and “Before Weld Notch” type welded joints within the framework of failure assessment diagram (FAD). A FAD diagram both evaluates failure due to brittle fracture or plastic collapse. They concluded that an excessive conservatism observed in the conventional procedure is reasonably reduced by applying the proposed methodology, Figure 12. Minami *et al.* (2010) investigated the effect of weld metal overmatch (too high yield stress of weld material relative to base material) on stress field and constraint in HAZ. They concluded that the constraint was increased with increasing overmatch ratio. Nevertheless, the strength mismatch effect was marginal under large scale yielding conditions, except for extreme overmatch conditions, Figure 11. Strength matching between weld metal and base metal

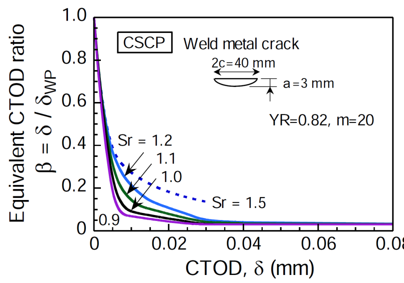

Figure 11: Influence of weld metal overmatch on equivalent CTOD ratio, Minami et al. (2010).

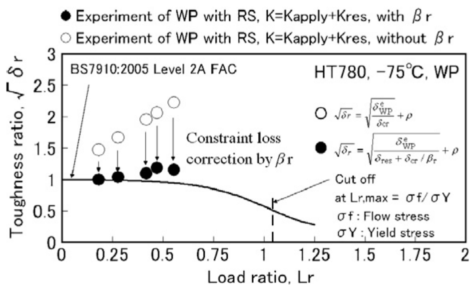

Figure 12: Prediction of brittle fracture initiation by FAD taking residual stress and constraint loss into account, Yamashita *et al.* (2010).

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is also an important factor influencing brittle fracture initiation. Ishikawa *et al.* (2007) previously showed that high hardness of weld metal resulted in lower fracture initiation toughness than expected from Charpy impact test properties at the weld bond in heavy thickness high-strength shipbuilding steel. Minami *et al.* (2011) pointed out that the strength matching effect changes considerably with notch locations. Weld metal overmatch decreases required toughness for the weld metal (WM) due to the shielding effect by the overmatch weld metal. Contrarily, the strength overmatch is not beneficial to HAZ toughness requirement because of the elevation of the stress field in the HAZ by the overmatch WM. They quantitatively estimated the influence of the strength matching and notch location considering the constraint loss correction factor, β, for CTOD.

3.2 Propagation of Brittle Fracture

Propagation of brittle fracture in welded steel structures could bring about sudden fatal accident. To avoid this type of fracture, double integrity concept, i.e. prevention of brittle fracture initiation and propagation, can be applied. For securing the arrest of brittle crack, once initiated, crack arrest toughness should be greater than crack driving force for a propagating crack. For this, improvement of crack arrest toughness of steels should be necessary along with measures to reduce crack driving force by e.g. improvement of weld geometries or reduction of residual stresses. Development of standard test methods for crack arrest toughness measurement is also an important issue.

3.2.1 Investigation of Brittle Fracture Propagation and Arrest

Kawabata *et al.* (2010) conducted a series of 500 mm wide crack arrest tests for establishing a standard test method for brittle crack arrest toughness, K_{ca}, of steel plates for ship structures. Effects of thickness and width of tab plate, distance between loading pins, temperature gradient and crack length on K_{ca} values were investigated for 16, 50 and 80 mm thick low carbon steel plates, together with numerical simulations of dynamic crack propagation by FEM. They determined the testing conditions for obtaining consistent K_{ca} values; tab plate thickness shall not be larger than 1.5 times that of test plate, tab plate width shall not be larger than 2 times that of test plate, distance between the loading pins shall be larger than 1.5 m for up to 350 mm crack propagation in the test plate, temperature gradient of the test plate shall not be greater than $0.25° C/mm$. These conditions were determined so that reflection of stress waves at tab plates or loading pins does not interfere with crack propagation and that the test gives a K_{ca} value consistent with that of duplex type crack arrest tests, which has no temperature gradient, Figure 13. For theoretical and numerical analyses, see Prabel *et al.* (2008) and Menouillard *et al.* (2010).

3.2.2 Cleavage and Brittle Fracture Propagation in Welded Components

It was previously conceived that a brittle crack which is initiated from a weld tends to deviate from the weld into the base metal due to tensile residual stress in the welding direction. However, Inoue *et al.* (2006) demonstrated that a crack propagates along a large heat-input welded joint of heavy gage plate. A Japanese research consortium conducted a series of large scale tests for investigating the behaviours of dynamic crack propagation and arrest in welded steel components and for establishing a criterion of brittle crack arrest. Handa *et al.* (2010) conducted a series of duplex type crack arrest tests and structural component model tests, simulating hatch-side coming and deck structure, using 60 and 75 mm thick high-strength steel plates. The structural

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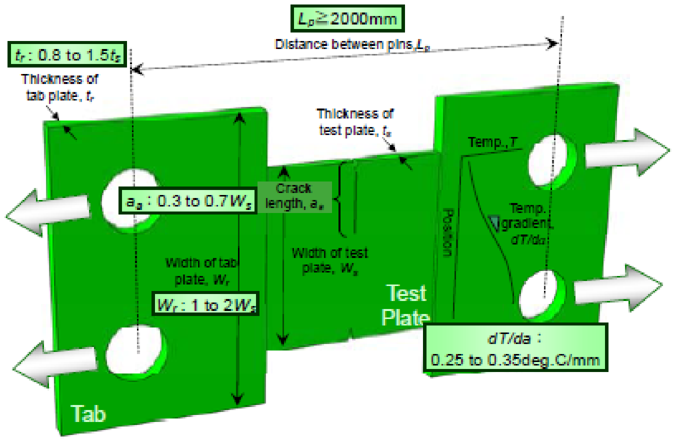

Figure 13: Proposed crack arrest testing conditions, Kawabata *et al.* (2010).

component model test under an applied stress of 257 MPa confirmed that, assuming weld penetration of the deck, brittle cracks can be arrested if the K_{ca} value of the test plate is 5,000 $N/mm^{3/2}$ or higher. In contrast, in the duplex type crack arrest tests of the same material, cracks propagated even if the K_{ca} value was 5,000 $N/mm^{3/2}$. This result indicate that the conditions for crack arrest are more relaxed in the structural component model tests than in the duplex type crack arrest tests, in which crack arrest was achieved with K_{ca} value larger than 6,000 $N/mm^{3/2}$ or higher. The test results also suggested the possibility that steel plates with heavier thicknesses needs higher K_{ca} value for crack arrest, Figure 14. Further, Inoue *et al.* (2010) conducted real-scale structural component model tests as well as ultra-wide duplex type crack arrest tests using 60 mm and 75 mm thick TMCP steels for clarifying the critical conditions for brittle crack arrest. They found that required K_{ca} value for crack arrest in the ultra-wide duplex test was 6,000 $N/mm^{3/2}$ or higher. Accounting for the structural discontinuity in the component considered, K_{ca} value of 6,000 $N/mm^{3/2}$

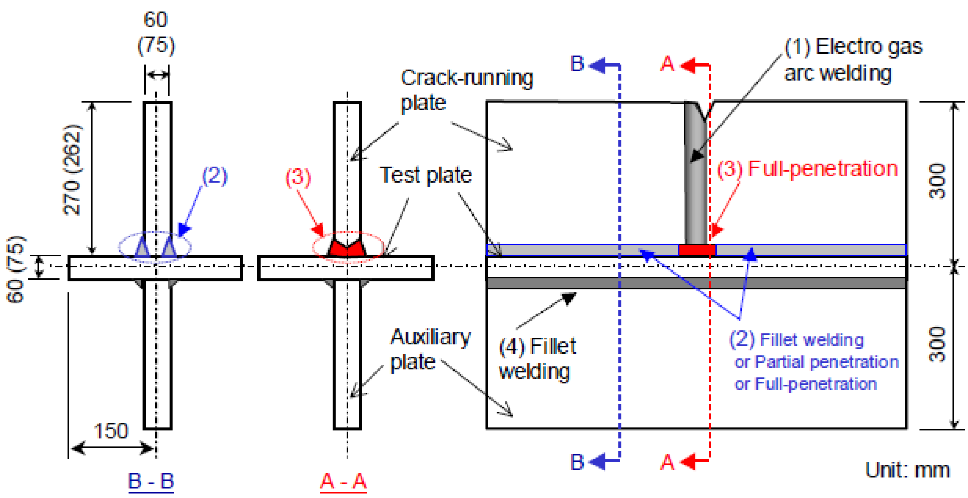

Figure 14: Structural component model tests for crack propagation and arrest, Handa *et al.* (2010).

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(a) LC-T1-1 (Arrest) (b) LC-T2-1 (Propagate)

Figure 15: Real scale structural component model tests for crack propagation and arrest, Inoue *et al.* (2010).

was considered sufficient for brittle crack arrest in the hatch-side coaming and deck structure, Figure 15.

An *et al.* (2008) conducted wide-plate crack arrest tests with temperature-gradient for large heat-input electro-gas welded joint of 50 and 80 mm thick plates. They obtained K_{ca} values 3,190 and 2,350 $N/mm^{3/2}$ for the both thicknesses at $-10° C$, which were about 40 % of those of the base plates. The brittle crack propagation paths were near the weld metal or fusion line, implying that the crack path was independent of the plate thickness. A crack arrest design strongly depends on whether the crack propagates along the weld or it deviates into base metal. Nakai *et al.* (2011) developed a three-dimensional numerical simulation model for brittle crack propagation path in the weld having toughness heterogeneity and welding residual stress distribution. Their model showed that the crack path is determined by a competition between stress state including residual stress and applied stress and toughness heterogeneity. Parametric calculations showed that a crack tends to deviate from the weld having shallower toughness valley at fusion line and under lower applied stress, which agreed well with the published data.

3.2.3 Example: Prevention of Brittle Fracture Propagation in a Container Ship

By applying relatively thick steel plates to large container ships, establishing technical requirements to prevent brittle fracture has become an urgent issue. Comprehensive studies on brittle crack propagation were carried out by a Japanese research consortium, Yamaguchi *et al.* (2010). As a result of this project, guidelines were developed with the aim to prevent large-scale failure of the hull structure by arresting brittle cracks at specific locations in the hull when such cracks were initiated unexpectedly. Their research outcome is summarized as; (a) brittle crack arrest toughness K_{ca} required for arresting long crack is 6,000 $N/mm^{3/2}$ for the actual structure of a container ship, (b) 300 mm is in general used as the required butt weld-shift. The developed guidelines are to set forth clear functional requirements for brittle crack arrest design in hatch-side coaming and deck structure in large container ships, Figure 16.

A Japanese joint research project, which is focusing on the safety-related issue of extremely thick steel plate applied to hull of large container ships, was conducted, Sumi *et al.* (2010). The project encompassed the prevention of brittle crack initiation from the welds as well as of brittle crack propagation, as mentioned above. The project proposed toughness requirement, K_c, as 4,000 $N/mm^{3/2}$ determined by deeply cracked

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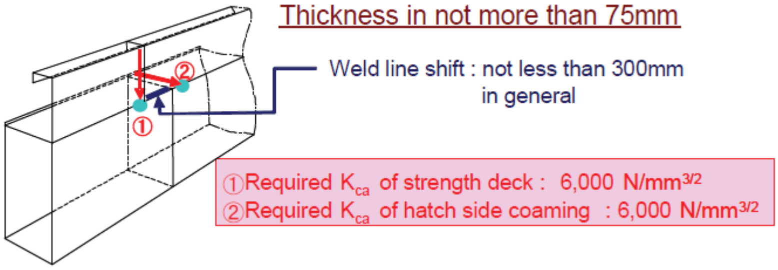

Figure 16: Guidelines for preventing brittle crack propagation in large containership structures, Yamaguchi *et al.* (2010a).

wide plate tests for the welds with plate thickness exceeding 50 mm, along with extensive analyses on fatigue crack propagation from assumed initial defects during service period. A number of ultrasonic testing was also conducted at shipyards for welds containing artificial defects to analyse the probabilistic nature of non-destructive testing. Regarding the prevention of brittle crack initiation, Shin *et al.* (2011) made fatigue crack propagation analysis for Fracture Crack Arrest, FCA butt-welded joint of hatch-side coaming, together with BS7910 brittle fracture assessment analysis. Minimum CTOD requirement for butt-welds was determined as 0.1 mm.

Doerk and Rörup (2009) investigated the toughness and quality requirements for YP47 steel welds (yield strength of 460) based on fracture mechanics. The authors investigated the effects of different influence parameters such as design temperature, fracture toughness, initial defect size, and shape of load spectra. By studying these parameters by fracture mechanics calculations, a safety concept for the avoidance of brittle fracture in YP47 welds was established. They concluded that for near surface defects "Inspection Based Design" during service life was necessary in order to prevent failure. Improvement of weld geometry for preventing brittle crack propagation in large container ships was studied by Toyoda *et al.* (2008) who proposed an unwelded breadth at the intersections between hatch-side coaming and strength deck, and confirmed the effect of the unwelded part by large-scale fracture testing and FEM analysis. They applied this concept to actual ship using butt-shift and chill plate. An *et al.* (2011) developed a brittle crack arrest technique in FCAW) and the combined process of EGW and FCAW using the arrest weld in the end of hatch-side coaming weld. They confirmed by large-scale testing that this concept could arrest a brittle crack without butt-shift in hatch side-coaming.

4 ADVANCES IN MATERIALS AND STRUCTURE DETAILS

The occurrence of fatigue, stress-corrosion cracking, and fracture in ship structures, particularly in high-strength steels, are now well recognized. The possibility of successfully dealing with these phenomena in ship structures are much better established now. Several advances in technology are currently available for analytical treatment and control. Advanced ship structures, which are presently emerging, such as high performance hydrofoil craft, involve the use of steels with significantly higher strength/density properties than the steels that have been traditionally used in the ship building industry. These new ship designs contemplate the structural application of alloys, such as 17-4 PH Stainless Steels, SY-130 steel, as well as 5000-series aluminium alloys and titanium.

Metal fatigue involves the initiation and growth of cracks under cyclic stresses where residual stresses remaining from manufacturing play an aggravating role. Metal fatigue

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takes on greater importance with increasing yield strength steels as they offer inferior fatigue crack growth resistance. Fracture is well acknowledged phenomenon to ship construction. Again, the problem applied to advanced ships is of brittleness associated with increasing yield strength, rather than brittleness associated with decreasing service temperature. For fracture, metallurgical and geometric factors become of primary concern. The embrittling effects of higher yield strength can be offset through metallurgical control, and the thinner section sizes associated with high-performance ships are less prone to brittle fracture than ordinary heavy section ship materials because of their greater ability for localized plastic deformation around crack tips.

4.1 Examples of Materials in Use

The structural steel specifications for commercial ships are developed and put into operation by a number of ship classification societies, including the American Bureau of Shipping (ABS) and the American Society for Testing and Materials (ASTM). These organizations have unified their requirements for structural steels into two classes: normal strength (235 MPa yield strength) and higher strength (317 and 352 MPa yield strength) (ASM: Carbon & Alloy Steels, 1996). The normal strength class consists of four grades of carbon-manganese steel, with the grading based on toughness. The higher strength class is also based on toughness, but they belong to a separate family of microalloyed high-strength low-alloy (HSLA) steels. Precipitation hardening mechanisms and grain refinement through the presence of small amounts of vanadium, niobium, and/or copper elevate their yield strength.

Aluminium is commonly used in other marine applications as well. These structures include main strength members such as hulls, deckhouses, and other applications such as stack enclosures, hatch covers, windows, air ports, accommodation ladders, gangways, bulkheads, deck plates, ventilation equipment, lifesaving equipment, hardware, fuel tanks, and bright trim (ASM: Aluminium, 1993). Aluminium-manganese (5xxx), and aluminium manganese-silicon (6xxx) alloys have been widely used for ship superstructures due to light weight and excellent corrosion properties. High strength aluminium-copper (2xxx) and aluminium-zinc-manganese (7xxx) alloys can also be used in marine atmospheres.

4.2 Extra High Strength Steels

The use of high strength steel has seen an increased demand lately in order to save weight and welding time, especially the pipeline industry is driving the research of high strength steel development, Shimamura *et al.* (2011) and Li *et al.* (2010). Welding high strength steel can be a challenge especially in order to obtain good toughness properties in the weld metal and HAZ since the weldability of steels depends on its hardenability. Hamada *et al.* (2009) investigated the tensile and Charpy properties of girth welds for high strength linepipe, they concluded that the use of dual torch provided better toughness values than a single torch which provided higher yield strength. They also recommended that further research should be put into investigating the carbon content in the weld metal, since they discovered that a somewhat higher carbon content lead to higher fraction of intergranular acicular ferrite which indicated that the tensile and toughness balance was improved.

Common fatigue design is independent of the materials yield strength, however in the low-cycle range, plastic deformation occurs due to high loading and the effect of the yield strength will have an effect on the achieved life. Fatigue codes put restrictions on allowable yield strength, e.g. DNV-RP-C203, allows steel for YS up to 960 MPa in

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air and 550 MPa for steel materials in seawater with cathodic protection or steel with free corrosion. Herion *et al.* (2011) concluded that the butt welds made of S690QL and S960QL gave much better results than the corresponding detail category or FAT-class (DC71-DC-80 according to EN 1993 1-9 (2010)), while S1100QL and S1300QL provide lower fatigue strength. The latter results were to due lack of adequate weld material, in addition the heat input during welding influences the strength of the materials negatively. Hrabowski and Herion (2009) investigated the effect of post weld heat treatment on steel grades S700MC, S960QL and S1100QL by using high frequency peening methods. They found that improvement gets even higher with increasing yield strength of the steel. The same effect was seen by Ummenhofer *et al.* (2011) who investigated the effect of high frequency hammer peening of 960 MPa steel and saw a 66 % increase in fatigue strength of the treated joints compared to the as welded joints.

4.3 Steel with Improved Crack Growth Properties

It is often assumed that the fatigue crack growth properties of structural steels fall in a common scatterband like in BS 7910. However studies have shown that improvement of the microstructure of the steel can lead to an increased life for the component in question. Katsumoto *et al.* (2005) and Konda *et al.* (2007) showed that the fatigue crack growth rates of fracture crack arrester (FCA) steel were reduced compared to conventional steel in side longitudinal structural model and side wide gusset welded joints. They also showed that the stress concentration at the weld toe of a FCA steel specimen is smaller than that of a conventional steel specimen. The steel has already been applied to some ships. The developed steel plate has been approved as FCA in grades AH36, DH36, EH36 and AH40, DH40, EH40 by Nippon Kaiji Kyokai, Lloyd's Register, Det Norske Veritas and American Bureau of Shipping. Sakano *et al.* (2005) investigated the fatigue life extension effect of FCA steel through fatigue tests using welded girder specimens made of FCA steel and a conventional high strength steel (JIS SM570Q), with welded joints between cross beam bottom flanges and main girder web. They showed that the fatigue strength of web gusset joint of FCA steel specimens is about 1.3 times higher than that of conventional steel specimens. Youn *et al.* (2007) carried out fatigue tests for FC and conventional steel weldments. They found that the fatigue strength of FCA steel weldment is in the upper region of the fatigue strength data band of conventional steel weldments, and the fatigue crack propagation rate in HAZ of FCA steel weld is smaller than that of the base metal of conventional steel.

Nakashima *et al.* (2005) examined the relation between fatigue crack growth rate and fatigue life of welded joint in steel with dispersed secondary phase. Fatigue crack growth tests of base metals and fatigue tests of gusset welded joint were carried out. They found that the fatigue life increases by 10 % when the growth rate decreases by half, and the fatigue life doubles when the growth rate decreases by a factor of 10. The developed fatigue crack arrester (FCA) steel can provide a new alternative for fatigue life improvement measures from the viewpoints of materials. Tentative design S-N curve for the FCA steel was newly defined, Hara *et al.* (2010), Konda *et al.* (2010). The steel was tentatively used in a stress-concentrated area in an LNG carrier. The proposed design S-N curve makes it easy to use FCA steels without any scantling increase or structural reinforcements resulting in steel weight increase. Thus, long target fatigue lives may be documented without applying post weld improvements like weld toe grinding, Figure 17.

Fatigue crack arrest (FCA) steel can be explained by the two following mechanics;

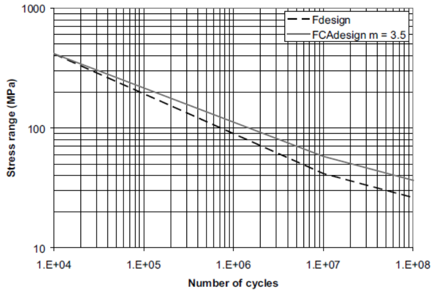

Figure 17: Tentatively determined S-N curves for Fatigue Crack Arrester steel, Konda *et al.* (2010).

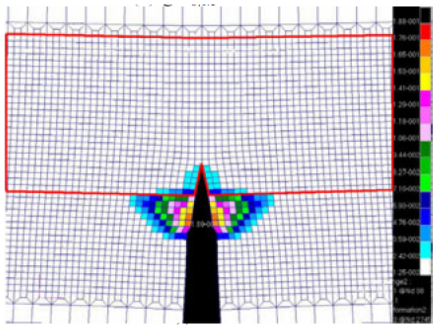

Figure 18: Meso-scopic FEM showing fatigue crack growth retardation at martensite phase in DP steel, Osawa *et al.* (2008).

- Increased fatigue initiation resistance at weld HAZ by suitable micro structures.
- Decreased crack growth rate in base material when a fatigue crack passes a grain boundary from a soft phase (feritte) to a hard phase (bainite) that is present in these new dual phase steels

Koda *et al.* (2010) carried out fatigue testing of FCA steel and a design S-N curve has been proposed based on 66 small scale tests of FCA steel and 18 tests from test specimens made from conventional steel. From the S-N test data they discovered that the slope of S-N curves for FCA steel and conventional steel is different, where insignificant effect was seen in the high stress area and benefit is seen in the high cycle region. The paper concluded that the fatigue life could be increased by a factor of 3 for a typical ship structure subjected to typical long term stress range distribution from wave actions.

The microstructures and fatigue crack growth rates (FCGRs) of EH36 thermo-mechanical control process (TMCP) steel weldments have been reported by Tsay *et al.* (1999). They show a modest increase in hardness of the heat-affected zone (HAZ) in the as-welded condition due to the low carbon equivalent (CE) of the steel. Microstructural observations indicate that the coarse-grained HAZ is composed of mainly lower bainite with some upper bainite. Fine-grained HAZ consisted of refined ferrite and bainite, together with interlath microphases. Although the impact toughness of specimens vary significantly with orientations with respect to the rolling direction, minor change in FCGRs of the TMCP steel plate was found. The lower FCGRs of the HAZ than those of the steel plate is attributed to the formation of low-carbon bainite with high toughness, regardless of the postweld heat treatment (PWHT). The evidence showed that the TMCP steel weld after tempering at $600^\circ\, C$ for 2 h possessed a better resistance to crack growth than the plain-C steel plate.

Fatigue life improvement by microstructural control of steel has been studied by meso-scopic and crystal plasticity based FEM, Osawa *et al.* (2008). Crack closure level was found to increase as a crack-tip approaches martensite-phase boundary in a ferrite-martensite dual phase (FMDP) steel. This change became more pronounced with martensite phase with higher hardness. Furthermore, the calculation results led to a prediction that the crack growth rate of the FMDP steels with polygonal and banded martensite phase becomes much higher than that with flattened and banded martensite phase because the cracks can slip through narrow slit between the martensite phases, Figure 18. Possible fatigue life prolongation by grain size refinement, Go-

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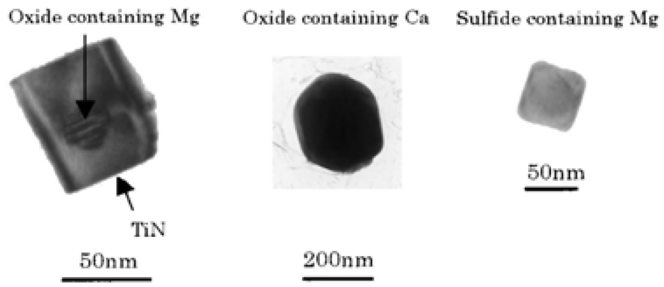

Figure 19: Pinning particles in steel for preventing HAZ grain growh, Shirahata *et al.* (2011).

toh *et al.* (2009), and the importance of the softening behavior of crystal and elastic property of inclusions, Tsutsumi *et al.* (2009), were predicted by numerical calculations.

4.4 Materials for Brittle Fracture Susceptible Structures

For realizing the double integrity against brittle fracture, it is indispensable to improve material's resistance to brittle fracture initiation at weld as well as brittle crack propagation at base metal through microstructural control of HAZ and base metal, respectively. YP460MPa class heavy section steel plates have been developed through strict control of rolling and cooling practice in the TMCP process, Otani *et al.* (2011), Kaneko *et al.* (2010), An *et al.* (2011). These steels were subjected to the temperature-gradient type crack arrest tests, showing K_{ca} values higher than 6,000 $N/mm^{3/2}$ at $-10° C$. Some of these steels have been applied to large container ships. Improvement of HAZ toughness are targeted to high heat input electro-gas welding and medium to low heat input multi-pass welding, the former being applied to butt-welding of thick section components in large container ships and the latter to offshore structures. Fine oxide and sulphide particles are dispersed in steel to prevent grain growth at HAZ of large heat-input welding, Kaneko *et al.* (2010), Shirahata *et al.* (2011), Figure 19. Fukunaga *et al.* (2010) presented the second generation Ti-oxide steels, which contains high amount of manganese, enhancing intragranular ferrite (IGF) transformation from Ti-oxide particles and suppressing ferrite side plate (FSP) microstructure at grain boundaries, both decreasing the effective grain size of HAZ and achieving high HAZ CTOD values at $-40° C$, Figure 20. Suh *et al.* (2011) proposed a new parameter of carbon equivalent type, representing HAZ toughness, Figure 21.

4.5 Materials for Cold Climate

Oil and gas exploration and production is moving into arctic areas. The reduction in ice-covered areas has rendered northern routes more advantages and in addition it is anticipated that as much as 25 % of the undiscovered oil and gas resources can be found in the Arctic. This means additional challenges for design, construction and operation of offshore installations and ships. In addition, very low temperatures are required for storage and transport of LNG. These low temperatures influence the fatigue and fracture properties of the material. An effort has been taken by the Barents 2020 project, where the goal is to harmonise industry standards for health, safety and the environment for the Barents Sea, where both Russian and Norwegian participants are involved, Sæbø and Cammaert (2011). However, none of these rules and guidelines is derived specifically for the arctic and cold temperature applications. Hence, the oil

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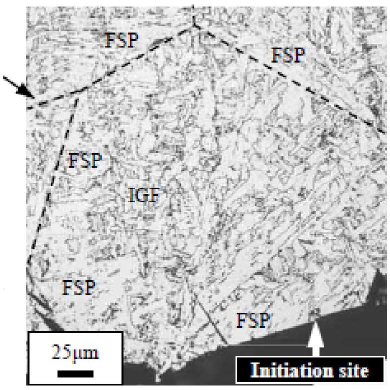

Figure 20: HAZ microstructure of the second generation Ti-O steel, Fukunaga *et al.* (2010).

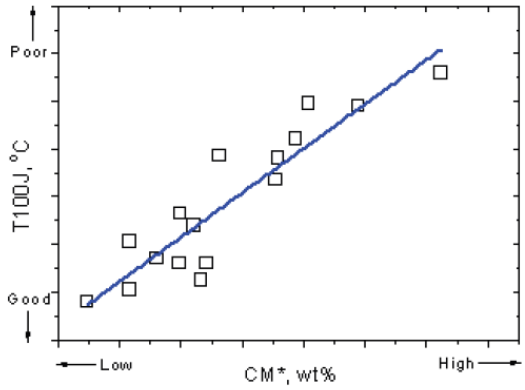

Figure 21: A proposed new alloying element parameter representing HAZ toughness, Suh *et al.* (2011)

and gas industry is looking for recommendations and guidelines for material selection and design for low operating temperatures.

A five year Arctic material research project supported by The Research Council of Norway, oil companies, offshore suppliers and contractors is investigating criteria and solutions for safe and cost-effective application of materials for hydrocarbon exploration and production in Arctic regions. One main task for the project is to carry out material and toughness testing of carbon steel at $-60^\circ C$ in order to qualify steel for low temperature applications and the main results were presented at the First Arctic Material Symposium at ISOPE2011. The results from the project showed a large scatter in the toughness results for 355 MPa and 420 MPa steels, Østby *et al.* (2011), Akselsen *et al.* (2011)and Welch *et al.* (2011). A probabilistic fracture mechanics evaluation was presented by Horn and Hauge (2011) in order to investigate the severity of the obtained fracture toughness distributions and the effect of the constraint of the different test specimens when it comes to structural integrity. The same toughness data was evaluated statistically by Hauge and Holm (2011) who presented a statistical interpretation of the toughness test data by looking at different models and they concluded that the SINTAP procedure provides in general a conservative estimate of the lower tail of the statistical distribution.

4.6 Honeycomb Structures

The application of lightweight honeycomb panels as the elements of ship structure provides benefits like; 20-30 % reduction in weight and material consumption as compared to traditional structures for like equal bearing capacity as conventional solutions. The application of laser welding makes the manufacturing of honeycomb structures processable and effective, Rybin (2010). The CRISM (Central Research Institute of Structural Materials) "Prometey" has developed a sequential series of welding procedures for laser and arc-laser welding providing the possibility of manufacturing honeycomb panels and ship structure components.

From the three point bending tests on the aluminium honeycomb sandwich beam specimen varying the honeycomb core cell thickness, it was observed that with an increase in the thickness of honeycomb core cell, the start of plastic deformation could be delayed, resulting in increase of ultimate strength. Also, the sandwich beam bending stiffness subsequent to plastic buckling becomes more moderate as the thickness of

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honeycomb core cell increases. This would imply that undesirable effects of instability in the structure after collapse can be reduced by using a larger thickness of core (Paik *et al.,* 1999).

5 DAMAGE CONTROL AND RISK-BASED ASSESSMENT

Fatigue assessment of welded structural components is associated with significant uncertainty in assessing fatigue life and the use of reliability theory and statistical methods. Uncertainties arise from both the loading and the resistance assessments. Fatigue uncertainties depend on the intended service life, nature of in-service inspection, availability and quality of S-N data and environmental loads data, and assessment methods employed. The objective of this section, which is discussed for the first time by this committee, is to review the recent developments in fatigue damage control and risk based assessment of marine structures. The effects of workmanship, inspection and quality and weld improvement with respect to fatigue strength are considered. The present status of uncertainties, reliability and risk related to fatigue damage are also reviewed.

5.1 Effect of Workmanship, Internal Defects, Welding Procedure, etc.

Welded joints are potential sites for initiation of a fatigue crack. A poor workmanship that can reduce the performance of a detail is weld spatter, unauthorised accidental arc strikes, attachments, corrosion pitting, weld flaws, poor fit-up, eccentricity and misalignment. The results of experimental and numerical studies aimed at defining the effects of weld penetration, root gap and misalignment on the fatigue resistance of cruciform structural details fabricated from steel have been presented by Polezhayeva and Dickin (2010). The investigation includes a literature survey on the subject from which relevant experimental data is incorporated to support recommendations. Based on the results obtained, recommendations were made for weld parameters and fit-up to achieve optimal fatigue performance, especially with regard to defining crack initiation location. The ratio of lack of penetration (LOP) to effective throat has been proposed as a means of determining crack initiation location. The effective throat is the fused weld throat measured from the end of the LOP perpendicular to the assumed straight weld surface. It has been concluded that for two-sided welded load-carrying T and cruciform joints, no failure occurs from the weld root for LOP/effective throat less than or equal to 0.5. For one-sided welded load-carrying joints, failure from the weld root can still occur at LOP/effective throat less than 0.5.

Chakarov *et al.* (2007) evaluated structural deterioration due to corrosion and the correlation between the status of degradation and stress concentration factor have been established. A probabilistic study of the effect of uncertain weld shape on the structural hot-spot stress distribution around the weld toe using a Monte-Carlo simulation and the finite element analysis has been presented by Gaspar *et al.* (2011). A structural detail consisting of a plate strip with a transversal butt welded joint and a tapered thickness step is used as case study. The results demonstrated that the SCF increases considerably if weld shape imperfections are considered. Normally both fatigue and corrosion will be present and their combined effect needs to be considered in that the decreased net section due to corrosion will increase the stress levels, which in turn increase the rate of crack growth (Garbatov *et al.,* 2002). The welding of ship structures is regarded as a process that requires a high level of control to develop finished product consistency. By its nature, welds may still contain low levels of defects. To reduce defect levels and improve the consistency of the welded products several factors have been identified by McPherson (2010) contributing to inferior performance.

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Some of these have been termed "management issues", i.e., technology and aspects that are well established and need to be part of the overall managed process. In addition, the differentiation between thick and thin plate has been made, highlighting their significantly different requirements.

To alleviate the stringent workmanship requirement on the conventional complete joint penetration (CJP) welds for tubular offshore structures. Qian *et al.* (2009) propose a new set of enhanced partial joint penetration (PJP+) welding details, which utilize a part of the brace wall as the inherent backing plate for the welding procedure. The PJP+ welds have similar SCF values as the CJP welds. The experimental results reported by Marshall *et al.* (2010) on a series of large-scale circular hollow section X-joints confirmed the satisfactory performance of the PJP+ welds, which demonstrate a fatigue life exceeding 10 times that estimated using the S-N curve in API RP 2A developed for tubular joints fabricated using the complete joint penetration welds.

Design should be performed such that fatigue cracking from the root is less likely than from the toe region. The reason for this is that a fatigue crack at the toe can be found by in-service inspection while a fatigue crack starting at the root cannot be discovered before the crack has grown through the weld. Fricke (2011) summarizes several approaches like the nominal stress approach, the structural stress approach, effective notch stress and the notch stress intensity approaches and stress propagation for fatigue assessment of weld roots. The different approaches have been applied to six examples, where minimum two approaches for each case have been evaluated (cruciform joints, fillet weld around attachment end, one-sided fillet weld around RHS joint, lap joint and cover plates, fillet-welded pipe penetration and laser-stake welded T-joint). The different cases were partly tested so that the results could be compared with experiments.

The possibility to specify the quality levels according to the requirements of fatigue design is of a high economic relevance. Hobbacher and Kassner (2010) describe the actual state of the art in terms of consistency of quality groups in ISO 5817 with fatigue properties. This direct relation gives the possibility to specify a weld quality for required fatigue strength and vice versa. They propose to revise the quality groups in the direction that for normal butt welds a quality group of B and for fillet welds a quality group of D might be sufficient. A correlation of the fatigue properties with the quality groups of ISO 5817 have been established at the example of 10 mm wall thickness and are conservative at higher wall thicknesses and throats too is proposed.

More details about the effect of workmanship, internal defects, welding procedure, etc. can be found out in the report of ISSC V.3 committee.

5.2 Inspections and Quality

The requirement of fatigue strength for design has to account for weld quality, which can be achieved at economically justifiable cost and by inspection of the structure. In addition to visual inspection, two methods of non-destructive testing are commonly used to detect the size of defect: radiography and ultrasonic. The acceptance criteria imply a corresponding limit on defect size and because of that there is a need to measure the size of detected defects. Knowing how likely a flaw will be found during an inspection is important for many reasons: as feedback to design, to provide guidance in setting inspection schedules, and as a common ground upon which to compare different inspection technologies. Inspection systems are inevitably driven to their extreme capability for finding small flaws. When applied to this extreme, not all flaws of the same size will be detected. In fact, repeat inspections of the same flaw will

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not necessary produce consistent hit or miss indications, and different size may have different detection probabilities. Because of this uncertainty in the inspection process, capability is characterized in terms of the probability of detection as a function of flaw size.

Berens and Hovey (1983) discussed the statistical nature of the NDE process and the different ways used for the estimate of POD, which could be from Hit/Miss data or from signal response data. He discussed also, the design of NDE reliability experiments and analysis illustrating the different factors affecting it and sample size requirements for the different POD estimation methods. Demsetz *et al.* (1996) investigated the different means of developing POD curves for marine structures, including the different factors affecting it. They gathered information regarding inspection practice and inspection performance in marine and in other industries. Then, they identified and developed methods for evaluating inspection performance. They estimated the POD curves for common inspection procedures and details, the costs of inspection for various inspection types and structures, and made quantitative estimates of the probability of detection of corrosion damage and the accuracy of measurement of such damage. The continuous degradation of a material due to both fatigue and corrosion has been studied by among others Brennan *et al.* (2008) who described the use of inspection reliability information in fitness-for-service and criticality assessments for ship and offshore structures. They adopt a concept of Probability of Detection (POD) and Probability of Sizing (POS) information with associated confidence measures into damage modelling. With this approach, operators can appreciate the benefit of conducting inspections and the resulting implications for quantitative risk assessments particularly where no defects are found. Their work also addresses the emerging trend towards monitoring with inspection and how operators and designers can benefit from future trends in structural health monitoring; see also Garbatov and Guedes Soares (2009a), Garbatov and Guedes Soares (2009b) and Ivanov (2009).

5.3 Fatigue Improvements

Upgrading the fatigue performance of a welded structure can be achieved by good detail design and by improvement methods, and a lot of research is carried out in this field and summed up in IIW Recommendations on Post Weld Fatigue Life Improvement of Steel and Aluminium Structures, which was revised 2010, Haagensen and Maddox (2010). The improvement methods can be classified as weld geometry modification methods and residual stress methods. The two methods used in industrial applications are weld toe grinding, such as a disk grinder or a rotary burr tool; tungsten inert gas (TIG) re-melting of the weld toe region; weld profile control, i.e. performing the welding such that the overall weld shape gives a low stress concentration and the weld metal blends smoothly with the plate; special electrodes with good wetting characteristics to give a favourable weld toe geometry; hammer peening, needle peening, shot peening and UIT of the weld toe region.

Tai and Miki (2011) studied the improvement effects of fatigue strength by hammer peening treatment on out-of-plane gusset plate specimens. They found that the improvement effect by hammer peening treatment under constant amplitude loading was quite high, especially in lower stress areas; however this effect was not seen for variable amplitude loading. One of the recent improvement methods and probably the most effective one is high frequency hammer peening. Le Quilliec *et al.* (2011) showed experimental results relating to high frequency hammer peening and concluded that developing a consistent and robust approach with the aim of defining the optimum

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operating conditions of the process is important. Maddox (2010b) compared three peening methods on virtually identical fillet welded specimens and concluded that the obtained improvement in fatigue strength were identical for 4-pass hammer peening, 4-pass needle peening and shot peening using condition E (0.8 mm diameter steel shot producing an Almen intensity of 0.024 to 0.028 A2). Mori *et al.* (2011) investigated the effect of UIT (Ultrasonic Impact Treatment) which is a weld toe improvement method by introducing compressive residual by impact on weld toe with hard pins vibrated by ultrasonic energy. From their study they concluded that significant increase in fatigue strength can be obtained by this method for low stress ratio, however the effect cannot be obtained in high stress ratio since the effect is mainly derived from compressive residual stress and not due to the modification of weld toe shape. The same technique was also investigated by Okawa *et al.* (2011) and they concluded that the fatigue strength of UIT treated welded joint was slightly decreased after application of preload, however, the benefit of UIT is significantly greater than that of grinding. Martinez (2010) investigated the fatigue test results for ultrasonic peening treated welds, and found a factor 4 in fatigue life extension compared to as-welded joints.

A probabilistic approach of high-cycle fatigue behaviour prediction of welded joints is presented by Sghaier *et al.* (2010). The approach takes into account the surface modifications induced by welding and the post-welding shot peening treatment. The Crossland criterion is used and adopted to the case of welded and shot peened welded parts and the reliability computation results are presented as iso-probabilistic Crossland diagrams for different welding and shot peening surface conditions. The approach is applied for validation of a butt-welded joint made of S550MC high strength steel. A comparison between the computed reliabilities and the experimental investigations show good agreement.

The weld profile improvement method is included in the AWS/API design rules in terms of the X curve that may be used generally if profile control is carried out. In the HSE UK S-N the curves for all types of joints can be moved by a factor of 1.3 on strength (2.2 on life) if grinding is carried out. With reference to the requirements about the fatigue design stipulated in the IACS CSR and based on the experience in plan approval and operation, fatigue design codes for the places in which fatigue often takes place are discussed by Zhan and Chen (2010). TIG (tungsten inert gas) dressing as a post-weld improvement techniques are advised to be supplemented into CSR because the weld toe is re-melted in order to remove the weld toe undercut or other irregularities and to reduce the stress concentration of the weld transition.

5.4 Uncertainty in Fatigue Assessment Diagrams and Fatigue Life Assessments

The SLA (Safety Level Approach) based GBS (Goal-Based new ship construction Standard) in IMO is seen as a representative instance for assessing the safety level. Developing risk-based method based on the SRA (Structural Reliability Analysis) for ship structural safety assessment has been a purpose of the study presented by Choung *et al.* (2010). Special focus was given on the development of several limit state functions and related uncertainties. The fatigue safety level, which corresponds to the reliability index or probability of failure, was calculated for each limit state functions as a result, the feasibility of applying risk-based approach to the design and safety assessment of ship structure was examined and demonstrated. The final crack size to be employed as the upper limit for the fracture mechanics analysis is

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taken as either equal to the plate thickness or to the crack size, which would cause an unacceptable risk of failure. The failure modes usually considered are fracture or plastic collapse. The stress intensity factor is used as the parameter controlling stress, strain, and energy fields in the neighbourhood of a crack tip. For materials, which fail by fracture under linear elastic conditions, the failure occurs at a critical value of the stress intensity factor. The stress intensity factor loses its validity as a linear elastic parameter in plastic region contained by surrounding elastic material. To analyse such situations properly it is necessary to carry out elastic-plastic stress analyses of cracked detail and to use alternative parameters to measure the severity of crack tip conditions such as the crack opening displacement and the J contour integral.

The methodology utilizes a failure assessment diagram (FAD) to determine if a failure has taken place, which assumes that failure will occur through either of two mechanisms: brittle fracture or plastic collapse. The main concept of the FAD is to provide a boundary curve that represents the locus of predicted failure points. Calculated points lying inside the boundary curve are assumed to be safe. Any cracks lying outside the boundary curve are considered to be unsafe. One of the most commonly used FADs is given by BS7910 (2005), for the assessment of flaws in metallic structures.

5.5 Suitability and Uncertainty of Physical Models - Reliability and Risk Assessment

In current practice, designs are chosen to satisfy specific safety and durability life and strength requirements by analyses of damage growth and residual strength. Decisions on materials, structural configurations, allowable stresses, etc. are based on the results of these analyses.

Analyses of crack growth damage, while deterministic, rely on input data such as initial flaw sizes, material and usage variability, etc. which are available in a statistical format. In addition to predicting mean values of damage accumulation, the methods can be used to predict the distribution of damage with time. The results of the probabilistic analyses are extremely sensitive to the initial distributions of the variables and the functions used to approximate them. Among the major variables to be considered are: material strength, crack growth rate, critical crack size, operational loads, crack detection capability, inspection techniques, frequency of inspection etc.

A probabilistic study of the effect of the weld shape imperfections on the structural hot-spot stress distribution along the weld toe using the Monte-Carlo simulation and finite element analysis method has been presented by Gaspar *et al.* (2009). To analyse the uncertainties of fatigue damage of welded structural joints a different approach has been employed by Garbatov and Guedes Soares (2010).

There are many published reliability methods in the literature. In fact, the sparsity of data associated with the major variables and the extreme sensitivity of the results to the distribution functions has limited the effectiveness and the confidence in the results. Furthermore, the design of a specified reliability level requires that the acceptable failure rate is established in advance, and that relationships should be established between reliability and normal design decision factors. For the concept of durability, probabilistic techniques may have the most direct impact, since the ultimate decision on the economic life is connected to the global population of cracks.

This problem is one of the major threats to the structural integrity of deteriorating ship structures; Garbatov and Guedes Soares (1998), Guedes Soares and Garbatov (1998) and Akpan *et al.* (2002). Due to randomness and epistemic uncertainties associated

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Table 1: Stochastic model

Variable	Distribution	Mean Value	Standard Deviation
Δ	Log-Normal	1.0	0.3
$\tilde{a}$	Log-Normal	5.754E+12	1.726E+12
B_L	Normal	0.85	0.255
B_s	Normal	1.0	0.12
B_H	Normal	1.0	0.20
B_Q	Normal	1.0	0.20
m	Deterministic	3	-
λ	Deterministic	0.900	-
μ	Deterministic	0.450	-

with the action of sea water waves and the sea environment as well as operation, fabrication, and modelling of ship structures, a probabilistic approach has to be applied to assess and predict their fatigue performance. The First Order and Second Order Reliability method (FORM/SORM) provide a way of evaluating the reliability efficiently with reasonably good accuracy, which is adequate for practical applications. Fatigue assessment of a tanker ship hull converted to a FPSO structure has been used here to demonstrate the use of FORM/SORM technique based on the S-N fatigue damage approach.

Garbatov *et al.* (2004) studied an upgrade of a FPSO planned for a 25 year service life after being converted from an oil tanker that operated 20 years in the North Atlantic. Full spectral fatigue damage for the FPSO was performed by the use of a hot-spot stress analysis, see Table 1 for the input parameters used in the evaluation. The formula used can be found in (Garbatov *et al.* 2004) and they are similar to equations 7.6 and 7.7 applied for the case study.

Table 2 presents the results of the fatigue reliability assessment of two details (HS1, HS2) of the oil tanker operating without restrictions during 20 years. The table also shows the reliability results assuming that the ship operates more 25 years in the North Atlantic as an oil tanker in addition to her normal service life of 20 years. The importance of the contribution of each variable to the uncertainty of the limit state function $g(x)$ can be assessed by the sensitivity factors which are determined by, see Garbatov *et al.* (2004) for details:

$$\alpha_i = -\frac{1}{\sqrt{\sum\limits_{i=1}^{\infty}\left(\frac{\partial g(\underline{x})}{\partial x_i}\right)^2}}\frac{\partial g(\underline{x})}{\partial x_i} \tag{4}$$

5.6 Ageing and Aged Ships and Offshore Structures

Many operating ships and offshore installations have now been in service for more than 25 years. Numerous of these structures are approaching or have exceeded their original design lives (50 % of the fixed platforms in the UK section have exceeded their

Table 2: Reliability indices of the oil tanker in the North Atlantic

	Tanker (20y)		Tanker (20+25y)+	
	HS 1	HS 2	HS 1	HS 2
P_f	2.17E-2	1.11E-1	9.67E-2	2.90E-1
β	2.019	1.219	1.300	0.552

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original design life, Stacey, 2011). Both the Petroleum Safety Authority (PSA) in Norway and the HSE offshore division in the UK have worked intensively on defining requirements for safe operation of offshore structures extending their original design lives. As input for the development in the UK, a survey of industry practices used in other sectors were conducted and reported by Sharp *et al.* (2011) including experience from operation of air crafts, nuclear and process plants, bridges and ships. It was concluded that the industries are dealing with the ageing in a way that commensurate with the resulting hazards and risks and that the offshore industry could benefit from the development of similar consistent and integrated approaches that are present in some of the other industries. Yamamoto *et al.* (2007) propose a fatigue management system using a sensor called the "hull ageing management system" and propose it as a pro-active safety management system for LNG carrier hull structural ageing and introduce a method to improve the accuracy of accumulated fatigue damage detection by using this sensor.

The problems related to assessing the serviceability and safety of aged steel ships including the assessment of the structural condition methods for repair, quantification of strength of deteriorated and repaired ships accounting for the uncertainties involved and cost-benefit and risk-based decision procedures for remedial actions have been the main objective in three consecutive reports: Bruce *et al.* (2003), Paik *et al.* (2006) and Wang *et al.* (2009).

In the North Sea, the number of fixed platforms exceeding their original design life is steady increasing with time. A structural reliability assessment tool was therefore developed by Gupta *et al.* (2011) with propose of identifying the most critical structures among the ageing platforms in the UK sector. Basic parameters such as age, building quality and possible erosion of air gap were included in the model. A detailed overview of issues related to ageing and management of Lifetime Extension (LE) of offshore facilities and an outline of corresponding overall risk assessment is presented in Hokstand *et al.* (2010). The report considers three aspects of ageing; (1) material degradation, (2) obsolescence, i.e. operations or technology being "out of date" and (3) organisational issues. The proposed LE process consists of six main activities for the assessment of the overall risk pictures. In the UK, the KP4 programme, "Ageing and life extension inspection programme for offshore installations" has been embarked by the HSE, which intend to move duty holders towards more proactive means in the management of ageing and life extension of offshore structures. An outline of the KP4 Asset Integrity Management system is presented in Stacey (2011). The principal elements of the management system are outlined being; (1) Policy, (2) Organisation, (3) Planning and Implementation, (4) Measurement of Performance and (5) Audit and Review and key issues for ageing installations are discussed.

Material degradation has a significant impact on the ageing of the structures and the evaluation of their safety. During an evaluation of possible life extension there are several key questions which have to be considered related to the material including original design, operation, as-is conditions and future conditions. It is therefore important that material and corrosion engineers get involved in the life extension. Hörnlund *et al.* (2011) emphasise that considerations shall be given to both known but also new and unexpected degradation mechanisms. A practical example of a lifetime extension of an offshore structure is presented by Haagensen *et al.* (2011), who described some of the challenges involved in the life extension of the floating production unit – Veslefrikk B. For this platform, the LE comprised repair of already existing cracks, inserted of cast details where the structure is especially fatigue prone and weld

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improvement of existing weld seams. A probabilistic fracture mechanics model was used to estimate future fatigue crack occurrence in critical braces.

- More testing of existing facilities that are decommissioned in order to learn from actual material degradation
- Development of material related key performance indicators
- International development of best practice for lifetime extension of platforms

6 DESIGN METHODS FOR SHIP AND OFFSHORE STRUCTURES

This chapter gives a review on design methods and codes which are applicable to the design of marine and offshore structures. The last ISSC Fatigue and Fracture Committee has given a comprehensive review on the topics in the ISSC Conference in 2009 (ISSC, 2009). Therefore, this report is focusing on the recent developments.

6.1 Design Codes

6.1.1 Common Structural Rules (CSR) for Oil Tankers and Bulk Carriers (2009, 2010, 2011)

The CSR are the result of the combined knowledge, experience and latest technical expertise of the world's leading classification societies. The CSR for Oil Tankers and Bulk Carriers can be applied to either double hull oil tankers or bulk carriers classed with the Society and contracted for construction on or after 1st of April 2006. The common structural rules (CSR) for oil tankers (OT) and bulk carriers (BC) began at different points in time and initially followed individual paths of developments. Some concepts from both the rules are discussed below with their similarities and differences:

- *Application*: The CSR applies to double hull oil tankers of 150 m in length and above, and to single and double-side-skin bulk carriers of 90 m in length or above. Both the CSR for OT and BC depend on the geometric characteristics of the ship such as 'L/B' ratio, 'B/D' ratio and block coefficient 'C_b' etc. The locations to be assessed for OT and BC are longitudinal stiffener end connections and primary structural joints (e.g. hopper knuckles and horizontal stringer ends for OT and hopper knuckles and hatch corners for BC) in the cargo hold region. Under the common structural rules, the basic design condition is 25 year design life in North Atlantic wave environment.
- *Design loads for fatigue requirements (Load Approach)*: CSR-OT uses envelope load method, in which the load assessment is based on the expected load history. The expected load history for the design life is characterized by the 10^{-4} probability level of the dynamic load value; the load history for each structural member is represented by Weibull probability distributions. For CSR-BC, the equivalent design wave (EDW) method is used to set the design loads.
- *Notch Stress approach*: The CSR-BC rules requires the notch stress to be obtained by multiplying the hot spot stress with a notch stress factor which is dependent on the weld type (i.e. butt or fillet weld) and weld treatment. It is assumed deep penetration welding falls under the category of fillet weld. The notch stress approach is not used in the CSR-OT rules.
- *Hot Spot Stress Definition*: The stress read out position for BC is defined at the structural intersection at the mid plane of the transverse attachment and at the edge of the longitudinal attachment, requiring an extrapolation of the element stresses closest to the vicinity of the hotspot. The OT rules procedure on the other hand define the stress read out point at the weld toe, requiring an interpolation (or extrapolation) of the element stress closest to the vicinity

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of the hotspot depending on weld leg length. The BC rules define the hotspot stress as the principal stress within 45° of the normal to the crack, while the OT rules define this as the stress normal to the weld.

- *Stress determination for stiffener connections*: The BC rules permit three methods for the fatigue stress assessment of stiffener connections, namely, direct method, superimposition method and simplified method. The OT rules generally expect only the "simplified" method to be applied, but does provide the option for "direct" method where the configuration of the end connections are substantially different from those shown in the rules.
- *Stress due to hull girder moments*: The main difference is that the BC rules obtains the hull girder hot spot stress by multiplying the nominal stress with a stress concentration factor for hull girder loads, while the OT rules operate with the nominal stress only. The OT rules also stipulates the hull girder stress to be obtained from an inertia based on 0.25 corrosion deduction, while BC rules applies one based on 0.5 corrosion deduction.
- *Stress due to local load*: The main difference is that the BC Rules apply a stress concentration factor (SCF) to the nominal stress to obtain the hotspot stress while the OT rules operate on the nominal stress directly. It is also noticed that the BC rules permit the stress concentration factors to be determined from FE analysis in lieu of the prescribed values in the rules. The OT rules accept this only where the attachment configuration is not covered in the rules.
- *Stress Combination approach*: The BC rules adopt an equivalent design wave approach where the load components are applied to the Finite Element model concurrently to represent head seas, following seas and beam seas conditions; and the hot spot stress are obtained directly for each of these design wave condition. The BC Rules term this the "direct method". The OT rules adopt an envelope load approach for fatigue in which case the component loads are applied individually to the FE model and the stresses from these component load cases are combined to obtain the hotspot stress. No particular terminology is given by the OT rules for this approach since this is the only approach permitted for determining hot spot stress.
- *Simplified hot spot stress method for hopper knuckle*: The BC rules provide an approach where the hot spot stress in way of the hopper knuckle can be determined using nominal stresses from a coarse mesh finite element model and stress concentration factors in lieu of fine mesh finite element models. The OT rules do not contain such provisions.
- *Long-term distribution of stress range*: A two-parameter Weibull function is used for long term stress distribution in both CSR rules. But, the presentation is different: the law is given in form of cumulative probability density function for CSR BC whereas CSR OT gives it in the form of a probability density function. CSR BC considers a Weibull shape parameter (ξ) which is equal to unity whereas CSR OT considers a Weibull shape parameter which depends on the ships length, on the type of member to be assessed and on the transversal position of the member.

6.1.2 Harmonized Common Structural Rules (CSR-H) for Oil Tankers and Bulk Carriers (status at 2012, scheduled for publishing in 2014)

The initially published versions of the Rules (CSR) for Oil Tankers and Bulk Carriers were developed separately and were based on different technical approaches. IACS is harmonizing the Common Structural Rule (CSR) for Oil Tankers and Bulk Carriers

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into a single set of rule book (at the moment using CSR-H to distinguish from currently applicable CSR rules). The CSR-H will consist of three parts; a common part for "general hull requirements" that will contain requirements for both ship types, and separate parts for "ship type specific" requirements applicable to Oil Tankers and Bulk Carriers respectively. Noting that the CSR were developed and adopted prior to the substantive development of the Goal Based Standard (GBS) provisions in IMO, the development of CSR-H provides an opportunity for IACS to consider and take account of the discussions and decisions taken in the development of the GBS. The development of CSR-H is also taking account of the experience gained in the application of the separate CSR, including feedback from industry partners. The goal of the CSR-H remains the same as the current CSR development, which is to establish unified rules and procedures for safer and robust ships, but now also includes the formal consideration of the IMO GBS. As the CSR-H is still under the development and the currently planned date for publishing is 1st of July 2014 (subject to change).

6.1.3 Fatigue Assessment due to Springing and Whipping

Whipping and springing caused fatigue on ships, particularly for large container ships, is becoming a concern for the industry. Major classifications including Lloyd's Register (2009) are under taking study and investigation on the issue. ABS (2010) released guidance notes on whipping and spring assessment for container carriers which include fatigue assessments. DNV (2007) gives guidance Note of CN no. 30.7 related to the assessment of the additional fatigue effect of wave induced vibrations of the hull girder.

6.1.4 Rules for Offshore Installations (Risers, Pipelines, FPSOs)

Rules for Risers

Riser systems exposed to ocean currents may experience in-line as well cross-flow Vortex Induced Vibrations (VIV). For VIV assessment the application of Computational Fluid Dynamics (CFD) has been explained in DNV-OSS-302 'Offshore Riser Systems' (2010). It suggests that the time domain fatigue damage assessment should be based on a recognised cycle counting approach, typically Rain Flow Counting (RFC).

An Offshore Standard guiding rule DNV-OS-F201 (2010) 'Dynamic Risers' includes a section on the fatigue assessment of risers which are subjected to repeated fluctuations (with ref. DNV RP-C203). The Code gives details regarding fatigue analyses procedures, narrow band and wide band fatigue damage assessment procedures and fatigue capacity S-N curves.

DNV-RP-F204 (2010) a code for 'Riser Fatigue', presents recommendations in relation to riser fatigue analyses based on fatigue tests and fracture mechanics. The standard introduces the basic fatigue damage methodology and global fatigue analysis procedures for the wave frequency and the low frequency fatigue. It also discusses requirements for combining wave frequency, low frequency and VIV fatigue damage. The Recommended Practice DNV-RP-F202 (2010) document gives criteria, requirements and guidance on structural design and analysis of riser systems made of composite materials exposed to static and dynamic loading for use in the offshore petroleum and natural gas industries.

Rules for Pipelines and piping

As we know that there are several examples of piping applications exposed to severe cyclic loadings where the need for a more comprehensive fatigue assessment is evident, for instance piping exposed to wave loads such as wellhead piping on jacket platforms

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and expansion loops on bridges. In such applications NORSOK L-002 (2009) suggests to refer the fatigue assessment method outlined in PD5500, Annex C.

DNV-RP-D101 (2008) is a code that accounts for the acoustic fatigue due to the vibrations produced by machinery such as reciprocating pumps and compressors. It suggests the simplified fatigue analysis when there is more than one additional cyclic load source of importance to the expansion and contraction or alternating bending stresses of a piping system.

For the submarine pipeline systems (DNV-OS-F101, 2010), the fatigue check shall include both low-cycle fatigue and high-cycle fatigue. A deterministic or spectral analysis approach is used as most of the loads which contribute to fatigue.

Rules for FPSOs

The ABS code (2010) gives the guidelines for 'Spectral-Based Fatigue Analysis for Floating Platform Storage and Offloading (FPSO) Installations' (for the fatigue assessment) in terms of either expected damage or life. The fatigue strength of structural details is established using the S-N curve approach that is specified in the referenced guide.

ABS Guide for Floating Production Installations (FPI, 2010) covers the fatigue design considerations for the following: Ship-type Installations, Column-Stabilised Installation, Tension leg Platform/Spar Installation, Existing Vessel converted to FPI or FPI conversion, Trading Vessel, Import and Export System and Mooring Systems.

Offshore Standard rules and regulations for the various offshore installations are as follows

The recommended practice DNV-RP-C203 (2010) 'Fatigue Design of Offshore Steel Structures' provides a general guideline for the fatigue design of offshore structures including FEM modelling guidelines and S-N curves for the application of the notch stress approach. The RP has been updated on requirements to grinding for fatigue life improvement and a section on low cycle fatigue in combination with high cycle fatigue has been added.

The standard DNV-OS-C102 (2009) 'Structural Design of Offshore Ships' over rules DNV-OS-C101 (Design of Offshore steel structures), ships constructed in steel for any defined environmental condition. For the evaluation of the fatigue limit state (FLS) the standard suggests that the effect of all significant loads contributing to the fatigue damage shall be considered. And the fatigue life shall be calculated considering the combined effects of global and local structural response.

For the FLS design of more recent offshore installations such as substructures for wind turbines and corresponding substations, DNV have compiled the codes DNV-OS-J101 (2010) and DNV-OS-J201 (2009).

The ISO 19900 series tries to bridge the international society by provision of a common set of rules for the offshore design including fixed steel offshore structures ISO 19902 (2007) and topsides 19901-003 (2010).

Lloyd's Register ShipRight-FOI (2008) analysis procedure propose a procedure for calculating fatigue damage due to loading and unloading of Floating Offshore Installation and three levels fatigue assessment procedures.

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6.1.5 Arctic Design Codes

Lloyd's Register (2011) has released new procedures under the notation, ShipRight FDA ICE, for fatigue design assessment of ships navigated in ice regions. The Arctic is estimated to hold about 20 % of the world's remaining recoverable hydrocarbon reserves and greater trade through the Arctic is driving demand for larger ice-class vessels, particularly oil tankers and LNG carriers. It is reported by Zhang *et al.* (2011) that 57 % of ice-class ships have cracks or fractures at an average age of 13.0 years. It is becoming increasingly important that the industry develops a good understanding of the fatigue strength of hull structures under ice loading. The FDA ICE procedure includes the following steps: 1) determination of ice data for trading routes; 2) ice impact frequency; 3) ice load distribution; 4) determination of structural stresses under ice loads; 5) fatigue damage calculations and S-N curves, and 6) fatigue acceptance criteria.

The International Maritime Organization (IMO) has recently approved the "Polar Code", a guide for ships in polar waters operations invites countries to adhere to these rules on a voluntary basis to be in effect as of January 1st 2011 and established regulations for cruise ships that travel to Antarctica. For the design of offshore platforms in arctic regions, ISO 19906 (2010) specifies requirements and provides recommendations and guidance for the design, construction, transportation and installation. In the design of fixed structures in arctic areas special attention shall be made to the risk of dynamic ice-structure interaction known as frequency lock-in, or self-excited vibration, which can arise when a sheet of ice acts continuously on a vertical structure at a moderate ice speed. The steady-state vibrations that arise due to the lock-in phenomenon can cause low-cycle fatigue in steel structures, ISO 19906 (2010).

7 CASE STUDY

The benchmark study is intended to show uncertainties in treating fatigue assessment of welded structures when unconventional loading pattern is applied to a welded joint. The main aim of the study is to call attention of structural designers on the uncertainties associated to fatigue checking procedures in presence of stress multiaxiality even if they are referring to well consolidated standard guidelines, and to focus attention of researchers on the open question of how to treat stress multiaxiality. A present status of the design rule requirements, being differently harmonized with the most up-to-date scientific criteria, have been discussed. Unlike the benchmark studies presented in the past ISSC reports (ISSC, 2000 and ISSC, 2003), where the procedures of classification societies were compared to investigate uncertainties in the different modelling approaches for stress/strain calculation and/or for damage calculation, it is the aim of the present study to outline an unclear standard frame where contradictions in proposed methodologies appear.

The starting point of the study has been the identification of a well stated structural problem, which is briefly described below, in order to facilitate replication of analyses. The benchmark study has been carried out on a simple structural geometry with smooth discontinuities, where full penetration fillet weld has a standard section shape and cyclic loadings are clearly relatesd to hull girder bending. To reduce the source of scatter in determination of the fatigue life, a comparison of the different approaches has been made by applying the outcome of calculations carried out on a shared FE model in combination with a common load history. The common stress-strain field has been calculated based on the ideal scheme of no imperfections related to gaps and misalignments and by neglecting corrosion effects. Since the procedures

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applied are the ones given by standard practice, fatigue checking implemented in the comparative study is a linear approach. Hence, a linear elastic FE analysis for mapping the stress-strain field has been used. This comparative study makes reference mainly to guidelines proposed by the Classification Societies, but considers also alternative procedures proposed by the recent applied research.

7.1 Selection and Description of the Case Study

The evolution in cruise ship which has occurred in the last few years has led to ships which are more comfortable and have grown in size and offer cabins with balcony extending all over the ship's sides. The resulting increase in the number of decks, the extensive use of high tensile steel to reduce weight and obtain benefits in terms of stability, and the broader openings giving access to balcony from cabins, result in a weaker global structure of the ship. Furthermore, prefabricated sections do not necessarily contribute to the local structural needs, as in case of the intersection between passing-through decks and side shell (also called outer longitudinal bulkhead). That intersection is certainly a critical area on the structure of any large modern cruise ship. It is the selected structural detail for the case study. Of course, the opening edges are of highest importance for the fatigue strength. However, their evaluation is very well covered by the rules. The focus of this benchmark is set to multiaxial fatigue of weld seams.

7.1.1 Description of the Case study: Basic Data

The cruise ship selected for the study is a large ship of about 90,000 GT and a length of about 300 m, recently built in one of the major European shipyards. Such a modern cruise ship has been designed for worldwide service luxury cruises, ref. Figure 22. For the selected welded connection, the local stresses are emphasized by vertical hull girder deformation and by the large openings on the longitudinal bulkhead, which act as stress raisers. Stress pattern in front of the weld line on deck suggests the hot spot to be subject to a weakly biaxial stress field where highest tension stresses are parallel to the weld line. On the other hand, stress field in front of the weld line on longitudinal bulkhead is more general, as stress flow lines are controlled by shape of openings corners.

The welded joint considered for the fatigue analysis is a cruciform joint where the passing element is the deck plate, on which the longitudinal bulkhead plate is joined

Figure 22: Superstructure of a modern cruise ship during the building.

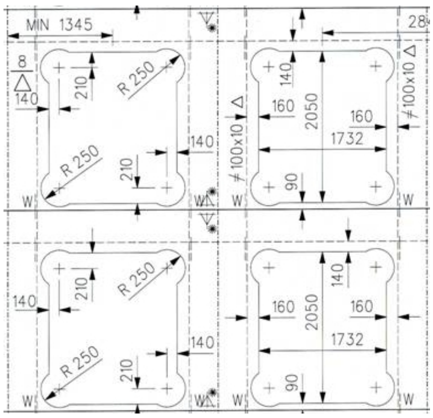

Figure 23: Particular of the drawing of the longitudinal bulkhead

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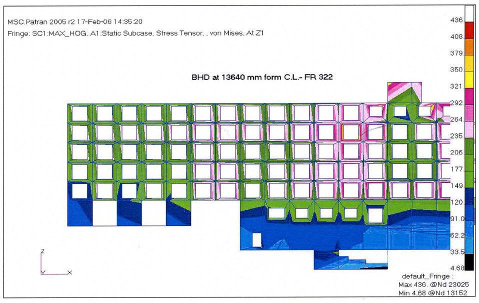

Figure 24: Particular of the coarse mesh FE model of the forward part of the outer longitudinal bulkhead.

Figure 25: Particular of the coarse mesh model and displacements collected for application to the boundaries of the intermediate model.

by a continuous manual longitudinal fully penetrated K-butt weld (45° single-V preparation). Thickness of deck plating at the intersection is $7\,mm$, reduced to $5.5\,mm$ at $110\,mm$ far from the weld line toward the balcony area, while the longitudinal bulkhead has a uniform thickness of $12\,mm$. The geometry of the openings on the outer longitudinal bulkhead is shown in Figure 23. The opening at the lower edge is close to the deck, especially at the lower corners with circular enlargement to reduce local stress concentrations. The whole structure is made by high tensile stress (minimum yield stress of $355\,MPa$).

Two hot spot locations have been identified as the most critical, both located at the continuous longitudinal weld between deck and longitudinal bulkhead, at the weld toes on deck and wall. Here, the longitudinal stresses due to vertical bending of the hull are transferred by the thick plates of the longitudinal bulkhead, through the longitudinal fillet weld, to the thin plates of the deck, causing the bending of the deck with a slight shear lag effect. So, stress concentration is expected at the weld on wall side and high stress levels are also possible on deck side.

Data on loading acting on the structure were made available by designers from a FE analysis. Due to the coarse mesh implemented in that model, where just four elements were used to model the outer longitudinal bulkhead around each opening, results are not accurate enough to identify the most critical area on the bulkhead. So, a refined model has been created to study the hot spot area.

The displacements applied to this intermediate model have been collected from the corresponding frame of the coarse mesh model, Figure 25 in the area were the highest stresses were detected for the two extreme cases of hogging and sagging of the ship's hull. Only translational deflections have been considered. Such load cases are based on the IACS vertical wave bending moment formulations. Hence all calculated stresses are related to the same probability of exceedance. All FEM calculations have been performed by using Patran/Nastran software.

7.1.2 Description of the Case Study: Local Stress Calculation

The intermediate sub-model has been obtained by cutting off the longitudinal bulkhead for an extension in height and length equal to four openings (each opening module is $2840\,mm$ long and $2720\,mm$ height), and with a transverse extension of deck equal

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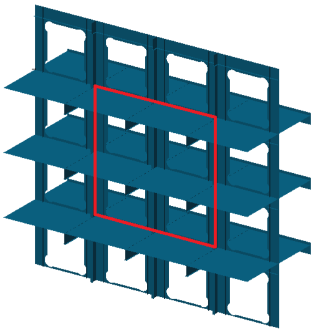

Figure 26: Intermediate FE sub-model.

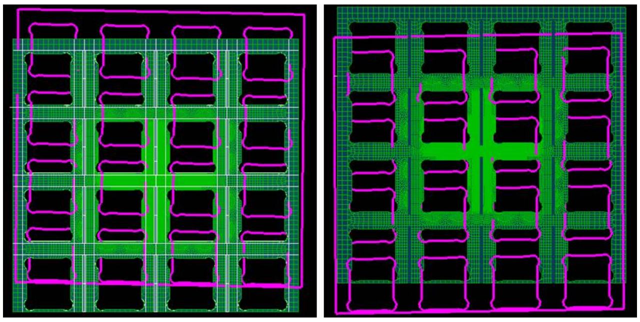

Figure 27: Deformations due to sagging and hogging on the intermediate model.

to about 2200 mm both inside and outside the longitudinal bulkhead, as shown in Figure 26. The mesh size has been set to accurately describe structural geometry, such as opening corners. The average dimension of elements is of about 100 mm. 8-node quadrilateral shell elements have been used, arranged in the mid-plane of the structural components. Displacements relevant to both the maximum hogging and sagging conditions at the boundary of the sub-model have been provided by the global hull model and have been applied to each intersection between the longitudinal bulkhead, frame and deck on the model boundary. The global stresses and displacements have emerged from the analysis of the intermediate sub-model and hogging and sagging effects are clearly visible from the deformations of the sub-model structure, ref. Figure 27, where primary stress flows are locally amplified at each opening. Stresses are higher at the lower edges of the openings both on deck and wall side.

The sub-sub model (local structure model) is like a double cross obtained from cutting off the longitudinal bulkhead at the intersection between the deck beam and the side shell frame, see Figure 28, for an extension in height and length equal to about a half of the opening height and length respectively, and with a reduced transverse extension of the deck both inside and outside the longitudinal bulkhead. The model includes the main supports of the longitudinal bulkhead and deck. The mesh size on each different part of the structure has been set to suit the relevant plate thickness and, at the hot spot, 8-node quadrilateral shell elements have been used, about $t \times t$ size; The full penetration weld seam itself required no extra effort in geometric model building. Boundary displacements relevant to sagging and hogging condition of the ship have been applied on all the nodes along the cut-off line of the model. Displacements have been adapted to the finer mesh by linear interpolation among given values.

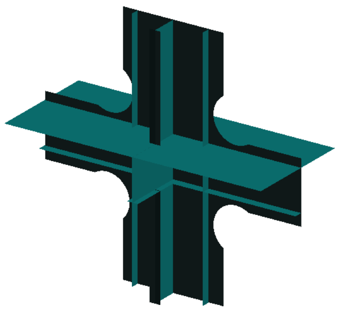

Figure 28: Local structure sub-model (view from inside the ship).

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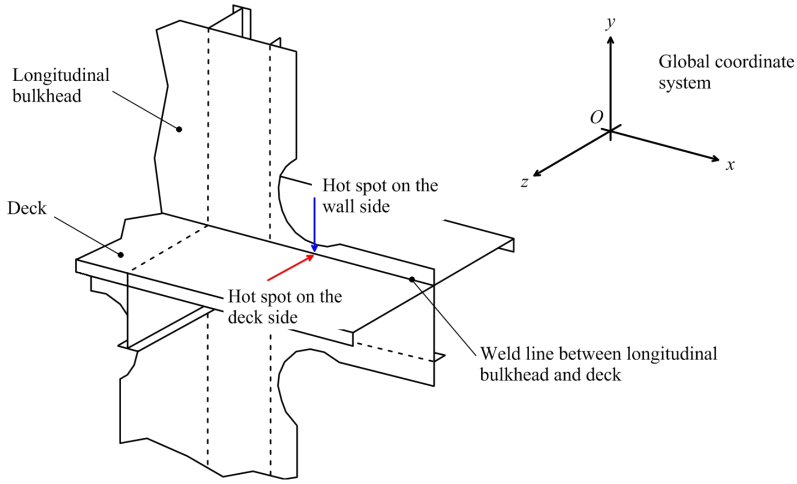

Figure 29: Particular of the structure near the hot spot area (view from outside the ship).

By solving the local structure model for the two loading cases, the stress ranges have been calculated at the weld joint between deck and longitudinal bulkhead: the outer weld toe line on deck and the upper weld toe line on bulkhead, They have been identified as the most critical areas.

A nodal line perpendicular to the weld line has been selected where stress intensities are the largest both on deck and wall (basing on general assumption regarding the hot spot extrapolation, hot spot stresses have been evaluated in different points near the selected critical point). Figure 29 shows a of part of the modelled structure, along with the location of the two hot spots and corresponding nodal lines. The nodal lines where stresses have been read out are located about 280 mm and 210 mm far from the vertical stiffener adjacent to the longitudinal bulkhead opening, for deck and bulkhead hot spot respectively. Hot spots are both located at the round corner of the opening, where the distance of the opening edge from the weld seam is of about 50 mm and 60 mm, for deck and bulkhead hot spot respectively. On both intermediate and local structure models, boundary effect on read out areas have been checked and congruence between the models has also been verified.

Both nodal stresses and element stresses have been collected at the selected nodal lines, to be used for hot spot extrapolation according to the analysis method. The stresses given in the following are referred to the global coordinate system, where x-axis is longitudinal from stern to bow and parallel to the weld toe line of the selected weld, y-axis is vertical from bottom to upper deck and z-axis is oriented outside ship. Outputs are given for the two layers of the elements: layer 1 lies on the upper surface of deck plate and on the outer surface of longitudinal bulkhead plate. Stresses are reported on the nodes and elements sorted by distance d_{HS} in mm from model hot spot (i.e. the idealized weld toe line). Element stresses have been averaged on values relevant to elements aligned on both sides of the nodal lines. The element type is Patran/Nastran SHELL8, featuring membrane plus bending capability. The stresses for the two ship's extreme design loading conditions (vertical hogging and sagging of the hull girder) are given in MPa in Table 3 and Table 4 for the two hot spot locations in components and as Von Mises stresses (σ_{VM}), both referred to the global coordinate system.

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Table 3: Stresses calculated at the weld toe line on longitudinal bulkhead plate.

load case	stress type	layer	d_{HS}	σ_{VM}	$\sigma_x = \sigma_{\|\|}$	$\sigma_y = \sigma_{\perp}$	$\tau_{xy} = \tau_{\|\|}$
hogging	nodal	1	2.56	101.26	87.87	38.91	-38.45
			5.13	103.45	90.55	38.69	-38.76
			7.69	105.85	93.40	38.35	-39.12
			10.25	108.33	96.16	38.12	-39.57
		2	2.56	102.21	88.41	40.66	-39.03
			5.13	104.43	91.07	40.38	-39.40
			7.69	106.84	93.90	40.00	-39.80
			10.25	109.33	96.65	39.72	-40.29
	element	1	2.56	101.19	88.01	38.72	-38.30
			7.69	105.80	93.56	38.14	-38.95
			12.82	110.95	99.41	37.43	-39.77
			17.95	116.68	105.61	36.55	-40.75
		2	2.56	102.14	88.56	40.46	-38.88
			7.69	106.78	94.07	39.78	-39.63
			12.82	111.96	99.89	38.98	-40.54
			17.95	117.71	106.06	38.00	-41.60
sagging	nodal	1	2.56	67.88	-58.59	-26.45	25.98
			5.13	69.27	-60.30	-26.26	26.17
			7.69	70.78	-62.14	-25.99	26.38
			10.25	72.34	-63.91	-25.79	26.65
		2	2.56	68.71	-58.98	-27.74	26.51
			5.13	70.11	-60.68	-27.50	26.73
			7.69	71.62	-62.51	-27.20	26.97
			10.25	73.19	-64.27	-26.97	27.27
	element	1	2.56	67.84	-58.68	-26.32	25.89
			7.69	70.74	-62.25	-25.85	26.27
			12.82	73.99	-66.00	-25.28	26.76
			17.95	77.61	-69.98	-24.61	27.34
		2	2.56	68.67	-59.08	-27.61	26.42
			7.69	71.59	-62.62	-27.06	26.86
			12.82	74.85	-66.35	-26.43	27.41
			17.95	78.48	-70.31	-25.69	28.05

7.2 Method of Investigation

7.2.1 Method Applied for Reference Stress Calculation

Within the cumulative damage procedure, the fatigue design of any structural detail is performed by making use of a reference parameter s derived by the stress-strain field measured or calculated in close vicinity of the crack site. The fatigue check is performed by comparing s with the strength value S, which is endurable at the same number of cycles N.

The local approach has been implemented based on the structural stress analysis. The "structural stress approach" ($s = \sigma_s$) takes into account only that part of the local stress concentration which is related to the structural geometry and allows to explicitly consider multiaxiality in the local stress field in front of the hot spot. In plate-type structures, the structural stress σ_s is commonly defined as the sum of a membrane and a bending stress at the hot spot, excluding the local nonlinear peak stress at the notch. The surface stress extrapolation is carried out on the stresses readout points which are located sufficiently far from the weld seam.

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Table 4: Stresses calculated at the weld toe line on deck plate.

load case	stress type	layer	d_{HS}	σ_{VM}	$\sigma_x = \sigma_{\|\|}$	$\sigma_y = \sigma_{\perp}$	$\tau_{xy} = \tau_{\|\|}$
hogging	nodal	1	3.50	79.88	74.37	-10.00	1.47
			7.01	78.41	73.19	-9.49	1.53
			10.51	77.10	72.14	-9.04	1.58
			14.02	75.79	71.08	-8.59	1.63
		2	3.50	83.74	78.23	-10.07	0.91
			7.01	82.28	77.06	-9.57	0.93
			10.51	80.98	76.00	-9.15	0.94
			14.02	79.67	74.93	-8.72	0.96
	element	1	3.50	79.84	74.33	-9.99	1.47
			7.01	77.08	72.11	-9.03	1.58
			10.51	74.59	70.10	-8.18	1.67
			14.02	72.34	68.28	-7.42	1.73
		2	3.50	83.71	78.20	-10.06	0.91
			7.01	80.95	75.97	-9.15	0.95
			10.51	78.48	73.95	-8.35	0.97
			14.02	76.25	72.11	-7.66	0.99
sagging	nodal	1	3.50	53.25	-49.68	6.48	-0.96
			7.01	52.30	-48.92	6.15	-1.00
			10.51	51.45	-48.23	5.86	-1.02
			14.02	50.59	-47.54	5.57	-1.05
		2	3.50	55.47	-51.97	6.43	-0.49
			7.01	54.52	-51.21	6.10	-0.50
			10.51	53.68	-50.52	5.82	-0.51
			14.02	52.83	-49.83	5.54	-0.52
	element	1	3.50	53.23	-49.66	6.48	-0.96
			7.01	51.43	-48.21	5.86	-1.03
			10.51	49.81	-46.90	5.31	-1.07
			14.02	48.35	-45.72	4.83	-1.11
		2	3.50	55.45	-51.95	6.42	-0.49
			7.01	53.66	-50.51	5.82	-0.51
			10.51	52.06	-49.20	5.30	-0.53
			14.02	50.61	-48.01	4.85	-0.54

7.2.2 Methods Applied for Stress Multiaxiality

When a welded joint is subject to a loading having a major component acting parallel to the weld line, fatigue cracking may no longer initiate along the weld toe, but initiates in the weld and then rotates to grow normal to the maximum principal stress direction. This means that the parallel stress has a significant role in the fatigue capacity of a structural detail and the notch at the weld toe does no longer significantly influence the fatigue capacity. Hence it becomes conservative to use the principal stress range together with an S-N curve for stress range normal to the weld toe.

Several methods have been proposed for taking into account stress multiaxiality. With reference to the load carrying penetrating fillet and butt welds, the biaxial-stress hypothesis represents the most general approach for fatigue assessments. There are mainly two ways to consider a biaxial stress state: reference principal stresses or the single components of the stress tensor, that is the tensile stress $\sigma_{\perp}$ acting normally to the weld, the weld parallel normal stress $\sigma_{||}$ (usually disregarded is such kind of approaches) and the weld parallel shear stress $\tau_{||}$. According to the case study, procedures set for proportional loading (i.e., in-phase stress components) are presented.

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The multiaxial fatigue damage for brittle materials may be calculated by referring to the principal stresses. Hence, the fatigue effective equivalent stress and the fatigue check criterion are defined as (σ_a means stress amplitude):

$$\sigma_{a,eq} = \frac{\sigma_{a\perp} + \sigma_{a\|}}{2} \pm \frac{1}{2}\sqrt{(\sigma_{a\perp} - \sigma_{a\|}) + 4\tau_{a\|}^2} \quad \text{and} \quad D \leq D_{per} \tag{5}$$

where D_{per} is the permissible damage sum. In general, according to this approach, the principal stress to be used should be approximately in line with the perpendicular to the weld toe, i.e. within a deviation β ranging from ±45° to ±60° (see Figure 3, where σ_1 and σ_2 are the principal stresses). Alternatively, the maximum principal stress is accounted for in the fatigue evaluation.

For ductile materials is often suggested to refer to the criterion of the distortion strain energy (generally referred to as the von Mises yield criterion) or to the criterion of the maximum shear stress (also known as the Tresca criterion). In both cases, the fatigue effective equivalent stress and the fatigue check criterion are expressed by:

$$\sigma_{a,eq} = \sqrt{\sigma_{a\perp}^2 + \alpha\tau_{a\|}^2} \quad \text{and} \quad D \leq D_{per} \tag{6}$$

where $\alpha = 3$ and $\alpha = 4$ for the Von Mises and the Tresca criterion respectively.

A similar relationship has also been proposed where α is set equal to 1, resulting in Eq. 7 to express the equivalent stress as the so called "resultant stress" σ_{res}, which is obtained by vector addition of the normal and shear stresses at the relevant part of the weld toe. The background is fracture mechanics studies of the growth of fatigue cracks inclined to the direction of loading, Maddox (2010). Resultant stress may be defined considering normal stresses irrespective of being parallel or perpendicular to weld toe line direction. So, when a weld is subject to a uniform uniaxial far field stress of amplitude $\sigma_{a,0}$, and θ is the angle between nominal applied stress and perpendicular to weld line, the weld may be assessed as a transverse weld if $\sigma_\perp$ is the dominant normal stress or as longitudinal weld if $\sigma_{||}$ is the dominant normal stress. So σ_{res} comes out to be respectively:

$$\begin{aligned} \sigma_{a,eq} = \sigma_{a,res} = \sqrt{\sigma_{a\perp}^2 + \tau_{a\|}^2} = \sigma_{a,0}\cos\theta \quad \text{(transverse weld)} \\ \sigma_{a,eq} = \sigma_{a,res} = \sqrt{\sigma_{a\|}^2 + \tau_{a\|}^2} = \sigma_{a,0}\sin\theta \quad \text{(longitudinal weld)} \end{aligned} \tag{7}$$

Another approach applied in the case of proportional biaxial variable-amplitude loading is based on a linear superposition of the damages caused by normal and shear stresses as acting independently. A simplified method for summing up normal and shear stress cumulative damages is to calculate them separately and adding their values powered to 2/3 please note: 2/3 is not consistent with Eq. 8. This results in the following equation (Bäckström, 2003; Hobbacher, 2009):

$$\left(\frac{\sigma_{a\perp,E}}{\sigma_{A\perp}}\right)^2 + \left(\frac{\tau_{a\|,E}}{\tau_{A\|}}\right)^2 = D_E^2 \leq D_{E,per}^2 \tag{8}$$

where the index E refers to the "equivalent stress amplitude" which is the constant amplitude stress equivalent, in terms of fatigue damage and the index A refers to the permissible stress amplitude at the same number of cycles N_L. Here also the concept of strength reduction parameter D_E is introduced, defined as the ratio between the fatigue effective equivalent stress and permissible stress amplitude acting perpendicular to the weld line. That relationship may also be applied for $\sigma_{||}$ instead $\sigma_\perp$.

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To generalize the formulation given in Eq. 8, the relative weight of shear stress effect to normal stress effect needs to be balanced. That is made by correcting the shear stress by a coefficient γ prior to enter the equation, so obtaining a formulation formally equal to that of Eq. 6. It has been proposed (Lotsberg as cited in Maddox, 2010) to deduce γ values by comparing design S-N curves for failure in shear with those for failure under normal stress. The assumption $\gamma = 1$ means equivalent stress as the resultant stress σ_{res}. Values in the range from 0.20 to 0.81 depending on the weld detail are proposed by Lotsberg and thus the effective stress reflects the assumption of less influence of the shear stress.

In all the mentioned criteria, the cumulative damage is calculated according to S-N curves defined for uniaxial loading. As for in-phase loading on steel structures, the value of the permissible damage sum D_{per} is generally limited to 1.0 or 0.5, while $D_{E,per}$ is fixed to 1.0. The fatigue effective equivalent stresses calculated according to the discussed methods are suitable for structural stress approach.

7.2.3 Method Applied for Cumulative Damage Calculation

As for the load history, all analysed approaches consider the use of a simplified statistical method for long term distribution of wave loads which may be implemented according to the Weibull probability density function $p_W(2s_a)$, where s_a is stress amplitude. When the significant value of s_a has been calculated together with its probability of exceedance $Q(2s_a)$, the load history may be approximated by the product $N_L \cdot p_W(2s_a)$, where N_L is the total number of cycles experienced by the ship during her entire lifetime. This approach assumes that the Weibull shape parameter k_W can be deduced by proper considerations on the type and location of the structural detail, and the Weibull scale parameter λ_W is derived as function of s_a, $Q(2s_a)$ and k_W.

For practical purposes, the S-N curve is generally simplified in a one-slope curve, defined by the two parameters m and $\log c$. Alternatively, also a bi-linear S-N curve with change in slope at certain knee point is used.

7.3 The Fatigue Life Prediction

Calculation carried out by the local structure model for the deck side shows a hot spot stress characterized by a weak biaxial state where ratio between $\sigma_{||}$ to $\sigma_{\perp}$ stresses is of about 13 % and ratio between $\tau_{||}$ and $\sigma_{\perp}$ is approximately 1 %. (Again, the edges are significantly higher loaded but not of interest here as their evaluation is well covered by rules.) The longitudinal normal stress $\sigma_{||}$ is by far the predominant stress at the hot spot. As for such stress component, a stress increase is hardly detectable along the nodal lines perpendicular to the weld line. On the other hand, at the wall side, the hot spot stress is characterized by a high biaxial state where the ratio between $\sigma_{||}$ to $\sigma_{\perp}$ stresses is of about 48 % and the ratio between $\tau_{||}$ and $\sigma_{\perp}$ is about 45 %. In this case, all stress components may play a significant role on fatigue damage. Procedures defined by different classification societies and by IIW have been applied in the present study and methods and outcomes are discussed in the following. All procedures refer to fatigue crack growth from the weld toe into the base material. It is also common practice in guidelines to assume a design life of 20 years and the limit value for the accumulated fatigue damage to 1.0. All procedures provide indications for a simplified calculation of the load history and give formulations to establish a proper value for the Weibull shape parameter λ. As for the case study, the calculated stress ranges is related to a probability of exceedance of 10^{-8} and the cumulative damage has been calculated by two-slope S-N curves.

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7.3.1 Procedures Disregarding Parallel Stresses

Traditional procedures implemented in classification society guidelines do not consider effects of parallel stress on fatigue life of a welded joint.

The GL rules for the hot spot concept do not account for biaxial stress states. Instead, the stress component perpendicular to the expected crack front is considered to be fatigue relevant only. For the calculation of the permissible hot-spot stress range on both location the FAT 100 S-N curve has been selected as resistance reference. The stresses close to the hot-spot (nodal stresses) have been linearly extrapolated to the hot-spot and fatigue damage calculation has been carried out within the permissible stress range approach by considering a series of corrections. On the basis of the selected S-N curve, the permissible stress has been obtained, equal to $417.60\,MPa$, while calculated reference stress is equal to $17.28\,MPa$. Fatigue damage obtained by applying GL rules is almost zero as predicted damage to limit damage ratio equals 0.04. It should be noted that the GL quotes a more refined procedure in his guidelines. However, this is not reflected by the rules.

A tentative of fatigue checking has been also performed within the Common Structural Rule approaches for oil tanker and bulk carrier. According to CSR for bulk carriers, the notch stress approach has been applied based on maximum principal stresses within 45° normal to the weld, obtained by extrapolation of element stresses to the hot spot based on values which are read out at distances of $0.5t$ and $1.5t$ away from the hot spot location. The calculated reference stress range is $17.27\,MPa$. The S-N curve selected for the analysis is the so called "B-curve". The reference stress was modified according to a series of corrections. Calculation gives a fatigue damage of almost zero.

Fatigue predictions based on CSR for oil tankers are performed within the structural stress approach where the reference stress is the normal stress perpendicular to weld toe line $\sigma_\perp$. It is defined as the element stress read out at distance of $0.5t$ away from the hot spot location. The calculated reference stress range is 15.40 MPa and the calculation gives again a fatigue damage of almost zero.

According to KR rules, some fictitious beams without stiffness (with very low sectional properties) are to be put on the connection lines of shell elements in order to determine the surface stress distributions of the shell elements. However, in this study the shell element stresses are used. That is justified by the smooth stress field in front of the hot spot. Due to adopting the concept of getting stress from the fictitious beam at locations $0.5t$ and $1.5t$, the biaxial stress state at the toe of weld bead is implicitly not taken into account by KR rule. So, only the stress component normal to the weld line is used for assessing the fatigue life at the weld toe. Damage calculation is based on the $\sigma_\perp$ normal stress as reference stress (calculated stress range of 17.19 MPa), and refers to the so called "D-curve" capability curve. Resulting fatigue damage is zero.

The procedures applied above are all implemented in different ways, but all of them make use of approximately the same value for the reference stress and all deliver similar results.

BV and RINA implemented a fatigue checking procedure based on a reference stress selected as "the principal stresses at the hot spots which form the smallest angle with the crack rising surface" and within those procedures an allowance is applied for stresses parallel to weld axis. The same approach is proposed by DNV and discussed in the following section as the DNV maximum principal stress approach.

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7.3.2 A Procedure Accounting the Parallel Stresses: The DNV Approach

DNV rules (CN-307) prescribe to calculate the cumulative damage on the basis of the maximum principal stress approach. The fatigue relevant stress is the maximum principal stress at the hot spot in a sector of $\beta = \pm 45°$ normal to the weld line, calculated by linear extrapolation of the individual stress components of the plane stress tensor. Some reductions in the fatigue damage accumulation are allowed. Within that approach, also the case of a governing stress parallel to the weld toe line is considered. As the S-N curves for welded joints include the effect of the local weld notch, if the governing stress direction is parallel with the weld direction a stress reduction factor K_P should be used on the principal stress range before entering into the S-N curve. The stress reduction factor will depend on the quality of the weld and for a manual fillet or butt weld is $K_P = 0.90$.

As for the present case, a number of parameters have been set. The S-N curve is for welded joints in protected environment (FAT 90 S-N curve). The applied stress range is 35.54 MPa for the hot spot on deck and 63.10 MPa for the hot spot on longitudinal bulkhead. A result in terms of cumulated damage is almost zero for both hot spots when considering the principal stress. The cumulative damage value again is very low, but it turns out to be plausible if it is considered that reference stress range, i.e. the stress range acting perpendicular to weld toe line, is very low.

An optional method for deriving the hot spot stress is proposed in DNV rules and is intended to replace the traditional procedure on a voluntary basis. In this procedure effective hot spot (extrapolated from FE read out points) is calculated as the maximum of both principal stress reduced by K_P and an equivalent stress obtained by a formulation similar to that given in Eq. 6 where α is set to 0.81. Alternatively, the effective hot spot stress is calculated on the basis of the stress at the read out point $0.5t$ from the weld toe line without any extrapolation. In this case, the maximum value calculated as above is increased by 12 %. In both cases, the resulting effective stress is made to account for one of the two possible fatigue pattern shown in Figure 30.

Calculations within the enhanced DNV approach have been carried out under the same hypotheses made for the traditional approach and using a stress range of 237.72 MPa for hot spot on deck and 324.16 MPa for hot spot on longitudinal bulkhead. The cumulative damage calculated according to the alternative approach cumulative damages $D = 0.25$ for hot spot on deck and $D = 0.79$ for hot spot on longitudinal bulkhead. The role of parallel stress is here emphasized by utilizing the parallel principal stress as reference stress, which is in this case are the maximum principal stress. Expected fatigue cracking pattern is that of the right picture of Figure 30.

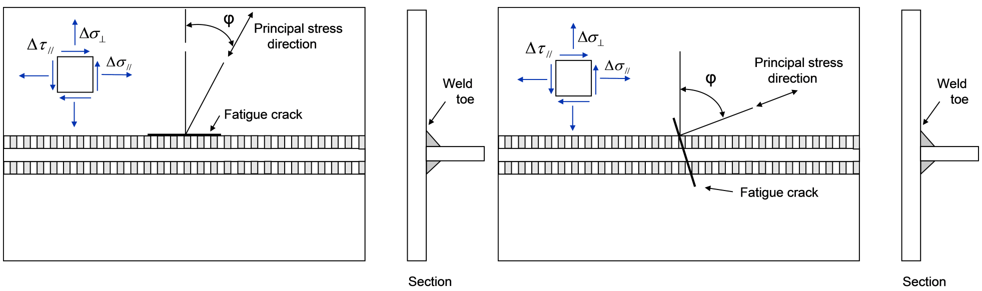

Figure 30: Fatigue cracking pattern when principal stress is approximately perpendicular or parallel to the weld toe line (DNV-CN30.7, 2010).

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7.3.3 IIW Guidelines for Stress Multiaxiality

Within the IIW approach, the fatigue analysis can be solved both by referring to maximum principal stresses and by summing up the effects of shear and normal stresses. In the case of variable amplitude loading, maximum principal stress is proposed as reference method, disregarding the direction of such stress. A limit Miner sum of $D = 0.5$ is recommended together with a modification of the shape of reference S-N curve. Alternatively, IIW suggests to calculate separately normal and shear stress cumulative damages and finally to verify their effects by a combination of both.Therefore, reference is made to a formulation as that given in Eq. 8, where the limit D_E is fixed equal to 1. The equivalent stress ranges are calculated utilizing the appropriate FAT classes for normal stress (parallel or perpendicular to weld toe line) and shear stress. The FAT class 90 is applied to normal stresses $\sigma_{||}$ and detail No. 323 "Continuous manual longitudinal fillet or butt weld". FAT class 100 is applied to shear stresses $\tau_{||}$. This procedure is only recommended for steel.

In the present study, a series of corrections have been applied on the stresses obtained by linear extrapolation between values corresponding to nodes $0.5t$ and $1.5t$ from the hot spot line. The Weibull shape factor and the total number of cycles are according to DNV guidelines. As for the method based on maximum principal stress, a stress range of $264.12\,MPa$ for the hot spot on deck and $360.46\,MPa$ for the hot spot on the longitudinal bulkhead has been referred to. The results in terms of cumulative damage are $D = 0.38$ for hot spot stress on deck and $D = 1.13$ for longitudinal bulkhead. The suggested damage limit is 0.5. In both cases hot spots appear about critical, and in the latter case the result shows that the fatigue resistance criterion is far from being satisfied.

The IIW-method on combination of the normal and shear stress cumulative damages deals with reference stresses $\sigma = 264.10\,MPa$ and $\tau = 34.52\,MPa$ for hot spot stress on deck, and $\sigma = 285.70\,MPa$ and $\tau = 129.11\,MPa$ for hot spot stress on longitudinal bulkhead. The combination of cumulative damages has been made basing on Eq. 8: for hot spot on deck and walland resulted in 0.52 and 0.65 respectively. Shear stress contributions are insignificant.

Importance of normal stresses parallel to the weld toe line is also highlight by Maddox (2010) who has proven by fatigue testing that fatigue loading beyond 60° from normal to a fillet weld can still produce weld toe failure. Laboratory tests were performed on plane specimens with attachments welded on different orientations from 0° to 90° with respect to the direction of loading (see Figure 31). A very good correlation of results in terms of fatigue capacity for different welded attachment orientations may be reached if the resultant stress range $\Delta\sigma_{res}$ is applied in the fatigue assessment. Maddox suggests for a nominal stress range $\Delta\sigma_0$ between $\theta = 45°$ and 90°, to assess the weld as longitudinal weld, with a fatigue crack controlled by the parallel stresses as shown in Figure 31. Consequently, a suggestion is made to base fatigue assessment on the resultant stress range $\Delta\sigma_{res} = \Delta\sigma_0 \sin\theta$, by using the normal stress $\sigma_{||}$ parallel to weld toe line. In the present study, the method based on Maddox's proposal an egligible shear contribution delivers the same results as the method based on combination of normal stress and shear stress damages.

7.4 Benchmark Study Conclusions

The present benchmark study is focused on the identification of the stresses to be used as the reference stresses to assess welds in case of stress biaxiality. Two cases have been studied: the hot spot location on deck where the welded joint is subject to

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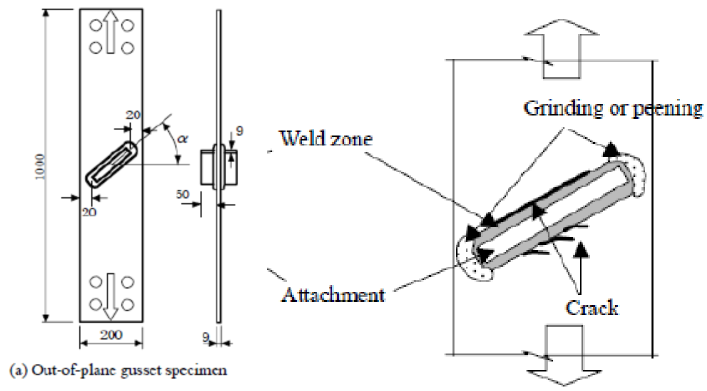

Figure 31: Test specimens and mode of fatigue cracking (Kim and Yamada, 2004 as cited in Maddox)

parallel loading (maximum principal stress parallel to weld toe line), and the hot spot on outer longitudinal bulkhead (maximum principal stress at about 30° to weld toe line). Different approaches have been implemented according to classification society's rules and scientific criteria. The different outcomes in terms of cumulated damage are summarized in Table 5 where σ_p stands for principal stress.

The low level of stresses normal to the fillet weld does not give advice on risk of fatigue cracking when traditional design rules are applied. In these cases the calculated fatigue damage D is about zero. The assessment is based on an approach of disregarding the effect of stresses parallel to the weld fillet. This approach, even if differently implemented by the classification societies, leads to a strong consistency between the calculated fatigue damages, but not with the scientific approaches.

A clear divergence from common indication of indefinite life is that given by DNV rules

Table 5: Fatigue damages resulting from different approaches

hot spot location: toe weld line on deck plate				
	method for fatigue checking	reference stress	limit value	D
GL	traditional method	$\sigma_\perp$	1.0	0.04
CSR(OT)	traditional method	max σ_P ($\beta = \pm$ 45°)	1.0	0.00
CSR(BK)	traditional method	$\sigma_\perp$	1.0	0.00
KR	traditional method	$\sigma_\perp$	1.0	0.00
DNV	traditional method	max σ_P ($\beta = \pm$ 45°)	1.0	0.00
DNV	enhanced method	max ($K_P\|\sigma_1\|$,$K_P\|\sigma_2\|$, σ_{res})	1.0	0.25
IIW	max principal stress based method	max ($\|\sigma_1\|$,$\|\sigma_2\|$)	0.5	0.38
IIW	combination of damages	max($\sigma_\perp$, $\sigma_{\sigma\|\|}$), $\tau_{\sigma\|\|}$	1.0	0.52
hot spot location: toe weld line on longitudinal bulkhead plate				
	method for fatigue checking	reference stress	limit value	D
CSR(OT)	traditional method	max σ_P ($\beta = \pm$ 45°)	1.0	0.03
CSR(BK)	traditional method	$\sigma_\perp$	1.0	0.00
IIW	max principal stress based method	max ($\|\sigma_1\|$,$\|\sigma_2\|$)	0.5	1.13
IIW	combination of damages	max($\sigma_\perp$, $\sigma_{\|\|}$), $\tau_{\|\|}$	1.0	0.65

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in the Classification Notes, N.30-7 "Fatigue Assessment of Ship Structures, 2010". The assess considers the stress biaxiality in front of the weld toe. The calculated fatigue capability is different from that previously outlined. Fatigue damage D comes out to be a small value but not trivial for the case when maximum principal stress is parallel to weld toe line, while for the case of maximum principal stress at about 30° to the weld toe line the fatigue damage shows a quite high value, but still not critical.

It is worth pointing out that some classification societies in their rules or guidelines also consider the case of a stress pattern predominantly parallel to weld line. Such procedures give results in accordance to those of the DNV enhanced method and IIW.

A different perspective is given by application of procedures based on the recommendations proposed by the research bodies, which define scientific criteria that, even if not ready to become standards, try to be more adherent to the physical phenomenon of stress multiaxiality in fatigue problems. A method reported by Hobbacher and Maddox have been applied. Resulting fatigue damages appear to deviate from each other, at least as for the quantitative evaluation of fatigue damage, but agree in pointing out the detail as a possible critical detail.

In conclusion, it is not clear if the examined structural detail is strong enough to withstand the load history considered, due to the considerable gap among the results obtained using different methods. Hence it is recommended that multiaxial fatigue is further investigated both by the researchers and the industry in order to come up with the best approach and harmonise the rules.

8 RECOMMENDED WORK FOR FURTHER RESEARCH

Recent years, the importance of crack initiation modelling for practical design gains increasing research interests. For high quality welds or treated welds, the crack-like weld defect does not exist, and thus, the initiation period can be a significant part of total fatigue life, Zhang and Maddox (2009) and Nykänen *et al.* (2009). In addition, short crack growth should also be investigated further in order to better line results from crack growth analysis and S-N fatigue analyses. The existing local concepts for welded joints does not capture crack initiation, since the S-N curves in the codes generally present the total fatigue life up to final failure, Radaj *et al.* (2009). Thus, a design approach, which can model separately the crack initiation and propagation, are required in the future. To obtain this, the existing theoretical models for crack initiation should be further developed. In the offshore community, fatigue evaluation is mostly based on nominal stress approach and S-N curves, however due to more complex and loaded geometries not directly covered by todays S-N curves, it is expected also better and more practicable local approaches in future will need to be developed.

Newbury (2010) presents a summary of the third ISOPE strain-based symposium focused on modelling, materials developments, and tensile and compressive strain capacity. It is concluded that there is no standardized method to characterize strain aging response, which is a critical factor affecting strain capacity. It is also stressed that there is no acceptable industry standard for SENT testing, which is a common test to assess the toughness level of pipelines. This issue ought to be further addressed in future work.

Design codes and associated design methods have a significant influence on the safety and integrity of the structure, and consequently, a fundamental impact on structural design. It is well-known that the uncertainties in any design method or design code are inherently high and not easy to quantify. It is recommended that the industry and

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the academia will continue to interact and work together towards the development of more robust methods and codes for design safer structures. Additionally, there is still a need for a common standard and guideline for designers working with fatigue and fracture. This was also pointed out by the members of the ISSC2009 report. However, it is anticipated that the outcome of the work carried out by the industry today will result in a common standard in the nearest future.

Effects of quality on fatigue strength was studied by Hobbacher and Kassner (2010), this is a very important topic which have high economical and safety related relevance; and it is recommended that this is a subject is further investigated.

Ageing of marine structures is a challenge for the society, as failures can have serious consequences such as loss of lives and significant pollutions. Thus, focus must be on the special issues of operating aged structures and the possible life extension of these. Offshore industry have come further in the development of analysis procedures of aged structures, and further research needs to address also safe operation of aged ships. Hence, a special working group within ISSC, Committee V.6 on Condition Assessment of Aged Ships, has been established for some time in order to investigate and focus on this topic more in detail.

New materials are continuously developed, and especially beneficial properties with respect to e.g. fatigue resistance and higher strength have been focus areas for steels. However, when used in large-scale structures, or cold climates, the systems perspective must be considered. Functionality and reliability of structural designs will probably change todays design and offer new opportunities, cf. goal-based standards principles. A growing trend to explore the possibility to use composite materials in ships will require that we in the near future better understand and can model these materials properties, failure modes and fatigue resistance.

9 CONCLUSIONS

The committee has reviewed recent works concerning the topics fatigue and fracture identified by the committee mandate. This report describes the results of a literature survey of more than 200 references, in addition to a benchmark addressing mutiaxial fatigue study carried out by the members. Based on the committee member's knowledge and interest, this report has focused on unstable crack propagation, multiaxial fatigue, new materials, damage control and risk-based assessment, and update of latest changes in design methods for ships and offshore structures. Topics discussed in details by the previous committee III.2 (2009) have only briefly been discussed in this report and it can be recommended to see the two reports in conjunction to each other to get a more detailed picture of the resent research within fatigue and fracture.

Section 2 presents a brief overview of the recent developments in fatigue assessment methods with focus on the initiation and propagation phase. The chapter has had special attention to multiaxial fatigue analysis procedures, which is still a quite new approach used in the oil and gas industry and maritime sector, still practical fatigue analyses is mostly based on first principal stresses.

Due to the growing interest of exploring oil and gas in the Arctic, in addition to shipping in harsh environment and the wish to build larger vessels, research within brittle fracture and unstable crack propagation have seen a high focus of research lately. Section 3 discusses some of the resent research within these topics with focus on methods for the analysis and experimental measurements of nucleation and propagation of brittle fracture with an example of how brittle crack propagation can be prevented in container ships.

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New developments and new findings on most commonly used materials seen in the offshore and shipping industry have been discussed in Section 4. Emphasis has been put on high strength steel, new steel with improved crack growth properties, materials for cold climate, honeycomb structures, etc. Material research has a high focus within the industry and it is important that findings beneficial for the marine structural design are incorporated into rules and guidelines.

In Section 5, methods suitable for damage control and risk-based assessment are reviewed, considering factors such as effect of workmanship; internal defects, welding procedure, etc. have been discussed. Attention is paid to the suitability and uncertainty of physical models, uncertainty in fatigue assessment diagrams and fatigue life assessments. In addition ageing of structures which is a challenge for the society, have been addressed with focus on special issues regarding operating of aged structures and the possible life extension of these. Both the Petroleum Safety Authority (PSA) in Norway and the HSE offshore division in UK have worked intensively on defining requirements for safe operation of offshore structures extending their original design lives, however these topics will most likely continuing to have a high priority within the marine structures communities.

Section 6 deals with fatigue design methods for ship and offshore structures and a review of update and comparison of design methods for ships and offshore structures, such as the Common Structural Rules (CSR) for oil tankers and bulk carriers, the Harmonized Common Structural Rules (CSR-H) for oil tankers and bulk carriers, rules for offshore installations and Arctic design codes have been addressed. The industry is continually updating their guidelines and recommendations in order to include the latest research.

Multiaxial fatigue procedures are not used to a large extent in ship and offshore design, despite that most structures are subjected to multi-axial stresses most design rules only consider the first principal stress. A benchmark study was presented in Section 7 focusing on multiaxial fatigue. The intention of the study is to show how fatigue assessment of welded structures are treated differently when unconventional loading pattern is to be applied on a simple welded joint. The results showed a discrepancy of obtained lives between the different rules and it is recommended that further work is put into the topics of multiaxial fatigue and the practical pint of it.

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COMMITTEE IV.1

DESIGN PRINCIPLES AND CRITERIA

COMMITTEE MANDATE

Concern for the quantification of general economic, safety and sustainability criteria (as there are reliability, availability, maintainability, dependability) for marine structures and for the development of appropriate principles for rational life-cycle design using these criteria. Special attention shall be given to the issue of Goal-Based Standards as presently proposed by IMO in respect of their objectives and requirements and plans for the implementation, and to their potential for success in achieving their aims taking account of possible differences with the safety and sustainability standards in ISO and similar standards developed for the offshore and other maritime industries and of the current regulatory framework for ship structures. The IMO-related work shall be performed at a time scale consistent with that necessary for submission of documents to the relevant IMO committees.

COMMITTEE MEMBERS

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Eirik Byklum
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KEYWORDS

Economics, maritime transport, human life, health, sustainability, noise, goal based standard, GBS, formal safety assessment, FSA, greenhouse gas, GHG, common structural rules, CSR, offshore wind turbines

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CONTENTS

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1 INTRODUCTION

Looking at discussions in public about industrial activities people can observe a shift of focus. Whereas discussions in the past were mainly focussing on the technological aspects and progress of development, now discussions concentrate on the consequences of technological development to humans, the environment and the economy. In other words the sustainability of industrial activities is the focus. The mandate for this Committee, which has been assembled for its second report period, emphasised this development.

OECD has spent much effort in recent years to analyse the condition of the seaborne transport industry and to give recommendations for its future development. The first report on The Environmental Effect of Freight in 1997 analysed seaborne transportation and found it to be comparatively environmentally friendly, however further OECD reports dealing with the maritime industry were less positive. The list of OECD reports specifically related to maritime shipping starts with Endresen (2008), continues with a study on the effects of the shipbuilding industry itself (OECD, 2010b) and ends with a report on the role of ports (OECD, 2011) which describes the impact on the environment around bigger international ports and the consequences for local authorities.

Further the International Maritime Organisation (IMO) has taken onto its agenda strategic directions that initiate activities to reduce the environmental impact of shipping and to improve the sustainability of all aspects of shipping, from shipbuilding, through ship operations to ship dismantling (IMO, 2010d).

As a consequence of the concerns outlined above the major part of the report of this Committee deals with methods used to assess the sustainability of the maritime industry, and covers aspects such as economic impact, impact to humans and impacts to the environment. Along with the usual literature review some methods are described in more detail.

Further, this report tries to describe the regulatory framework that is dominated by a dual system, consisting of on the one hand of classification requirements and on the other of international legal requirements (from the IMO and flag states), but is now being extended by yet a third interest group, the port state authorities, who are raising further requirements. Intending to differentiate between random impacts like sea loads and the respective responses and systemic impacts like emissions from ships to the environment the following two sections are titled control of random impacts and control of systemic impacts.

During the last years, especially in Europe, many activities started to install offshore wind energy plants, as a consequence attention has been paid to some aspects the offshore wind energy industry which is contributes its part to a sustainable utilization of natural resources.

The next important development for the maritime industry is the IMO's Goal Based Standards which were adopted during the 87th session of the Maritime Safety Committee (MSC 87) in May 2010. In continuation of this Committee's previous work this Report discusses the possible consequences of future development of Rules and Regulations in the maritime sector.

2 THE GLOSSARY

Within this report a few terms will be used that have different meanings in different contexts. To allow a common understanding within this context a glossary will list the

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Table 1: Categories of losses and examples

<table>
<tr><th colspan="2"></th><th>Humans</th><th colspan="2">Environment</th><th>Assets</th></tr>
<tr><td>Systemic</td><td>Loss generated by a certain event (probability of occurrence = 1)</td><td rowspan="2">Fatalities, injuries, permanent or transient disabilities (health, disease problems), physical or psychological disturbances</td><td rowspan="2">permanent or transient loss of biodiversity, utilisation of fossil resources</td><td>GHG emissions from a ship</td><td rowspan="2">failure, damage, unavailability of assets, operating costs, building costs</td></tr>
<tr><td>Random</td><td>Loss generated by a random event (probability of occurence < 1)</td><td>oil spill from a tanker ship</td></tr>
</table>

definitions as used in the context of this report. In the context of the present report all definitions are to be interpreted as applied to the field of structural design

Sustainability: An activity is sustainable if it is proved that it adds value to the society, i.e. it improves the quality of life of the members and does not prevent future generations to achieve similar improvements. The expected value of the impact of a sustainable activity on the long term needs to be positive, i.e. the benefits should overcome the losses. The reference time range for the evaluation of single terms of the balance above mentioned should be set in order to capture all possible implications (with an intergenerational perspective, if applicable).

"Companies are being encouraged, and will increasingly be forced, to take 'cradle-to-grave' responsibility for their products, which of course includes shipping" (Landamore and Campbell, 2010).

Corporate Social Responsibility: Attitude of a corporation to pursue sustainable activities

Loss: Any adverse impact of a structural system, it may include terms regarding humans, environment or assets. Depending on the probability of occurrence of the events at the basis of the losses they can be divided into systemic and random.

The total expected loss is meant as an integral in the time and probability domain of the various contributions.

Accident: Random event generating losses

Safety: A structural system is safe if it does not impair sustainability through an excessive expected loss due to accidents (i.e. to random events).

Risk: Expected loss due to random events (probability times consequences)

Regulatory framework: In the existing practical applications of regulatory frameworks, different sets of requirements address specific performances. They, all together, should pursue sustainability in a specific field (in particular shipbuilding and ship operation)

Performance: Performance of a structural system in this context is a quantity that allows to assess if the system is sustainable. Benefits and losses for the society are respectively positive and negative performances. Summed together they provide an assessment in terms of Sustainability, which is the ultimate performance. (A positive value of sustainability is the final target to be aimed at).

Performance based rules vs. prescriptive rules: In principle, a performance based rule should always refer explicitly to the final target for the assessment (positive sustainability, in the present report). In all practical implementations of Rules the final target is broken down into partial targets of different levels of generality. The less general is

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the target, the lower degree of freedom is allowed in the choice of the design solution. It is to be noted that this practical way of constructing a regulatory framework may have the effect of neglecting solutions that do not satisfy a specific target, but may be able to achieve the final goal.

A performance-based set of Rules implies a 'calibration' of lower level targets to targets at a higher level (and ultimately to the final target: sustainability). If this calibration is not performed, the term 'prescriptive Rules' applies, as the requirement is introduced in an 'axiomatic' way (i.e. without a proper justification in terms of achievement of the final target).

In the IMO context 'Goal Based Standards' can be seen as a synonymous of 'Performance Based Rules'

Functional requirement: In the practical implementation of a regulatory framework, specific targets can be set, represented by functional requirements. Such targets can be set at different levels. In the framework of the development of performance based rules it should be proved that their fulfilment implies to improve Sustainability.

Full Cost Accounting: In the context of this report, FCA is a synonymous of sustainability assessment.

3 THE CONCEPT OF DESIGN PRINCIPLES AND CRITERIA

3.1 Design Principles and Criteria in Context

The principles guiding the design of vessels, and therefore the criteria used to develop the best designs, have evolved over time. It is useful to consider that evolution in order to understand the focus of design today, and how society's concern for sustainability can be identified in the evolving design principles and criteria.

There are many definitions of sustainability (see the Glossary), however it is now widely accepted that the concept has three pillars: economic, societal, and environmental. The evolution of design can be shown to have sequentially added each of these three areas, or pillars, to the required criteria, such that now it can be considered that we are striving to achieve 'design for sustainability'. This analysis was first introduced in the 2009 Design Principles and Criteria Report (from ISSC Committee IV.1), where a matrix diagram was presented that illustrated this analysis. A version of the matrix diagram is reproduced in Figure 1.

In this diagram the costs associated with the three areas of sustainability (economic, societal and environmental), are divided into two categories: costs that are an inevitable part of the operation, and can therefore be considered systemic; and potential costs that are possible if an unintended event occurs, and so can be considered accidental.

The chronology of the embedding of these six categories of concern into the design process has been as follows:

- Economic principles and critieria: design has always focused on minimising the cost of constructing a vessel, and of operating it - these economic concerns must have been present even before the theory of economics itself had been devised. Subsequently criteria were developed that sought to prevent the costs being incurred due to accidental loss of the vessel and cargo, an early example being the minimum freeboard mark.

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Sustainability Pillar	Systemic Costs: Continuous and Inevitable	Accidental Costs: Spasmodic and Potential
Economic	Initial & operating costs (Owners, Designers' and Builders' concern)	Loss of vessel (Owners and Insurers' concern)
Societal	Health and Safety of Life (Societal concern)	Injury and Loss of Life (Owner and societal concern)
Environmental	Environmental Impact (Recent societal concern)	Pollution (Owner and Societal concern)

Figure 1: The matrix of concerns that comprise Design for Sustainability (from the Impact Matrix presented in ISSC 2009, Report of Committee IV.1)

- Social principles and criteria: the safety of those aboard the vessel, crew and passengers, grew as a concern in the 19th century, eventually being formalized in the first SOLAS convention in 1914. These concerns initially concentrated on the loss of life due to accidents, however during the 20th century an increasing emphasis has been placed on health as well as safety, and so requirements have been introduced to ensure that in the normal operation of any commercial activity the health of the operators (and the public) is not compromised.
- Environmental principles and criteria: environmental concerns first focused on the damage suffered by nature as a result of accidental pollution form events such as the loss of a tanker. It is only in the last few decades that it has been widely recognized that commercial activity can not be allowed to routinely damage the environment as an unavoidable part of the operation of any system.

This brief (and simplified) description of the chronology of the evolution of concerns that underlie the design of ships is reflected in the diagram below. It can be seen that it is the relatively recent realization (or at least widespread acceptance) of the environmental impact that human activity is having around the globe that has led to a change in society's priorities. The ongoing development of the principles and criteria reflect society's desire that sustainability considerations drive the design of ships and offshore structures. In this chapter the current methods for the analysis of the three pillars of sustainability are described.

3.2 Analysis Methods for the Economics of Maritime Transport

Recent research advances in the economics of maritime transport discuss issues related to the value of ships, design methods to maximize this for stakeholders, shipbuilding as a service, ship speed etc. Here the way these concepts reflect on ship design principles and criteria will be discussed. First however, some statistics on the economics of maritime transport will be provided.

Observing the world trade figures (UNCTAD 2011) we can clearly state that without the seaborne shipping, world trade would not be possible on the scale necessary for the modern world to functions. Around 90 % of world trade is carried by the international shipping industry and this accounts for 4.5 trillion USD of exported goods. According to the same statistics, this figure brings 380 billion USD in freight rates, which is equivalent to about 5 % of total world trade.

These figures indicate the efficiency of shipping. The ratio between the total freight rates and goods transported leads shows that on average less than 10 % of the value of goods transported is required undertake that transportation using the shipping of the world. Even if the annual investment in newbuilding is add to this, in the order of 100 billion USD (SAJ, 2010), the overall system is still very lean.

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3.2.1 Economics of Shipbuilding

Modern shipbuilding demands a new approach that accounts for the opinions of multiple stakeholders. Traditionally, "ship designs were often developed by a stove pipe [i.e. isolated] design organization without the direct, early participation of the future ship's builder, ship owner, operators and maintainers" (Gale, 2003). In contrast, modern design teams employ Concurrent Engineering principles, which require the consideration of all the stakeholders' preferences. It indicates that the ship valuation should be approached from the perspectives of different parties involved in the shipbuilding process.

The conventional ship value assessment adopts the Net Present Value (NPV) (Stopford, 1997) approach, which only measures the tangible aspects of the ship, including ship's features and functions, discounted through time. NPV therefore fails to capture the importance of partnership and cooperation between the stakeholders of the shipbuilding industry.

Forsström (2005) studied the importance of the relationship between the shipyards as sellers, and the owners as buyers and turnkey suppliers, and concluded that interdependency triggers stakeholders to continue the relationships, recognising that they can to create more value together than independently.

Wang (2008), building on this, found that currently there is insufficient understanding of the value of a ship by the ship owner and shipyard. A more complete understanding will enable designers to reduce the problems of over and under-engineering, prevent ship owners from making unrealistic requirements and avoid shipyards doing inappropriate things such as installing poorly performing equipment. The author also concluded that for unique and sophisticated ships, like cruise ships, successful building was only possible if there was a strong relationship between the stakeholders that allowed flexibility to bridge all technical challenges. Less sophisticated ships, like bulk carriers or tankers, are built strictly according to specifications, and any demands for alterations are met with resistance. The dominant factor of value for these kinds of ships is price, while for the sophisticated ships, the value is held in the passenger experience and the uniqueness that the ship has in the market.

This fact led many yards building cruise ships to extend their business activities to support the owner in the post delivery phase, offering to their clients not just a product, i.e. a ship, but a shipbuilding service. This service would include a maintenance service for the ship, but the primary objective was to engage in the refitting and enlargements of vessels in order to rejuvenate them after a certain period of time, perhaps 10 to 15 years.

Klanac *et al.* (2011) studied the aspect of a "true service yard", in which, following the modern business paradigm of production companies as service companies, a shipyard would get involved in providing transportation capacity. Instead of selling its product, i.e. the ship, it would offer it on the charter market. The benefits of this business model are found in the increased asset value of the yard, longterm production planning, which enables innovation, continuous inflow of income, reduced requirements for cash backup etc.

3.2.2 Economics of Ship Operations

Noticing the shipping industry's trend toward the reduction of operating speed due to the rising oil prices and reduced economic activity in 2010 and onwards, Klanac *et al.* (2010a) performed an analysis to identify optimal speeds dependence on freight

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rates. Following the premise of economic equilibrium, it was possible to draw a functional relationship between the optimal ship speed and the freight rates, assuming constant transport capacity. Further to this, the relationship was also established with the cost of ship operations. Considering that the biggest cost in operation is the fuel, it is possible to estimate the optimal ship speed and the corresponding freight rate for a given price of fuel. Extending the result of this analysis into the present day situation of rising oil prices, or the addition of CO_2 taxes, we can expect that the ship speed will need to be further reduced if the economic equilibrium is to be maintained. Only a rise in the world economy could reverse this trend, but if the requirement to reduce the CO_2 emissions from shipping is accepted then maintaining the slow speed steaming and building more ships might in the long term build a more sustainable approach to 'greener' shipping industry.

3.2.3 Economics of Maritime Accidents

The circumstances surrounding a spill incident are complex and unique. Predicting the per-unit costs of a spill response is a highly imprecise science since the factors impacting cost are as complex as the factors impacting the degree of damage the spilled oil will cause. Clearly, one universal per-unit cost is meaningless in the face of these complex factors, see Schmidt Etkin (1999, 2000).

On the other hand, the spill response, or the clean up is a minor part of the costs. The major part of the costs relates to the socio-economic damage to the community affected by pollution, and in this way a lot of variations can be averaged, so building a model with confidence. In this respect Friis-Hansen and Ditlevsen (2003), using previously reported spill damages (Grey, 1999) established a probabilistic model. Klanac *et al.* (2010b) updated the model with figures related to reported major accidents from 2000 to 2008 (IOPC, 2009).

Klanac and Varsta (2011) studied the international legal framework of IOPC fund (IOPC, 2005), and considered how it impacts on the overall pollution damage. They found that risk distribution is unbalanced as a result of the scheme of liabilities determined according to the maritime conventions, namely the CLC 1992 and the IOPC 1992 fund. An additional imbalance amongst stakeholders is due to the distribution of influence on risk management. The public has a very low influence on risk management, principally setting only the minimum requirements through the actions of its representatives in the IMO or their Flag States. The biggest influence and responsibility is on the yard designing and building the structure, while the influence of

Figure 2: Principal distribution of the environmental risk of spillage among stakeholders for a small to medium tanker (40 to 75 thousand tons DWT), and the influence of these stakeholders on risk management (Klanac and Varsta, 2011).

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ship and cargo owners on risk management are inversely proportional to their share of the risk. Figure 2 interprets this statement graphically, although it assumes that ship structural design as the sole risk control option. Klanac *et al.* (2007) and Klanac and Varsta (2011) propose this ship structural design method based on multi criterion decision-making to minimize the negative effect of this unbalanced distributions of risks.

3.2.4 Economics of Ship Dismantling and Recycling

EC (2007a) performed a comparative study amongst others on the economic options of ship dismantling to avoid careless and "illegal" beaching in India and Bangladesh. From the results of the case analysis the most attractive alternative to beaching in Asia is dismantling at Turkish sites. The second-best alternative seems to be the procedure of pre-cleaning of hazardous material in Europe and then dismantling in Asia. The high cost of European labour coupled with the cost of complying with all workers' health and safety and associated environmental regulations in Europe is the reason why the scenario with full green dismantling in EU is the least attractive alternative.

In their study for the US Navy, Hess *et al.* (2001) analysed among other common dismantling strategies the reefing of naval ships (i.e. creating artificial reefs with the vessel). They concluded that reefing is the only option that has the potential to create revenue in the form of taxes from businesses associated with reef usage beyond the ship-disposal costs.

Recently, Classification societies started to implement Green Passport to the ship's class notation to distinguish ship which posses onboard Inventory of Hazardous Material (IHM). Following the convention of IMO (2009), this notation has been established partly to safeguard life onboard, but predominantly to safeguard the life of the personnel involved in ship dismantling and recycling. IHM contains the list of all hazardous materials permanently stored onboard, inside of ship hull and accommodation, and the ship equipment. Any changes in these subsystems should be also noted in the IHM in such a way that IHM permanently represents the actual status of hazardous material onboard. Gaining Green Passport notation provides strong marketing for the owner on the second hand ship market. There is a common understanding also that in the phase of ship dismantling, better price can be gained for a vessel carrying a Green Passport.

3.3 Analysis Methods for Human Life and Health

3.3.1 Approaches to the Valuation of Human Life, Health and Safety

During engineering projects such as shipbuilding projects decisions have to be done how the performance of a system and namely its safety can be improved. This goes along with changes of costs of the project, may it be increased or decreased costs. As a consequence the engineer needs a support to determine the consequences of an option, as this may be a risk control option in the terminology of formal safety assessments, to improve the performance with regard to the costs. In this context one of the most difficult issues in examining different risk control options for making engineering design decisions and policy formulation is the valuation of human life, health and safety in monetary terms which have meanings in pricing decisions. However in the fields of technology, medicine and insurance decisions are taken that sometimes also involve the possibility of human suffering or death. These decisions are usually made by politicians, taking into account the aversion towards human suffering in an intuitive way. An analysis of these decisions shows, however, that the implicit value of a human life is always finite.

The economic aspect of the problem is, that the scarce national means have to be divided over many investments, among which are a number of possible investments in health and safety. Any rational decision mechanism must therefore be able to weigh the probability of profit against the probability of saving lives and enhancing health. The growing application of risk based design methods makes it necessary to estimate the value of a human life, health and safety in addition to an assessment of the economic damage involved with failure of the system under design.

Generally the most common approach is to conduct a cost and benefit analysis. One such analysis is to study the outcomes of political or societal decision processes, the investments made in a society to enlarge the probability of saving an extra life. The cost, or investment made in practical cases to save an expected extra life (the investment divided by the decrease in expected number of casualties due to the investment) is denoted by CSX. This CSX value seems to be able to serve as a valuation of human life, as it indicates the willingness to pay for the saving of a life. The problem with this approach is that the resulting CSX values differ widely. The values reported in literature, see Brookshire (1980), Crouch (1982) and Ramsberg (1997), ranges from $1,000 for investments in sport and recreation to $100,000,000 for investments in the nuclear industry. In the marine industry it is generally assumed the value to be $3,000,000. Many authors mention this wide range as an indication that decisions concerning the protection of human life are irrational. The tacit assumption is that the CSX value should be a constant number. However it would be even more difficult to monetize health and safety. Most insurance policies do attach a monetary value to “physical” damages to human body.

Holland (2002) and Kelman (2005) contend that the characteristic value monism of cost-benefit analysis renders the practice inadequate for guiding environmental policy formation: not all choices are tradeoffs made on quantitative assessments of preference satisfactions, Holland (2002), and some goods human life among them cannot and should not be measured in monetary terms. Economist Robert Solow (2005) contends that cost-benefit analysis need not necessarily operate by “monetizing everything from mother love to patriotism”. Amartya Sen (2001) notes that a foundational component of cost-benefit analysis is “broadly consequentialist evaluation”, i.e. a decision is evaluated based on the costs and benfits of its consequences. At a basic level, cost-benefit analysis can include within the scope of its reasoning diverse goods - including so-called “human costs,” such as rights and duties, and environmental costs. Sen acknowledges that cost-benefit analysis is not fully compatible with a deontological ethical framework, but he notes that it can accommodate in its calculations respect for rights and duties, safety, health, environmental, and other concerns.

If, despite ethical objections, a price has to be put on a human life, an objective number is the present value of the Net National Product (NNP) per head of the country under study (Net National Product = Gross National Product (GNP) minus Depreciation). The consequence of this approach is that the value of human life in a developing country is considerable lower. This may seem strange and unethical, but it actually accentuates one advantage of the economic optimization of safety, that is, the proposed investments in safety are affordable in the context of the national economy.

Another method is the Life-Quality Index approach (LQI) which is another means of applying the cost benefit analysis approach. The LQI is a tool for the assessment of risk reduction initiatives that would enhance safety and quality of life. The LQI is a substantial improvement for rationalizing the process for setting safety standards (Nathwani *et al.*, 1997; Pandey *et al.*, 2006). It is a tool for the assessment of risk

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reduction initiatives that would support the public interest and enhance safety and quality of life. The LQI is equivalent to a multi-attribute utility function being consistent with the principles of rational decision analysis. It is further refined to consider the issues of discounting of life years, competing background risks, and population age and mortality distribution.

Rackwitz (2002, 2004a,b) and Rackwitz *et al.* (2005) expanded the LQI framework and applied it to determine optimal safety levels in civil engineering infrastructures. Maes *et al.* (2003) applied LQI for optimising the life-cycle cost of structures. The LQI model has also been applied to the cost-benefit analysis of air quality standards and nuclear safety design practices by Pandey and Nathwani (2003).

If economists, ethicists, and policy-makers alike seek methods of cost benefit analysis that are more adept, then the practice can be retained as an evaluative and decisional tool that can explicitly and helpfully facilitate the decision-making process. Kelman (2005) criticizes cost-benefit analysis for its characteristic inability to take into consideration rights and duties as things that have prima facie moral validity. He also contends that we should not always readily assign monetary values to non-marketed goods such as human life, health, and environmental stability. Holland (2002) similarly contends that cost-benefit analysis, at least in its cruder forms, lacks the capacity to grasp adequately the value of goods - both marketed and non-marketed - and to take into account how the value of goods and relative weights are formed. The above analysis reflects on cost-benefit analysis as an evaluative and decisional tool that is marked by explicit evaluation, broadly consequentialist reasoning, and additive accounting. Within the restrictions that these three principles bear for the practice of cost-benefit analysis, the discipline is surely limited. Other conventional structural and valuational features such as non-iterative and non-parametric valuation and market-centered valuation (including reliance on willingness to pay, and exclusion of social choice options) are common but not in themselves essential to the practice of cost-benefit analysis. Various approaches to cost-benefit analysis can be adopted. Monetary commensurability is not always required, thus value pluralism can be introduced. Market-centered and willingness-to-pay valuation are conventional but can be practiced in conjunction with other methods of valuation. Goods can be weighed on non-monetary scales of value and social choice options can be considered. Economists can use iterative valuation and value parameters and thereby keep the process open to changes in value assessments and qualitative judgments. Simple arithmetic alone does not have to determine the process. We can develop or improve the method of cost-benefit analysis rather than discard it as inherently morally inadequate.

3.3.2 Occupational Health

In its strategy IMO has focused on the development of Goal Based new ship construction Standards (GBS), where a more holistic approach towards the ship and its systems is applied. The second approach has a more risk-based and holistic attitude and is called the safety level approach (GBS-SLA), included the safety of seafarer (occupational health), passengers and safety of third parties. Juhl (2007) investigated common ideas and problems of vessels' crew occupational health and safety (OHS). The intention with GBS - and in this respect especially with regard to SLA - is that the standard is an overarching and holistic approach which covers all functions and systems on board. The argument is that if there were a safety standard in place for all systems and workplaces on board, it would indirectly reflect positively on the health and safety of the crew, i.e. the OHS. To the author's opinion, communication between

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ships' design and ships' ergonomics has been non-existent, and it is overdue for the working environment and the prevention of personnel accidents to be taken into consideration in the construction phase, where it is both cheaper and more efficient to create the solutions that efficiently prevents work-related accidents.

Permanent means of access to spaces that require surveys are commonly comprised of walkways, platforms, ramps, ladders, and hatches (see McSweeney *et al.*, 2007, ABS, 2009). Each form of access is unique in design, construction, and arrangement including the potential hazards associated with their use. These hazards include falling over guardrails, off walkways or ladders, stepping into or falling through deck openings, climbing on ladders that are damaged or slippery, or head strikes against overhead obstacles or surfaces. Recently, IMO amended the SOLAS requirements for means of access to vessel tanks and holds. In response, IACS developed Unified Interpretations to provide vessels owners with guidance about how to meet the intent of the SOLAS amendments.

For example, ABS ergonomics approach used for developing ABS own guideline ABS (2003) is described. Recognizing that much of the access criteria could be refined/enhanced by the application of ergonomics criteria, ABS has prepared the Guide for Means of Access to Tanks and Holds for Inspection with an associated notation (PMA+). The PMA+ notation combines the IMO means of access requirements with ergonomics criteria. It is believed that this additional guidance will provide vessel owners with a means to enhance personnel safety associated with survey and inspection activities.

Postural stability is one of the key topics for the maritime sector, Nocerino *et al.* (2011), as wave induced ship motions make the maintenance of upright stance demanding and moving in a controlled manner very difficult, negatively affecting safety of personnel working onboard. Mariners have to concentrate on standing upright while performing the allotted task, avoiding risk of potential injury. Crew members of fishing vessels, navy craft, and supply vessels all experience conditions of work that are different from those faced by workers in other sectors. The fatality rate for fishers is typically several times higher than for other employees, making fishing a very hazardous activity. For validating theoretical models aiming to simulate the postural behaviour of working personnel a possible method is the execution of trials onboard full-scale ships. Nocerino *et al.* (2011) describe an innovative motion acquisition system that is usable onboard ships while accomplishing the daily mission. The system integrates different techniques (photogrammetry, inertial measurements, global positioning system) for acquiring both ship and human motions. Its core is an own-developed low-cost motion capture system fundamental in analysing and understanding the measurements from the inertial sensors. Preliminary laboratory tests and results from measurement campaigns onboard are also presented.

3.3.3 Maritime Labour Convention

The International Labour Organization (ILO) provides legal instruments aimed at protecting and improving working conditions, including those of seafarers. Recently, the ILO produced the Maritime Labour Convention, 2006 (MLC).

The MLC provides a comprehensive code regarding seafarers' rights, and the obligations of States and vessel Owners with respect to these rights. The MLC incorporates the fundamental principles of many ILO Conventions and updates standards of 68 existing ILO Conventions into one document. The MLC comprises three different but

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related parts: the Articles, the Regulations, and the Code. The Articles and Regulations set out the core rights and principles and the basic obligations of Members ratifying the MLC. The Code contains the details for the implementation of the Regulations. The Regulations and the Code are organized into general areas under five Titles:

- Title 1: Minimum requirements for seafarers to work on a ship.
- Title 2: Conditions of employment.
- Title 3: Accommodation, recreational facilities, food and catering.
- Title 4: Health protection, medical care, welfare, and social security protection.
- Title 5: Compliance and enforcement.

Title 3 of the MLC, "Accommodation, recreational facilities, food and catering" addresses issues related to quality of life at sea, including the physical design of seafarer accommodations and the characteristics of the ambient environment which seafarers are exposed to during work, rest, and recreation.

Guidance for complying with the Title 3 requirements is provided in ABS (2010a). This Guide is based on ABS' interpretation of the intent of the Part A requirements and on what ABS considers satisfactory compliance with the Part A requirements. This Guide provides the assessment criteria and measurement methodology for obtaining an ABS Maritime Labour Convention (MLC) Accommodations (ACCOM) notation (MLC-ACCOM). This Guide focuses on five categories of design criteria addressed in MLC. These categories are accommodations design, whole-body vibration, noise, indoor climatic variables, and lighting.

3.3.4 Noise Impact

The subject of noise impact is here considered as an example of systemic impact on humans. The subject is covered not because it is believed to be more important than others, but because noise impact has been only recently been recognised to be important and some efforts are presently being devoted to analyse its effects. The relatively recent development of the analysis, however, gives additional problems in inserting this element in the global evaluation of sustainability.

The impact of noise produced by transportation means it takes the double aspect of emissions towards the inner part of the vehicle and towards the external space. This is a common feature of road vehicles, trains, airplanes and ships.

In the specific case of surface marine vehicles, external acoustic pollution is represented by airborne and waterborne emissions (the latter being typical of this type of vehicle) while the internal transmission is represented by airborne as well as structure-borne noise transmission. The propagation of noise both inside and outside ships features peculiar aspects in comparison with other transportation means because of the dimensions and the complexity of the vessel source (external radiation in air and the sea), because of the medium involved in transmission (waterborne emissions) and to the specific features (stiffness/mass characteristics) of the ship structure.

On a global scale, from the point of view of a sustainability assessment of the shipping process, all these types of radiation have a negative impact and are to be considered as negative terms (losses) in the balance of sustainability. The subject of the quantification and control of the noise impact of ships is being studied by the SILENV project within the 7 Framework Programme of the European Union (www.silenv.eu).

The impact that noise radiation has in the three fields above mentioned has quite various features, regarding different categories of receivers and different perspectives

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within the same category. The noise internal to ships affects the crew members and (if applicable) the passengers of the ship. The time duration of the exposure to noise and the psychological attitude towards it (both influencing the quantification of the impact) are different for the two classes of persons, which are both part of the transportation process.

External noise radiation into air may, on the other hand, affect third parties: inhabitants of areas surrounding ports, channels and coasts impacted by intense shipping traffic. In this case, the exposure time may vary from a few minutes for the ship sailing to a few hours for the ship charging or discharging at port. The frequency content and the main sources generating the noise signal differ from the case of the noise internal to the ship and differ also if the ship is sailing or in harbour.

Finally, noise emissions in water affect the marine ecosystem and its inhabitants, with effects that can vary greatly according to the type of animals (with sensibilities very much different from each others), geographical areas and situations. This subject will be covered in the next section.

A proper quantification of the effect of noise radiation from ships should therefore take into consideration all these aspects. From the point of view of the control of the noise impact the various situations differ considerably, too.

When considering the noise internal to ships, all the elements of the 'acoustic circuit' (source-transmission path-receiver) are located in the vessel. The performance to be assessed (negative effects of noise) is therefore depending entirely on characteristics of the ship and can be predicted and controlled at a design stage of the ship, with little or no influences from other elements.

On the contrary, the impact of the external radiation of airborne noise depends not only on the source (ship as a whole) but also on the characteristics of the surrounding areas (e.g. port, channel or coast geography, orography, meteorological conditions, distribution of buildings and inhabitants in the area, etc.). A quantification of the impact, therefore, involves consideration of element external to the ship and not controlled at a design stage.

Impact of Noise and Vibration Onboard

As mentioned for example in Badino *et al.* (2011a), the problem of health and comfort for crew and passengers on board has been considered for a few decades, leading to quite a structured and detailed framework of Norms and Requirements: several Regulatory Bodies dealt with this problem. Among them:

- The ILO (International Labour Organisation): Given the very broad mission of the organization, the aspect of noise and vibration for workers is treated in very general documents, covering also a large number of other issues, but not in a quantitative way. This applies in particular to the documents relevant to the maritime sector, references ILO (2006), ILO (2007a) and ILO (2007b).
- IMO (International Maritime Organisation): The IMO normative framework gives a more quantitative evaluation of noise effects, setting precise objectives for noise control. The key document in this respect is the IMO Noise Code (IMO, 1981, see also IMO, 1974 and IMO, 1975). For the purpose of the present report, it is interesting to note that two types of requirements are set:
  - limits on the instantaneous sound pressure levels in various locations on board (levels in dB(A)). By instantaneous is here meant a value that is obtained from a short term average, of the order of minutes. Such levels

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can be interpreted as limits in the sound power perceived by the human ear, (the characteristics of the human hearing apparatus being represented by the A-filtering)

– limits on the total exposure to noise (in principle in all the locations visited by the seafarer during the 24 hours), expressed in equivalent levels: $L_{eq}(24)$, see eq. (1). This can be seen as a limit on the total perceived sound energy during the typical day.

$$L_{eq}(24hours) = 10\log_{10}\frac{1}{24h}\int_{24h}\left(\frac{p_A(\tau)}{p_0}\right)^2 d\tau \qquad (1)$$

where p_A is instantaneous A-weighted sound pressure; p_0 is reference pressure.

Even though not explicitly stated, the former type of requirement is meant to prevent 'immediate' effects of noise on the seafarer, ranging from permanent to transient impairment of hearing capabilities (in case of higher noise levels), to masking effects of signals or communication, to stress due to noise inducing underperformances while performing duties. The second type of requirements is devoted to the prevention of accumulation of damage in time for workers exposed for long periods to noisy environments. The two classes of requirements correspond therefore to different classes of consequences.

- Class Societies (Comfort Class notations): The aim of these additional (voluntary) notations is to evaluate the shipboard habitability and to assess with an independent certification the comfort of crew and passengers on board all kind of ships following noise and vibration criteria. Comparing the noise limits with the IMO ones (as regards crew spaces, the only ones treated in IMO, 1981) it is noted that the dB(A) limits of the lower comfort grade are close to the IMO original limits while in the higher grades limits are lower. No provisions are set in the Comfort Classes for long term exposures (using indicators like the $L_{eq}(24)$ or others).

For more detailed comments on the normative framework for the noise internal to ships, the reader is addressed to the relevant literature. In particular in Badino *et al.* (2011c) it is noted that acoustic comfort is one of the most important factors that passengers and crew usually consider to assess their on board wellness. However, at present, rules mostly refer to merely energetic indexes, as the A-weighted sound level, not considering elements with great impact on the acoustic annoyance, such as the spectral composition of noise or the repetition over time. The paper proposes a few enhanced acoustic criteria and methods to value the noise annoyance on board ships, derived from civil engineering context and notes that such criteria seem able to improve the present indicators for comfort evaluation classes, taking into consideration low frequency sound or relevant tonal components.

In addition to the literature devoted to the definition of noise requirements, a number of technical papers are found on the subject of practical means to analyse noise transmission and achieve an effective noise control on board:

- Beltran *et al.* (2011) describe a model and onboard investigation of two Ro-Ro vessels of environmental impact Noise and Vibrations on board. Correlation between theoretical and test data is discussed.
- Incel *et al.* (2009) presents a case study conducted by two sister ships, one with special noise insulation materials while the other without any special treatment.

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Noise reductions have been conducted for the base ship and special noise reduction techniques such as floating floors, visco-elastic insulations etc. have been applied to comply stringent noise levels. The prediction method and efficiency of the special noise insulation material effects are demonstrated both by calculations and by full scale measurements. Full scale results are in good agreement with the noise levels at the lower decks. However the agreements between predictions and measurements are low at the upper deck levels. This may originate due to the noise from air conditioning, ventilation and the funnel. Differences between two ships on the noise spectrum clearly indicate that higher frequencies are affected more from the visco-elastic noise reduction measures. Lower frequencies may even be resulted in noise increase.

- Cotta *et al.* (2011) discusses a practical application of Comfort Class Notation. It introduces the main characteristics of a Comfort Rule on Board, presents the general testing conditions and also highlights additional requirements for passenger ships greater than 65 m length. The main features that each Register requires today to classify a ship with a Class Notation are presented. From the comparison between Rules Notations and Technical Specification Limits (TSL) it is possible to note how in passenger areas maximum accepted limit values are close to the best comfort class in every conditions analyzed, on the contrary noise and vibration values accepted in crew cabins and accommodations have maximum limits close to the lower Class Notations. Probably this discrepancy is related to the difficulties to have a homogeneous definition of comfort on board.

Impact of External Airborne Noise Emissions from Ships

As mentioned in Badino *et al.* (2011b,d), the characterisation of the whole ship as a source of airborne radiated noise is in itself a challenging task, due to the dimensions of the ship, the directivity of the emission, the dependency on the operating conditions (sailing or at quay: i.e a moving or a stationary source for a receiver ashore). The subject is covered in part by ISO Standards for the case of inland waterways (ISO, 2000) and for recreational crafts (ISO 2007, 2009). These standards deal with measurement procedures, but do not contain limits. In EU (2003b) limits for airborne noise are given for recreational crafts in function of the engine power. Such limits are to be measured according to ISO (2007), ISO (2009).

Limits and measurement procedures for this topic are being studied within the SILENV project (http://www.silenv.eu/)

When evaluating the impact of the noise emitted, it is to be noted that, as above mentioned, the actual emission patterns are highly dependent on the local characteristics of the surrounding area: obstacles, reflecting surfaces (hills, buildings) even meteorological situation. On top of this, the receiving positions (location and distribution of inhabitants with respect to the ship) are also much dependent on the local characteristics.

Indicators that can be used as units for describing the impact of noise emission from ships are on the other hand available from other engineering fields, but need to be adapted.

Two main European directives deal with the problem of industrial airborne noise: the European Directive 2002/49/EC (EU, 2002) and the European Directive 2003/44/EC (EU, 2003b). The first one applies to environmental noise to which humans are exposed in particular built-up areas, in public parks or other quiet areas in urban agglomerations, in quiet areas in open country, near schools, hospitals and other noise-sensitive

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buildings and areas. The indicators used are L_{den} and L_{night} (day-evening-night levels), that are equivalent levels defined as follow:

$$L_{\text{den}} = 10lg\frac{1}{24}\left(12 \cdot 10^{\frac{L_{\text{day}}}{10}} + 4 \cdot 10^{\frac{L_{ev,}+5}{10}} + 8 \cdot 10^{\frac{L_{\text{night}}+10}{10}}\right) \tag{2}$$

where L_{day}, L_{evening} and L_{night} are A-weighted long-term average sound level as defined in ISO 1996-2: 1987.

As apparent, in the above definition, the noise energy in the different periods of the day is weighted differently to build up a 'weighted equivalent level'.

The aim of these indicators is to correlate the measurement of sound pressure level and the percentage of people who have negative effects on their health due to a prolonged exposure to an examined noise source. The original target of such indicators are continuous noise emissions from industrial plants or similar. The application to the case of ships, passing by or at anchor, may require some adaptations, due to the comparatively short exposure time.

In Badino *et al.* (2011d) some negative conclusions were drawn about the present normative situation, which appears to be fragmented and not very well defined in terms of design emission values for ships. In the same paper, however, the Noise Strategic Mapping is identified as a useful tool to set up a control methodology for noise levels in maritime ports. As it implies the definition of an evaluation methodology of the noise levels produced by ports activities in general and by ships in particular, it can very well be used to assess the impact in terms of number of people affected and inherent noise levels (or equivalent levels, possibly weighted).

Still the question of how to weight, in monetary or other terms the exposure to noise (however evaluated) remains open.

Comments on the Evaluation of Ship Noise Impact on Human Life

In the preceding sections, the impact of noise on humans has been addressed separating the effects on people involved in the transportation process (crew and passengers inside the ship) from third parties. The classification to some extent is based on the absolute levels of noise to which the various categories are exposed: the crew on board is in more close contact with sources and for longer periods, passengers are less exposed both in terms of levels and time, external people are likely to be subjected to lower levels (even though not necessarily for shorter times). The differences in acceptable levels and also the indicators that are used to quantify the effects reflect the different roles played by the various categories. The limits have also different targets, ranging from the prevention of body damage due to short and/or long term exposures to avoidance of direct/indirect interference with working activities to the enforcement of less easily defined feelings of 'comfort' or 'well being'.

From the point of view of a proper evaluation of the balance between design efforts to prevent noise and benefits of reducing it, it can be said that extreme consequences (body damages) and inherent scenarios are more easily defined than lighter consequences. This is reflected also in the time sequence in which the various aspects have been addressed by the regulatory bodies: the first norms for crew health date back three decades, Comfort Classes were issued in the 90thies and most norms for outdoor noise have been delivered in the last decade.

In principle, however, all classes of consequences should be identified and weighted for their impact on human life.

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3.4 Analysis Methods for the Environment

3.4.1 Recent Concerns on Environmental Analysis of Ships

The Environment can be taken to refer to any one of a number of areas: the effect of shipping as an industry on marine life and ecosystems, impacts of routine operation such as the leaching of coating systems like TBT, the impact of ship borne noise and vibration; or one off accidental emissions such as an oil spill. It can also refer to effects on the global environment as a whole, the contribution of CO_2 emissions to global warming, or other life cycle impacts such as the depletion of non-renewable resources such as iron and oil.

Over the past ten years, interest in these impacts from all spheres of human activity has increased, and this is reflected in the existing literature on the subject, authors such as Bebbington (Baxter *et al.* 2003, 2004a,b; Bebbington, 2007a,b; Bebbington *et al.*, 2001, 2006, 2007; Bebbington and Frame, 2003; Bebbington and McGregor, 2005; Bebbington and Thomson, 1996); Cabezas-Basurko (Cabezas-Basurko, 2010; Cabezas-Basurko *et al.*, 2007), Corbett (Corbett *et al.* 2007; Corbett and Koehler, 2003, 2004); Fet (2002) and Landamore (Landamore *et al.* 2006, 2007a,b, 2008, 2009, 2010), along with others, have carried out research aimed at better understanding the true environmental impact of ships and shipping, and how best to mitigate this, thus ensuring a sustainable industry model, that is one which can continue to operate profitably now and in the foreseeable future.

3.4.2 Impact of Greenhouse Gas Emissions

Although International shipping contributes only about 3 % of global CO_2 emissions (IMO, 2008a, Endresen *et al.* 2008), according to the EU targets (EC, 2007) the GHG emission need to be reduced by 50 − 85 % in 2050 compared to today's level (IPCC, 2007) and, therefore, there is an ongoing debate regarding how much the sector could be expected to reduce emissions and how the reduction could be achieved (Van Dender and Crist, 2008, Gehring, 2008).

Substantial work has been developed in recent years on the study of the environmental impact of the shipping activity as reviewed by Gaspar and Balland (2010). Two recent conferences exemplify the concern of the sector in the theme, namely the International Symposium on Ship Design and Construction - Environmentally Friendly Ship in Tokyo (ISSDC 2009) and the Ship Design and Operation for Environmental Sustainability in London (RINA 2010).

Gaspar and Balland (2010) have suggested an approach towards the integration of environmental performance in the early stages of ship design, focusing on energy efficiency and air emissions. The integration process consists in 5 tasks to be performed during the conceptual phase, in which methods are applied to estimate economical, technical and environmental key performance indicators (KPI), creating thus trade-offs and evaluating as soon as possible the pros and cons of the design.

Several technical and economical measures lead to changes in the environmental factors, such as the hull optimization (Hochkirch and Bertram, 2008) or the machinery system configuration (Gaspar *et al.*, 2010). However, a balanced full cost/benefit analysis of the operation is required if the true cost to society, industry and the environment is to be accurately measured, so as to ensure that efforts to reduce emissions to air from shipping do not unnecessarily prejudice another area of sustainability. In this way options for reducing the impact of shipping can be properly compared and the most beneficial to a sustainable future can be assessed (Landamore and Campbell, 2010).

Eide *et al.* (2009) have proposed a methodology for assessing the cost-effectiveness of technical and operational measures for reducing CO_2 emissions from shipping, through the development of an evaluation parameter called the CATCH (Cost of Averting a Tonne of CO_2-eq Heating) and a decision criterion for the implementation of measures, against which the evaluation parameter should be evaluated. The methodology proposed is in line with the Intergovernmental Panel on Climate Change (IPCC) and with regulatory work using Formal Safety Assessment at the IMO.

The decision parameter for emission reduction CATCH has been established using the same approach adopted in the development of the decision parameter, NCAF (Net Cost of Averting a Fatality), already included in the FSA guidelines (IMO, 2007, 2004), and the similar parameter for assessing measures for oil spill reduction, CATS (Cost of Averting a Tonne of oil Spill) (Skjong *et al.*, 2005).

Eide *et al.* (2009) suggested that CATCH $< 50\,\$/T$ CO_2-eq should be used as a decision criterion for investment in GHG emission reduction measures for shipping. A number of specific technical and operational measures for reducing CO2 emissions has been analysed for selected ships showing that several measures are cost effective according to the proposed criterion. Assuming independence between the measures, the cost effective measures (not including speed reduction) considered by Eide *et al.* (2009) add up to an emission reduction in the order of 30 % for the bulk carrier, and 40 % for the container vessel.

Alvik *et al.* (2010) present a similar study about the cost benefit of several measures to diminish the CO_2 emissions, indicating that 30 – 60 % of the current emissions level can be diminished by 2030 if all the measures were included in the design/operation process. Shi *et al.* (2009) discuss the return of investment for design and operational energy saving measures for a container ship without, however, defining a methodology to calculate it.

3.4.3 Impact of Noise Radiated into the Water

A systemic impact on humans due to airborne noise has been considered in this report (above). Here is added the systemic impact on the environment due to underwater noise radiated by commercial vessels is analysed. Once again it is a type of impact produced by shipping activities that has gained attention in recent times.

There has been a rising concern about the negative effects that underwater radiated noise (URN) has on the marine wildlife in general and in particular on marine mammals. In these animals, acoustic communication and perception has acquired a privileged role compared with other senses and other zoological groups (see Andrè *et al.*, 2011).

The topic has become officially an object of discussion within IMO since 2001. In the last years a Correspondence Group on “Noise from commercial shipping and its adverse impact on marine life” has been active and issued several documents, containing also a ranking of quieting strategies (IMO 2009e, 2009f, 2010d).

As mentioned in Andrè *et al.* (2011) the technical problem of the evaluation of the mentioned environmental impact of ships’ URN, includes, as always in acoustical terms, quantification of the source levels, of the transmission losses and of the receivers’ perception of noise. The cited paper examines the role of noise emissions from shipping

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and explores how the emissions can be surveyed and how their impact can be quantified, in order to establish a target for the control of such emissions. The paper builds on the first results of the project SILENV, funded with the 7th Framework programme of the European Union (www.silenv.eu).

As reported in the mentioned paper, two standards have been recently issued for the characterisation of underwater noise signature by commercial vessels, respectively by the American National Standards Institute together with the Acoustical Society of America (ANSI/ASA, 2009) and by DNV (within the Silent Class Notation: DNV, 2010).

The problem of the characterisation of the ship source is strictly linked to the propagation loss issue: surveys are taken at a certain distance from the ship (of the order of few hundreds of meters), and therefore reflections from the sea surface (depending on the sea state) and from the bottom (depending on the composition) are to be taken into account in the processing of data, as well as possible uncertainties related to the actual relative position of hydrophones with respect to the ship. In some cases, also sound celerity profile in the water column may affect results. The same phenomena (with different relative influences) affect also the propagation of noise from the ship to the receivers, making the transmission problem much influenced by local parameters. A further complication in the impact assessment is represented by the extreme variety in the types of animals affected with different sensitivities and reactions to noise.

With reference to marine mammals, two main types of impact from shipping noise have been identified in Andrè *et al.* (2011): behavioural changes (abandoning their habitat or alter their feeding or living habits) and disruption in long range communication (noise masking their vocalisms). Unfortunately, a proper evaluation of these effects for the mysticetes family (the largest marine mammals, with the highest ecological value) is not possible, because audiograms for these large animals are not available as well as information about the critical band-width of their hearing apparatus.

On the basis of the above, it is clear that a regulatory framework on this aspect can only be based (and this is the foreseeable trend) on the enforcement of technology-based limits, i.e. on limits on the radiated pressure levels inspired by good practice rather than by the actual 'needs' of the receivers (unknown, for the time being).

As regards practical issues regarding investigations about the environmental impact due to Underwater radiated noise, Beltran *et al.* (2011) describes models and surveys performed onboard of two Ro-Ro vessels. Correlation between theoretical and test data is discussed.

3.5 Synthesis of the Analysis Methods

As is common in maritime research, it is useful to look to other industries for existing models and best practice; in safety and human life and health (social impacts) the benchmark is often set by the aviation industry, while in environmental mitigation it is the automobile (encompassing all road-borne transport) industry which has faced the most scrutiny, and therefore invested the most in research, in recent years. That is not to say that, for example, the rail industry does not also have lessons from which the maritime industry can learn. Economic realities underpin all business decisions, and as such are a key to any realistic model which hopes to assess impact.

The concept of a full cost account (Landamore and Campbell, 2010; Bebbington *et al.*, 2001) of a business, industry or process attempts to consider all the facets of influence of that system and assigns them all equal significance; by aping the format of a profit and loss account (balance sheet), this method of assessment reduces all these competing spheres of influence to a common base line – that of their economic cost – not only those incurred directly by the company (for example) in question, but all external costs, whoever actually bears them within the system. Whilst still an incomplete model, it does encourage dialogue underpinned by the true realities of the system's level of sustainability.

3.5.1 Sustainability, Indicators and Indices

The importance that the term sustainability has gained between policy makers and scientific researchers can be attributed to its use in the Brundtland Commission's report, Our Common Future (UNWCED, 1987), which linked the term to development. This report emphasized the economic aspects of sustainability by defining sustainable development as "economic development that meets the needs of the present generation without compromising the ability of future generations to meet their own needs."

Sustainable shipping is a new concept that is now emerging as an area of concern (ISSC, 2009). Cabezas *et al.* (2008) have defined sustainable shipping or a sustainable waterborne transport as "a cost-effective commercial activity, in which the environmental load is not bigger than that which the environment can currently and in the future bear, and that the social community (directly and indirectly) in contact with it is not being negatively affected".

In the last decade several sustainability assessment methodologies have been proposed (e.g. Cabezas *et al.*, 2008; Singh *et al.*, 2009; OECD, 2010; Ness *et al.*, 2007). These are used to develop integrated policies which take full account of the three sustainable development dimensions: economic, social, and environmental, and which include cross-cutting and short and long-term considerations.

To achieve and maintain sustainability, policy-makers require timely information which demonstrates whether a system is generally becoming more or less sustainable, and specific information on which characteristics need the most improvement. In this context sustainability indicators and indices have been proposed and developed to measure and monitor the performance of the system in terms of each sustainability stream.

A number of global, national, regional, and sectorial indicators and indices related to environmental performance or sustainability have been developed by governmental sectors, scientific research institutions and non-governmental organizations (NGOs), as recently reviewed by Singh *et al.* (2009).

An indicator is a variable that describes one characteristic of the state of a system, usually through observed or estimated data. Some indicators may give information about the position of the system relative to particular sustainability boundaries or goals ("distance-to-target" indicators).

When many indicators are used, they are either presented in a framework of categories, or aggregated into an index (also called composite indicator). An "index" is a quantitative aggregation of many indicators and can provide a simplified, coherent, multidimensional view of a system. Sustainability indices have been developed specifically to help policy-makers in these respects. Indices usually give a static overview of a system, but when calculated periodically, they can indicate whether the system is becoming more or less sustainable, and can highlight which factors are most responsible for driving the system. Sets of sustainability indicators, and aggregation of these indicators into indices, are increasingly used to make policy decisions (Hezri and

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Dovers, 2006) and it is critical to understand index strengths, weaknesses, biases, and scale dependence when using them (Mayer, 2008; Ness *et al.*, 2007).

The need for an integral systematic approach to indicators definition and measurement is recognised in order to give well-structured methodologies, easy to reproduce and to assure that all important aspects are included in the measurement. However, before developing the methodology and the indicators what is needed is the clear definition of the policy goals towards sustainability.

Ness *et al.* (2007) developed a holistic framework for sustainability assessment tool. It consists of three umbrellas or general categorisation areas; these areas are (1) indicators and indices, which are further broken down into non-integrated and integrated, (2) product related assessment tools with the focus on the material and/or energy flows of a product or service from a life cycle perspective, and (3) integrated assessment, which are a collection of tools usually focused on policy change or project implementation.

A new holistic methodology for sustainability analysis of ships has been also proposed by Cabezas *et al.* (2008). The procedure consists of itemising the ship into different systems that are separately analysed and assessed taking a life cycle approach in order to see its pollution through its life time, and its life cycle costs and social implications in order to get a numerical sustainability index. The next stage of this research is to model environmental, economic and social performances of ships in order to obtain reliable data about the level of sustainability.

Although there are various international efforts on measuring sustainability, only few of them have an integral approach taking into account environmental, economic and social aspects. In most cases the focus is on one of the three aspects. Although, it could be argued that they could serve supplementary to each other, sustainability is more than an aggregation of the important issues, it is also about their inter linkages and the dynamics developed in a system (Singh *et al.*, 2009).

Composite indicators may conduct to misleading, non-robust decisions if they are poorly constructed or misinterpreted. Typically correlations among indicators and compensability between indicators are two critical issues that are not taken into consideration. Indicators of sustainable development should be selected and negotiated by the appropriate communities of interest and composite indicators must be constructed within a coherent framework.

One specific example of a Sustainability Index and its application in several diverse cases is given in detail in the next section.

3.5.2 Triple I (III) – Inclusive Impact Index for Assessment of Sustainability

Triple I (III: Inclusive Impact Index) is the index to evaluate sustainability of the human activity, which is developed by the Inclusive Marine Pressure Assessment & Classification Technology (IMPACT) Committee of the Japan Society of Naval Architects and Ocean Engineers. The basics and the application of the concept have already been described by one example in the previous report of this committee. Here some examples of sustainability assessments using Triple I published during the period of this committee will be given.

Yuzui and Kaneko (2011) applied the Triple I to inclusive environmental impact assessment for single-hull and double-hull tankers with the same dead-weight ton. They firstly applied the method of Life Cycle Assessment (LCA) to evaluate *EF* by calculating CO_2 emission at each stage such as building, navigating (25 years), demolition,

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and recycle(production of stretching steel). They found that EF of double-hull tanker increases by about 4.6 % compared with that of single-hull tanker. Secondly, they estimated the Human Risk (HR) from the fatality risk by accidents during navigation by using Lloyd's Register Fairplay (LPFP) casualty data. They found that HR of double-hull tanker is a quarter of that of single-hull tanker. Note that they use β in the equation of Triple I as 3 million US$ per fatality, which is used as the maximum cost to avert a fatality in cost benefit assessment of safety FSA. Thirdly, they calculated Ecological Risk (ER). Only the risk from oil spills resulting from accidents during navigation is considered. Though compensation cost at oil spill accident, such as clean-up cost, property damage and tourism damage, is considered as environmental risk in the FSA of IMO, they consider them in the cost term (C) in equation (1) in their evaluation of Triple I. Instead, ER is estimated as polluted productive area by diffusing oil. They found that ER of double-hull tanker is a 1/18 of single hull-tanker. Figure 3 shows the computed Triple I for single-hull and double-hull tankers. They concluded that Triple I for double-hull tanker is about 1/5 of that of single-hull tanker. This means that double-hull tanker is a more beneficial system than single-hull tanker. Finally, they proposed that the concept of Triple I is used for cost benefit assessment to propose effective Risk Control Options (RCO). In the case of cost benefit assessment by safety or environmental FSA, cost-effectiveness of an RCO is evaluated by the index called GCAF (Gross Costs of Averting a Fatality) or CATS (Cost of Averting a Ton of oil Spill). Because the Triple I can be the index which considers risks both safety and environmental, they proposed the following ΔIII for cost benefit assessment.

$$\Delta III = \gamma \left(\delta \Delta ER_{cats} + \beta \Delta HR + \Delta C\right) \tag{3}$$

where ΔHR is the change of HR due to the optional RCO, ΔC is the cost to install the RCO and ΔER_{cats} is oil spill reduction of a RCO. They concluded that ΔIII_C is effective as the index which considers safety FSA and environmental FSA at the same time.

Yoshimoto and Tabeta (2011) assessed the environmental impact of an artificial up welling technology using a seabed mound by the Triple I. In the calculation of EF, direct environmental impacts by CO_2 emission due to construction of the seabed mound is estimated using the environmental input-output analysis. Also indirect effect, such as reduction of environmental impacts by the increased production of fish, is also considered which could be several times larger than the direct effects. It is concluded that Triple I indicates that the artificial up welling technology will be sustainable when the indirect effect is considered.

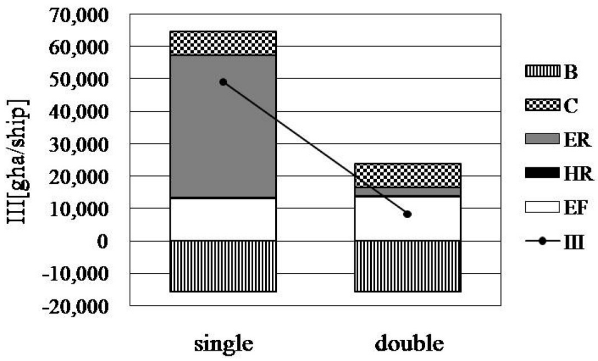

Figure 3: Triple I of single-hull and double-hull tanker (Yuzui and Kaneko, 2011)

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Ohtsuka (2011) assessed the sustainability of the ocean nutrient enhancer which fertilize ocean by up welling deep ocean water (DOW) and can enhance marine primary production. Triple I of both the prototype of ocean nutrient enhancer, TAKUMI, and the large enhancer designed for commercial use is calculated. They conclude that the large enhancer designed for commercial use is adequately sustainable because it can up well large quantities of DOW from greater depth, though the prototype is unsustainable.

To mitigate the global warming, ocean sequestration of CO_2 has been proposed. Because the technology has risks on deep ocean ecosystems, its implementation needs public acceptance through environmental impact assessment. Omiya and Sato (2011) presents a methodology to calculate Triple I for the CO_2 ocean sequestration (COS) and compared with the effect of ocean surface acidification (OSA) and its consequent impacts in the deep ocean. Because ecological risk (ER) is not easy to obtain in many cases, sometimes Triple I without ER and HR as shown in equation (3), which is called "Triple I light", is used for simplicity. However, this study particularly focuses on the quantification of ecological risk (ER). ER is defined by the production of quantified damage of an endpoint and its occurrence probability. The end point ER is assumed to be the extinction of a particular species. The extinction probability was estimated as the occurrence probability of the reduction rates in the number of species caused by either OSA or COS, by using expert questionnaire and statistical semi-quantification method. Based on the computed Triple I, it is concluded that the CO_2 ocean sequestration technology is positively admitted as effective.

Duan *et al.* (2011) assessed sustainability of the water purification technologies for the Tokyo Bay. The self-cleaning technologies of artificial tidal flat creation, and eelgrass field restoration were assessed together with the external load reduction technology of the sewage treatment enhancing. A numerical model is employed for simulating the environmental and ecological impact. Because estimation of ecological risk (ER) is the bottleneck in calculating the Triple I, this paper also focused on a scheme of estimating the ecological risk (ER) where the risk of extinction of species is considered. The final assessment results on the water purification technologies suggest that the effort in seaside are the more effective than those in landside; and the artificial tidal flat creation can get larger effect than the eelgrass field restoration.

Since the global sustainability is the most important for human society, the ocean has been expected to play an essential role by providing food, energy and space. However, large scale developments with utilization of ocean need to be carried out in harmonious with the environment to ensure the sustainable and promising future. For the purpose, an inclusive impact assessment, such as assessment by using Triple I, during the planning period for the development becomes more and more important.

3.5.3 Developments in Full Cost Accounting

Landamore and Campbell (2010) identify and discuss some of the methodological challenges facing the development of a model for environment-focused full cost accounting with an international shipping context. The focus is on forming the framework within which a simplified system for assessing the sustainability of shipping, which still reflects all the most important facets of the industry. For what is a new thought experiment in the GHG management of the shipping industry, this study introduces the context, reviews the relevant literature and then discusses the methodological approach that might be adopted and utilised. Specifically, they introduce the full cost accounting sustainability assessment model (SAM), which, although designed for assessing the

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impact of an individual project, is adapted and applied to the shipping industry as a whole. Importantly, Bebbington *et al.* (2001) argue that full cost assessment is not an end itself but a "means by which market prices can be corrected ... to create an economic system that is more likely to deliver sustainable development". In this respect, the paper places FCA within its broader context whilst exploring some of the issues involved in its implementation.

UNCTAD's (2009) Expert Meeting on Maritime Transport and the Climate Change Challenge highlighted that timeframe was a real concern:

> "Current trends in terms of energy consumption and carbon path suggested that if no action were taken within the following two years ... the world would forever miss the opportunity to stabilise emissions at "manageable" levels [and] a global and concerted solution was urgently required. ... [N]egotiations towards regulation of CO_2 emissions from international shipping should be pursued with all due speed."

If the shipping industry is to effectively and sustainably reduce its environmental impact, a model for assessing that impact against a cost base is required (Landamore and Campbell, 2010).

Environmental analysis of ships and shipping is a relatively new activity. Recent moves by IMO, particularly the Marine Environment Protection Committee (MEPC) (IMO, 2010b), to consider the Greenhouse Gas Emissions (GHG) of ships and shipping (IMO, 2010), coupled with the political shift towards a focus on reducing the impact of activity on climate change mean that for the first time ship owners, operators and designers are seriously considering the emissions generated by their operations. Currently the IMO are using two methods for the primary assessment (and eventual control) of emissions from shipping, the Energy Efficiency Design Index (EEDI); and the Energy Efficiency Operational Index (EEOI); (IMO, 2009b, 2009d) which assess the design and operational performance of a ship against a curve of achievable performance generated from the existing ship population (Landamore and Campbell, 2010).

EEDI calculates an assessment of the efficiency of the ship design, it is meant to stimulate innovation and technical development of all the elements influencing the energy efficiency of a ship, thus making it possible to design and build intrinsically energy efficient ships of the future. EEOI works on a similar principle, but it considers the operational emissions of the ship, thereby gauging the effectiveness of any measures adopted to reduce energy consumption. It has been applied by IMO Member States and the shipping industry on a trial basis; it provides a figure, expressed in grams of CO_2 per tonne mile, for the efficiency of a specific ship, enabling comparison of its energy or fuel efficiency to similar ships (Landamore and Campbell, 2010). Many other models have been developed to compare the carbon emissions of different methods of transporting a specified cargo (e.g. Kühlwein and Friedrich, 2000; Corbett and Koehler, 2003, 2004; Corbett *et al.*, 2007; Endresen *et al.*, 2003; MOSES Project, 2007; IAPH, 2009a,b,c; Faber *et al.*, 2010; Browne *et al.*, 2009; Leonardi and Browne, 2009; ESPO, 2009; McKinnon, 2010) and some (e.g. Ademe, 2009; VNF, 2008) have included measures of wider impacts such as noise pollution and congestion. Simplified assessment of the emissions from shipping has often followed on from research in rail and road transport (e.g. TRL, 2010; Argonne National Laboratory, 2009; ARTEMIS Project, 2009), and is therefore rarely tailored to the characteristics of maritime operation.

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Whilst the impact of the whole activity (whole life) on all aspects - social and economical as well as environmental, needs to be considered if the sustainability of the operation is to be assessed, from an environmental point of view, the emissions during transit generally dwarf other impacts (Landamore and Campbell, 2010). A life cycle analysis (LCA; Frankl and Rubik, 1999; West and Manta, 1996) carried out on a short sea container ship (port to port) operating across the North Sea by the CREATE3S project (Landamore *et al.*, 2009, 2010) assessed the emissions deriving from the burning of fuel to power the ship as almost 90 % of the overall life cycle emissions of the ship. While the operational profile of this type of ship and cargo means this is likely to be an extreme example, it is clear that a significant factor for shipping is emissions to air from the engines, hence the IMO focus thus far on this aspect.

A number of full-cost accounting (FCA) approaches have been developed and applied by academics, non-governmental organisations and corporations, with the most sustained period of inquiry having been since 1990. However, the overall number of publications in the public domain remains small, and most applications have tended to be ad-hoc, experimental and incomplete in nature, with little consistency in application, although the Sustainability Assessment Model (SAM) offers some hope (Davies, 2009). See Table 2 for a summary of the key FCA applications and associated literature to date.

The Sustainability Assessment Model (SAM) was initially developed to assess the economic, resource, environmental and social impacts of a single project over its full life cycle and translates all impacts into monetary amounts using a damage cost approach. Figure 4 shows a notional SAM signature (see Baxter *et al.*, 2003) for details of the original model; for application of the SAM (see Baxter *et al.*, 2004a,b; Bebbington and Mcgregor, 2005; Bebbington, 2007a,b; Bebbington and Frame, 2007; Bebbington *et al.*, 2006 and 2007; Xing *et al.*, 2007 and 2008).

Bebbington *et al.* (2001) also report that implicit within, and underwriting, the European Commission's call for FCA are two assumptions: that current prices do not reflect the 'eco-logical truth', that is they do not reflect the true cost to society or the planet of the product, process or service; and secondly that if the market price of a product, for example, were to reflect accurately the environmental cost of that product, then market forces would encourage consumers to switch to 'more ethical' choices through financial incentives.

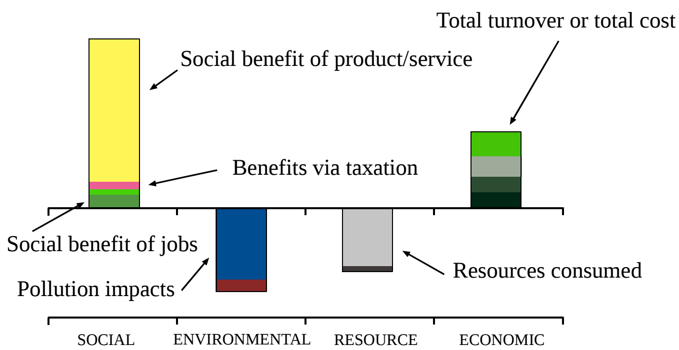

Figure 4: The SAM signature. Source: Bebbington *et al.* (2006)

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Table 2: Summary of the development of FCA (by literature): reproduced from Davies (2009)

Date of publication of relevant literature:	Type of literature (by author): *Literature explaining applications:*	*Concept development literature:*	Overview of applications sorted by major characteristic: Costing focus: Stream 1 Avoidance/ restoration costs	Stream 2 Damage costs	Stream 3 Balance sheet/ other focus
1992	Huizing & Dekker	Rubenstein, Gray	BSO/Origin		
1993		Gray et al			
1994	Rubenstein	Gray	Rubenstein		Rubenstein's green balance sheet
1996	USEPA			Ontario Hydro	
1997		Boone & Rubenstein			
2000	Atkinson			Powergen	
(Forum 2000-03)	Howes		Forum's ECA: Interface Europe Anglian Water Wessex Water Water UK		
Ongoing	Wessex Water				
Ongoing	Water UK				
2001	Bebbington & Gray		The SCC & Landcare Research		
2001 to date	Figge et al (multiple)				Figge & Hahn Sus'l Value
2002 - ongoing	Bebbington/ Bebbington et al	Bebbington/ Bebbington et al		BP Sustainability Assessment Model (SAM), and the construction and UD SAMs	
	Frame & Cavanagh	Brown & Frame			
		Bebbington & MacGregor			
		Xing et al			
2003	Jones				Jones' natural inventory valuation model
2003 (to 2006)	Richardson & Bent		Forum's Sustainability Accounting methodology:		
	Bent		AlcCo	AlcCo	
	Taplin et al		ChemCo		
2004	Antheaume		Antheaume	Antheaume	
2005	Herbohn			Herbohn	
2007		Antheaume			

4 REGULATORY APPROACHES TO SUSTAINABILITY AND SAFETY IN THE MARITIME INDUSTRY

4.1 Development of the Regulatory Framework in the Maritime Industry

4.1.1 International Regulations

The present regulatory framework for the maritime industry is a dual system where on the one hand the classification societies set up technical requirements and on the other hand the flag states set up a combination of legal and technical requirements.

The goal of requirements of the classification societies is to achieve a technically safe ship structure, propulsion plant and equipment that allow a safe operation of the ship. The present scope of classification rules and their development is further described below.

Driven by prominent accidents IMO and its predecessors developed requirements for

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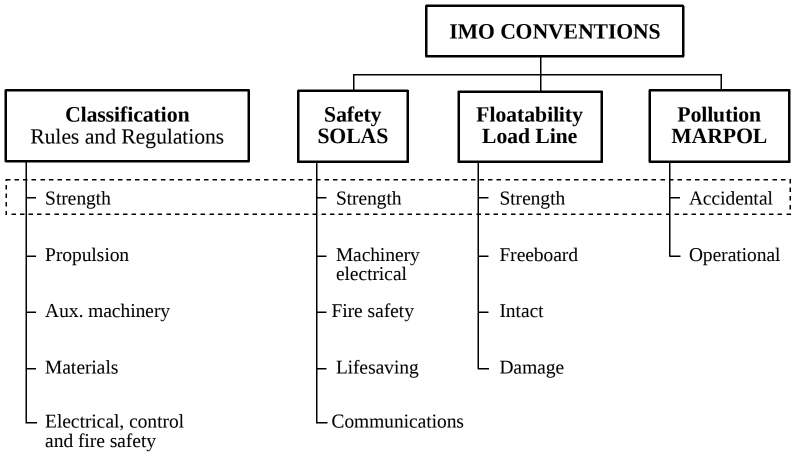

Figure 5: Scope of Classification Rules and IMO conventions

Construction (subdivision, fire protection), Life saving appliances, Radio communication and Nautical equipment of ships in the international trade. Later on oil pollution was recognized as a matter of concern and regulations for the prevention of oil pollution and other kinds of pollution were developed. Other Codes developed by IMO are the Intact Stability Code, which is not mandatory, the ISM Code, the ISPS Code and the MODU Code (which is not mandatory).

Again driven by major accidents IMO developed requirements which are overlapping the rules of the classification societies as there are general strength requirements, requirements for the strength and tightness of hatch covers and other closing appliances. Figure 5 shows the scope of both regulatory regimes and in dotted lines the overlaps.

The link between the rules of classification societies and the international regulations is given by SOLAS Chapter II-1, Regulation 3-1 which says that classification is required as a statutory requirement:

> "*Structural, mechanical and electrical requirements for ships:* In addition to the requirements contained elsewhere in the present regulations, ships shall be designed, constructed and maintained in compliance with the structural, mechanical and electrical requirements of a classification society which is recognized by the Administration in accordance with the provisions of regulation XI/1, or with applicable national standards of the Administration which provide an equivalent level of safety."

The latest IMO mission statement for the period 2012 to 2017 (IMO, 2011b) reiterates that IMO will not only work on safety issues but also on sustainability and environmental issues: "The mission of the International Maritime Organization (IMO) as a United Nations specialized agency is to promote safe, secure, environmentally sound, efficient and sustainable shipping through cooperation. This will be accomplished by adopting the highest practicable standards of maritime safety and security, efficiency of navigation and prevention and control of pollution from ships, as well as through consideration of the related legal matters and effective implementation of IMO's instruments with a view to their universal and uniform application."

The resolution identifies general trends which, among others, require IMO to identify activities that could have adverse impact on the environment and to contribute to

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reduce the atmospheric pollution of shipping. Further a "cradle to grave" concept for new ships will be developed and implemented to allow environmentally friendly recycling of ships in the future. From these trends several strategic directions have been derived and laid down in IMO (2011b).

4.1.2 Regional Requirements of Port Authorities

In addition to the above internationally accepted regulatory regime regional or national requirements exist which tend to diverge due to different political acceptances of occupational risks or environmental impacts caused by ships.

OECD (2010c,d,e,f and 2011) give an overview of the different approaches to reduce the environmental impact of ports with regard to land consumption, noise impact or air pollution. All reports describe how development of ports is affected by environmental aspects and what kinds of environmental impact assessments have to be carried out in context of possible port expansions. It can be observed that requirements developed by some port authorities will have an impact on future ships' designs especially with regard to any kind of emission.

The activities of the ports of Los Angeles and Long Beach are described in OECD (2010c). The report gives an impression how national and local regulations on avoiding air pollution and water pollution may overlap. Both ports have developed a Clean Air Action Plan to improve the air quality in that area. The ports have committed to use pollution-based impact fees so that polluters pay their part to improve air quality. The ports agreed to develop tariff-based incentives and requirements, such as vessel speed reduction incentives and port-mandated fuel requirements and committed to work with the air quality regulatory agencies (AQMD, CARB and EPA) to establish San Pedro Bay air quality standards. Further the ports intend to provide shore based electric power supply to ships within five years from 2010.

The requirements regarding pollution of water are set up by various authorities either national or local. These requirements are complex, often overlapping, and sometimes conflicting. As an example, California state law currently prohibits the discharge of liquid wastes except for sewage from many vessels. Whereas, the U.S. Environmental Protection Agency is currently in the rulemaking process to establish non discharge zones that would make sewage discharges a violation of federal law.

Regulation of all sources of water pollution from vessels operating in California is at least comparable with that of other countries. The zero living organisms limit on ballast water discharges that becomes effective in 2020 is as stringent as possible. The ports are developing best management practices manuals to deal with port housekeeping.

Vancouver follows a similar approach to incentive ship owners to reduce air pollution (OECD, 2010d) by introducing a Harbour Dues Program being rolled out in 2010. It establishes harbour dues which are payable for the first five visits by a particular vessel during the calendar year, within three air emission standards named "Gold", "Silver" and "Bronze" which are bound to class notations of classification societies for environmental protection measures. Depending on the degree of exhaust gas cleaning measures one of the three tariffs apply where "Gold" represents the lowest due to be paid for the highest degree of exhaust gas cleaning.

In context of a planned expansion of the port areas environmental organisations have taken legal action against the Port of Rotterdam Authority (OECD, 2010e). To solve these disputes, alliances were concluded with two environmental organisations in the

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context of the environmental impact of the construction of Maasvlakte 2. These organisations stopped their legal actions against the Port Authority in exchange for environmental projects.

The following summarises the most relevant activities of the Port of Rotterdam which will affect seagoing ships. There will be an environmental differentiation regarding NO_X and SO_X emission of port dues which is being discussed under the revision of the current port due system. The reduction target set is 50 % in 2025 compared to 1990. As a start shore-side electricity for inland barges is being introduced. A pilot project will be up-scaled to all inland berths in the Rotterdam port area. (Measures affecting the port infrastructure or the hinterland traffics were not taken over from the original source)

Due to increased cargo volume to be handled at the port of Busan and its increasing impact on the environment the Korean government decided to develop Busan New Port 25 km from the city centre intending to convert the old port Busan North into a residential area later. In OECD (2010f) plans and measures are described how to reduce the environmental impact by improving the infrastructure for hinterland traffic, optimizing the cargo handling within the port, reducing CO_2 emissions by using electric rail mounted gantry cranes in the port or offering electric power supply for ships in the port.

Further to the regulations of MARPOL, from 1 January 2012, the sulphur content of fuel oil will be regulated in Korea as follows:

- The sulphur content of diesel is to be less than 1.0 %, however, the sulphur content of diesel used in ships operating only in territorial water and EEZ is to be less than 0.05 %,
- The sulphur content of heavy oil A, heavy oil B, heavy oil C is to be less than 2.0 %, 3.0 % and 4.5 % respectively.

The Marine Environment Management Law of Korea stipulates that fuel oil suppliers should submit the samples of fuel oil with the specification of fuel oil to the ship-owner. And the Korean Government officials will carry out ship inspections to check the oil samples and specification.

4.2 Control of Random Impacts

As mentioned in the introduction the impacts influencing a ship design can be divided into random impacts and systemic impacts. For each category tolerable values of responses of a structure are defined. These tolerable values can be allowable stresses, deformations with regard to structural strength, a defined safety against the ultimate collapse of the hull girder or ship accelerations or healing angles with regard to ship motions. In view of this assumption one can say that class rules deal with random impacts.

4.2.1 Class Rules

The purpose of a Classification Society, as put forward in the IACS Charter (IACS, 2009a), is to provide classification and statutory services and assistance to the maritime industry and regulatory bodies as regards maritime safety and pollution prevention, based on the accumulation of maritime knowledge and technology. The classification society verifies the structural strength of the ship hull as well as the reliability and function of the machinery systems, through the development and application of own rules and by verifying compliance with international and/or national statutory regulations on behalf of flag Administrations.

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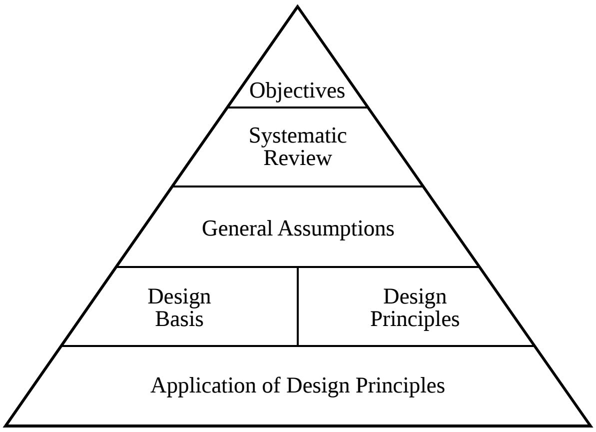

Figure 6: Rules framework

Classification Rules have been developed over many years by each classification society through extensive research and development and service experience and are subject to constant refinement. With the large number of ships in the world, the classification societies have had a very large amount of data to base the rule development on, and the safety level has been continuously increasing. In addition, Unified Requirements have been agreed by IACS Members and transposed into the individual members' rules. Statutory requirements developed at IMO are incorporated into class rules when appropriate, and where necessary Unified Interpretations of them are adopted by IACS.

However, to base the requirements for new ships on the experience from old ships does not necessarily promote innovation in ship design. With the introduction of goal-based standards, it is the role of the classification societies to develop specific rules that will meet the goals and functional requirements specified by IMO. It is the intention that the goals prescribed by IMO may be achieved by alternative designs that offer an equivalent level of safety, while promoting new technology and greater innovation within the shipping industry.

The CSR rules (IACS, 2006a,b) were the first attempt to develop new rules which would meet the objective of the Goal Based Standards. The CSR were developed based on a set of top-level goals and objectives, and a framework was made to show how the rule requirements would ensure that ships built in compliance with the rules meet the top-level goals and objectives, Figure 6. The framework of the Rules represents a 'top-down approach' that provides transparency and ensures that the structural requirements developed reflect the overall objectives.

The levels of the Rule framework address the following issues:

- the Objectives state the clear and unambiguous goals of the Rules with respect to safety and performance aspects. These objectives provide the basis for deriving the detailed structural acceptance criteria.
- the Systematic Review identifies and evaluates the hazards due to operational and environmental influences and the likely consequences of these on the structure of a ship, in order that these can be addressed in the Rules and thereby minimised.
- the General Assumptions specify aspects that are beyond the scope of the Rules,

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but affect the application and effectiveness of the rules. These include references to other international regulations and industry standards, e.g. SOLAS.

- the Design Basis specifies the premises that the Design Principles of the Rules are based on, in terms of design parameters and the assumptions about the ship operation.
- the Design Principles define the fundamental principles used for the structural requirements in the Rules with respect to loads, structural capacity and assessment criteria, to meet the hazards identified by the systematic review.
- the Application of the Design Principles describes what criteria are used to demonstrate that the structure meets the Objectives. It includes definition of load and capacity models, and corresponding acceptance criteria.

4.2.2 Rule Development

In order to demonstrate in a general way how classification societies should develop ship rules to meet the philosophy behind IMO Goal-Based New Ship Construction Standards, IACS recently developed a new Guideline for hull structural rule development (IACS, 2009b), which was submitted to IMO at MSC 86. The objective of the Guideline is to provide guidance, for any classification society that is a recognized organization, on the development of ship structural classification rules, by specifying general principles to be followed in the rule development process, as well as general design principles and requirements that should be considered when developing rules. The IACS Guideline provides a recommended process for classification structural rule development that will contribute to its consistency and transparency. The Guideline can be used to support new rule development and has been developed with the view that the rules should be in compliance with relevant aspects of Tier I and Tier II of the GBS.

The guideline also describes the relation between the class rules and the Maritime Safety Regime. The boundaries and relationships between rules and the Maritime Safety Regime follow a safety hierarchy with the Maritime Safety Regime at the top level. This regime regulates the design, construction and operation of ships through a diverse set of requirements including international and national Regulations and industry Standards, which may influence the ship structure rules.

The guideline emphasizes the importance of a systematic rule development process, where the overall safety objective is clearly identified before starting the development of the actual rule requirements. This should be followed by a Formal Safety Assessment (FSA), as described in the IMO Guidelines for Formal Safety Assessment (IMO, 2001) or a Systematic Review, which can be considered as a reduced version of a full FSA. The process generally follows from the complexity of the issue to be addressed in the rules, but should as a minimum include the following steps:

- Hazard identification
- Consequence evaluation
- Critical hazard management

According to the guideline, the rules are to be developed based on the following overall basic principles, where requirements to transparency, modularity and consistency are applied whenever possible:

- Structural safety can be demonstrated for all hazards identified for each design situations in the systematic review
- The structural safety can be demonstrated by utilising limit state methods

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- The design complies with the Design Basis
- Consistent load scenarios are applied to all aspects of the structural assessment
- Structural requirements with respect to loads, capacity models and assessment criteria are presented in a modular format, and each component is clearly identified
- Material properties are documented for high criticality class elements exposed to loads and service temperatures enhancing the risk for brittle fracture

The guideline specifies that the rules are to be based on the commonly known principles of limit state design. A limit state can be defined as a condition beyond which the structure, or part of a structure, no longer satisfies the requirements. The structural performance of the hull or components of it should generally be described with reference to a specified set of limit states that separate desired states of the structure from undesired states.

The rule requirements may be presented in various formats, or a combination of formats, depending on the nature of the specific requirement. Typical rule formats follow typical design methodologies. The working stress design (WSD) format is a practical format which has been used as the main method to verify the structural design in the rules. For certain critical failure modes, the Partial Factor Format (PFF) is used in order to increase the consistency of the safety level, and determine the actual safety margins with more accuracy. In the CSR Rules (IACS, 2006a,b), the PFF is used for the Ultimate Hull Girder Strength check. During the development of the rules, the partial safety factors were calibrated by Structural Reliability Analysis (SRA).

Rule requirements are usually expressed as a combination of prescriptive requirements and direct calculation requirements. The prescriptive requirements are in the form of minimum requirements and load-based prescriptive requirements. The minimum requirements are to a large degree developed based on experience, and are to cover effects that are not explicitly covered by other rule requirements. The load-based prescriptive requirements are normally used for most of the structural members, while direct calculation may be required for members where the load and structural response is difficult to assess accurately by simplified formulations.

Although ship rules are to a large degree prescriptive in the format, it is a basic principle that safety equivalence may be applied. Hence, innovative designs or alternative calculation methods may be accepted provided that calculations are carried out to demonstrate that the safety level is at least equivalent to a standard, well proven design.

4.2.3 Other Class Aspects

Traditionally, classification rules have been mostly concerned with the ship structural integrity, while safety for humans has been covered by regulatory requirements, in particular SOLAS requirements. However, there is not always a clear line between the two, and sometimes requirements related to human safety also affect the ship structure. Examples are requirements to Permanent Means of Access (PMA), bulwarks and guardrails.

There is also an ongoing discussion about how climate change may affect future ship traffic and ship design. Class Rules need to continuously include state-of-the art knowledge about meteorological (temperature, pressure, wind) and oceanographic (waves, current) conditions. Ship standards have been discussed increasingly by industry and academia in the last decades in several international forums. There are potential safety,

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economic, and environmental advantages in utilizing the recent knowledge about meteorological and oceanographic conditions (met-ocean conditions) and investigating its implication for design and operation of marine structures. Bitner-Gregersen *et al.* (2011) concluded that observed and projected changes in wave climate may have large impact on tanker design practice, and that class rules may need to be updated to reflect this. However, further studies are called for to describe and quantify potential implications of climate change on safe design

4.2.4 Rational Treatment of Accidental Scenarios for Hull Girder Verification

Accidental loads can also be categorised as random impacts. In context with the introduction of the Goal Based Standards class rules for the main types of ships will most probably be reformulated taking accidental scenarios into account. First steps are made with the Common Structural Rules (CSR) for oil tankers (IACS, 2010b) and bulk carriers (IACS, 2010a).

This important evolution can be seen as part of a wider trend towards the adoption of Performance Based Design (PBD) criteria, taking place also in other fields of engineering (see e.g. Rizzuto, 2009). In the development and assessment of the design, PBD criteria imply a clear identification of the objectives for the design itself and a consistent formulation of the checks that explicitly aim at attaining those objectives. These characteristics of the new formulations imply also the possibility of alternative check procedures by means of direct computations, based on the same explicit framework.

A key aspect of the performances identification is in fact the identification of the conditions in which the structure is meant to operate during its life, which are represented at a design level by design scenarios. Such design scenarios represent in principle in a discrete way the continuous spectrum of actual situations the structure will experience: in order to be effective, they need to be realistic and representative of significant situations.

When defining a reference scenario for structural checks, it is necessary to set a series of characteristics that later need to be quantified in terms of design scenario. These elements of the scenario should allow quantifying the strength and loading quantities that are at the basis of the check.

Design scenarios (or design situations, as they are named in CSR-Tankers: IACS, 2010b) have always been behind the formulation of structural checks in Rules for ship construction. However, only in the recent formulations of Class Rules and in conjunction with the Goal Based reconsideration of the normative framework in ship design at IMO, an explicit identification of design scenarios started to appear in Rules (see Rizzo and Rizzuto, 2007). The trend can also be seen as connected with the increasing use of direct computations and direct applications of first principles to the design process, which in turn are aspects of the implementation of Performance Based Design criteria (Rizzuto, 2009).

For an intact tanker ship, design scenarios for hull girder checks are quite well defined in IACS (2010b). Even though the single elements of this reference scenario can be improved in terms of details and/or in terms of realism, a framework for the scenario description is present and direct computations coherent with the scenario can in principle (and in practice) be performed.

Checks for the hull girder strength in accidental conditions are also covered in the recent CSR, even though without reference to a precise scenario. In the text, however, accidental conditions are always associated to flooding.

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In IACS (2010b), the effects of the flooding on the hull girder still water bending moments are evaluated by considering the cargo holds as being individually flooded up to the equilibrium waterline in all the loading conditions on which the design of the ship has been based. The envelope obtained for any combination of considered loading conditions and flooded cargo holds is assumed for the check. Wave loads are modelled with 80 % of the intact ship design bending moment, corresponding to the IACS UR S11 (IACS, 2001).

No particular justification is provided for this quantification of the wave load, which would correspond to a return period of about half year for the intact ship. The scenario includes therefore a realistic static load and a not negligible, but notional, dynamic load. The capacity to be checked is the intact one.

No specific check is available for the longitudinal strength of damaged tankers, according to the provisions of section 9-1 in CSR-Tankers (IACS, 2010b): only static local loads corresponding to the draught in the flooded condition are applied in this scenario (see also section 2-4.2.7 of IACS, 2010b).

The variety of damage states, depending on type, location and extension of the damage enlarges considerably the space of possible accidental conditions that in principle need to be considered in the design. A natural evolution in the definition of the damage state is the adoption of probabilistic models that can weigh the various scenarios according to their probability of occurrence.

In shipbuilding, accidental conditions are since long included in the verification of buoyancy and stability performances of the ship. The concept itself of subdivision of the hull in watertight compartments is based on a damage scenario, and, as known, the first Design Norms on this subject date back to the establishment of IMO and the first issue of the SOLAS convention. Also the introduction of probabilistic methods was earlier realised in the framework of the assessment of damage stability of ships and has later spread to the assessment of the environmental impact due to accidents. Curiously enough, a probabilistic description of the accidental scenarios is still lacking in structural design, where, on the opposite, probabilistic methods have a long-standing tradition in the assessment of intact systems (probabilistic definition of loads and reliability assessment of structures).

The problem of a proper characterization of a design scenario in accidental conditions for the hull girder verification has been recently discussed by Luís *et al.* (2009), Teixeira and Guedes Soares (2010) and Rizzuto *et al.* (2010). In particular Rizzuto *et al.* (2010) have examined the various elements that an effective characterisation of a design scenario for a ship in damage conditions should include, highlighting the need for a proper accounting of the relationships among such elements. The dependencies on the damage extension and position of the corresponding static and dynamic loads and of the residual structural capacity of the ship were discussed, as well as the key point of the correlation between the environmental conditions during the accident (and in the immediate aftermath). Such a complexity has been illustrated by means of Bayesian Networks (Jensen, 2001) that have also provided quantitative results for comparative evaluations in a very specific scenario.

Even though the specificity of the analysis developed by Rizzuto *et al.* (2010) did not allow any firm conclusion on the selection of a design scenario for grounding events, the work intended to give a contribution from a procedural point of view for a better treatment of accidental situations in the formulation of design checks in accidental conditions.

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4.2.5 Stability

Requirements to stability have to large extent been developed following accidents. Stability requirements concern the relevant requirements to the intact ship and requirements to the ship when subject to damage and subsequent flooding.

The requirements to intact stability shall ensure that the ship does not capsize under any circumstance of normal operation and environmental conditions that might be expected. The intact stability was traditionally handled by IMO as a Code which in effect was voluntary as it was outside the scope of the Conventions. Its applicability was therefore subject to the decision of the flag state. This could lead to different standards depending on the flag state, and IACS introduced in 1988 compliance with the IMO Intact code as a Unified Requirement. From 2009 the IMO Intact code has been made mandatory by amendments to SOLAS and the International Convention on Load Lines (ICLL).

Damage stability has traditionally been part of the conventions. In the earliest versions of SOLAS there were damage stability requirements to passenger ships and later this was followed by requirements to cargo ships having a reduced freeboard in accordance with the ICLL. All mandatory damage stability requirements up to 1992 were of the deterministic type, i.e. requirements in the form of specific damage extent assumptions and corresponding criteria for survival.

Given the stochastic nature of e.g. a damage following a collision the deterministic requirements can in theory not be seen as to cover a known safety level.

By introduction of the probabilistic rule concept for cargo ships in SOLAS from 1992 there was in place a methodology that could reflect the capability of the vessel to survive a damage following a collision without setting deterministic requirements to location of bulkheads. In the probabilistic concept the ships attained index A, shall then be greater than the required level R. The attained index A is the sum of all possible damage cases, having a probability factor derived from statistics multiplied with their respective probability for survival. The level of R has been based on calculations carried out of sample ships of different size and types. The probabilistic concept was introduced to passenger ships by SOLAS amendments coming into force in 2009 following the work of the HARDER project (Rusaas, 2003).

The EU funded project GoalDS started up in 2009. GoalDS is an acronym for **Goal** based **D**amage **S**tability. In the EU funded project SAFEDOR, Formal Safety Assessments were carried out for several ship types including Cruise ships and Ro-Pax. This was also reported to IMO, see ref. (IMO, 2008b) and (IMO, 2008c). In these reports it was concluded that the safety level of both ships types could be increased by implementing Risk Control Options cost efficiently in accordance with the FSA guidelines, and this was one of the motivations for establishing the GoalDS project.

The GoalDS project consists of the following major parts:

- Characteristics of collision and grounding damages (statistical distribution)
- Probability for survival collision and grounding damages
- Standard risk models for collision and grounding
- Propose level of required R based on cost benefit analyses
- Following a careful validation of results forward proposal to IMO

The basic probability distribution for extent of damage due to collision or grounding has been established by search in accident databases and class records. The probability for survival has been based on numerical simulations and model tests.

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In order to have a basis for proposing the level of R as new rules it is necessary to have sample of ships that is representative for the range of size and types that the proposed rules shall cover. Additionally, yard's and operator's experience are of invaluable importance in order to estimate cost and benefits of Risk Control Options.

Freedom in Design

The cruise and Ro-Pax ship segment covers a big variation in size and designs. There are clear benefits for the operator when a set of rules that represents a safety level instead of prescriptive requirements can be applied. The ship can be designed to reflect the intended needs for a specific operation. Damage stability requirements based on the probabilistic concept are very well suited to fit into a risk based rules. This would however not rule out that prescriptive requirements in addition introduced in order to account for a specific hazard.

Future Development

A project such as GoalDS can also be repeated for ship types other than Cruise and Ro-Pax. Following the IMO FSA Guidelines ensures a transparent process in the rule development process and should eliminate that some decisions are taken that are not properly based on the relevant considerations of risks.

4.3 Control of Systemic Impacts

Acceptance of systemic impacts has changed during the last years all over the world. As a consequence regulatory bodies have implemented regulations to control these impacts caused by ballast water and air pollution. The recent regulatory activities of the IMO regarding energy efficiency can be seen under two aspects. Firstly the decreasing reserves of fossil fuels force us to minimize their consumption secondly the reduction of fuel consumption leads to a reduction of air pollution. The following three subsections will describe measures to control these impacts

4.3.1 Ballast Water

Invasions of marine species to new environments are often aided by human activities among which the shipping industry is one of the major, but unintentional, vectors. Ships can provide suitable platform for transportation of marine species in the form of attaching to the ship's hull/sea chest and also being transported, at different life cycle stage, through ballast water (Bax *et al.*, 2003; Anil, 2006). Research on the subject showed that shipping, on average, is responsible for 25 % and 52 % of introductions of Non-indigenous species (NIS) into European waters (Stretaris *et al.*, 2005) and coastal waters in the North America (Fofonoff *et al.*, 2003) respectively. Cleaner ballast tanks, increased ship's transit speeds and improved management of ports have made ballast tanks of commercial ships a hospitable means of transport throughout the world (Bax *et al.*, 2003). It has been estimated that approximately 3.5 billion tonnes of ballast water are transported annually (Endresen *et al.*, 2004). There is, therefore, a vital need for mitigating technology to be developed to manage/prevent this constant movement of organisms to new areas, where they are establishing populations to the detriment of the local flora and fauna.

The major advancement in managing ballast water came in 2004 when the 'International Convention for the Control and Management of Ships' Ballast Water and Sediments' was formed by the IMO. Two key standards were determined as part of this convention: the Ballast Water Exchange Standard (Regulation D-1) and the Ballast Water Performance Standard (Regulation D-2). Regulation D-2 (D-2 discharge

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standard) states the limit of the allowable number of viable organisms that can be discharged from the ships (IMO, 2004b). The determination and publication of Regulation D-2 was extremely important in terms of developing new ballast water treatments as the industry was given an efficiency standard to meet. This convention will enter into force 12 months after it has been ratified by 30 states which represent 35 % of the world's merchant shipping tonnage (IMO, 2004b). However, 33 states representing approx 26.5 % of the world's tonnage have currently (Feb. 2012) ratified the convention.

Since adoption of the Convention, research and industry have been working to find effective systems capable of meeting the D-2 discharge standard for when the convention enters into force. There are two generic types of technology (Figure 7) used in ballast water treatment. Since mid 2001, Newcastle University has been extensively involved in the ballast water treatment research through two European funded projects, MARTOP and BaWaPla, under the 5th and 6th framework programmes. The main aim of these projects was to promote the knowledge and help related industry in the development of sustainable ballast water treatment system.

By 2010 nine treatment systems have received IMO type approval certification and it is also expected that nine other treatment technologies to receive their type approval by 2012 (Lloyds Register, 2010).

Although there are several type approved treatment technologies available in the market, but some challenges such as online measurement of the performance of treatment systems, sampling regime that is representative of discharged ballast water and enforcement of the Convention, do exist and need to be attempted.

Compliance with standards is essential for effective implementation of any environmental regulation. Sampling, as well as adequate inspection and monitoring, are

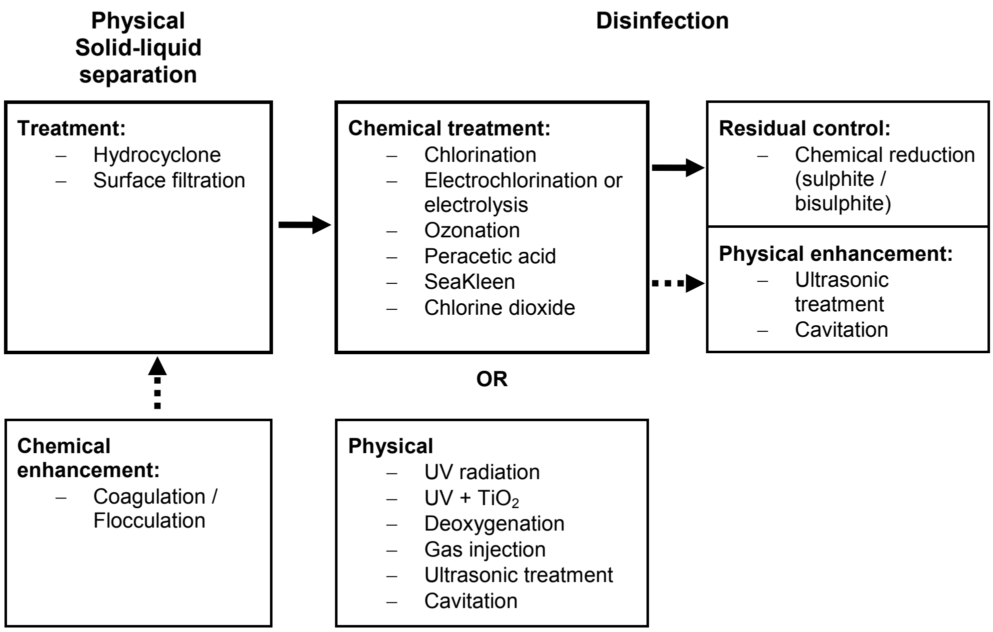

Figure 7: Generic ballast water treatment technology process option (Lloyds Register, 2010)

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equally essential in any environmental pollution control or prevention policy (RCEP, 1998). To ensure ships ballast discharges meet Regulation D-2, sampling is required to determine the number of viable organisms present in the ballast water (Pazouki *et al.* 2009). In addition according to the G2 guideline of the Convention those samples, used to determine a ship's compliance, must be 'representative' of the 'whole' ballast water to be discharged (IMO, 2008d). Representativeness of ballast water samples has not, however, yet been discussed clearly and while G2 guideline states that representative samples are required it does not provide clear guidelines on how to obtain these samples. Pazouki *et al.* (2009) have defined and acknowledged in their work that the samples collected for the enforcement of the Convention must be both statistically and biologically representative. Obtaining samples which fulfil both of these objectives is extremely difficult to achieve. Basurko and Mesbahi (2011) and Miller *et al.* (2011) have proposed, using different statistical approaches, to determine the volume of water required for statistical representation. The results in each study, however, vary widely, highlighting the lack of standard approach.

Currently, organisations from the UK, BE, NL, DE, DK, NO and SE are involved as partner or sub-partner in a project for regional cohesion, innovation and future strategies in ballast water policies and management. The aim of the project is to focus on Coherence and harmonisation for implementation, monitoring and enforcement of the ballast water Convention as well as development of future strategies to reduce ship-borne biological invasions.

4.3.2 Air Pollution by Ships

Marine engines, in order to be cost effective, operate on extremely low-grade fuel with high sulphur and aromatic content. Other form of transportation both land and air based systems use quite different and better quality fuels. Burning low quality fuel causes harmful emissions from ships, which eventually leads to acid rain, global climate change, particularly over oceans and damaging public health for those communities living near major port areas (Pazouki, 2002).

An important step in the control of emissions from ships came in May 2004 with the ratification of Annex VI of the MARPOL 73/78 Convention and subsequently entered into force in 19th of May 2005. The regulations in the annex set limits on sulphur oxide and nitrogen oxide emissions from ship exhaust as well as particulate matter and prohibits deliberate emissions of ozone depleting substances. From May 2005, all large ships built after January 2000 trading in international waters have to use marine fuels containing no more than 4.5 % sulphur, or no more than 1.5 % sulphur in SECA (Sulphur Emission Control Areas), and comply with the IMO Tier I NO_X limit valid for nominal engine speed (CNSS website and references therein).

Despite of the concerns about emissions from ships, demand for global shipping has steadily risen as international trade has increased. From 2000 to 2007, the volume (in tons) of world exports increased by 5.5 %, on average, annually. Interestingly, over 80 % of that trade has been transported via shipping (WTO, 2008; UNCTAD, 2008).

While legislation is in force, the increasing trend in transportation of goods by shipping will offset the positive environmental impact of enforced regulations and will lead to further growth in ship emissions. In this respect, in 2008 IMO agreed on stricter measures that can significantly reduce ships' emissions, Table 3 shows the first and recent regulations for NO_X and SO_X of annex VI (IMO, 2008e).

Climate change is the other concern of regulatory bodies and environmentalists. Maritime shipping is estimated to represent around 3 % of worldwide GHG emissions.

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Table 3: MARPOL ANNEX VI Regulations for NO_X and Sulphur (IMO, 2008e)

NOx – Regulations				Sulphur Regulations		
	Diesel engines installed on ships	Engine speed (n) in rpm	Max. allow. NO_X emissions in g/kWh		SECA	Global
Tier I (engine based controls)	1 Jan. 2000 to 1 Jan. 2011	< 130	17.0	2000	1.5 %	4.5 %
		$130 \leq n \leq 2000$	$45.0 \cdot n^{-0.2}$	2010	1.0 %	
		$n \geq 2000$	9.8	2012		3.5 %
Tier II (engine based controls)	After 1 Jan. 2011	< 130	14.4	2015	0.1 %	
		$130 \leq n \leq 2000$	$44.0 \cdot n^{-0.23}$	2020 [a]		0.5 %
		$n \geq 2000$	7.7	[a] Alternative date is 2025, to be decided by a review in 2018		
Tier III	After 1 Jan 2011 when operating in ECA	< 130	3.4			
		$130 \leq n \leq 2000$	$9.0 \cdot n^{-0.2}$			
		≥ 2000	2.0			

Due to the expected growth of international trade, maritime emissions are expected to increase by a factor of 2-3 in 2050 if no action is taken.

The European Union has committed to a 20 % reduction in GHG emissions by 2020, compared to 1990, and the Commission also gave its commitment to reduce shipping emissions by 40–50 % by 2050, compared to 2005 in the recently published transport White Paper (EC, 2011).

Currently there are some measures and mitigating technologies available that reduce the ships' emissions. In Table 4 an overview of different measures and their reduction

Table 4: Measures for the reduction of air pollutants from ships and their reduction potential (http://cleantech.cnss.no)

Category	Technology aimed to reduce	NO_X	SO_X	CO_X	PM
	NO_X				
Water addition	Direct Water Injection	max. 60 %		+0-2 %	Max. 50 %
	Exhaust Gas Recirculation	20-85 %			
	Humid Air Motors	20-80 %			
	Combustion Air Saturation System	30-60 %			
	Water in fuel (e.g. 20 % emulsion)	20 %			40-60 %
Engine modification	Internal Engine Modification				
	- slide valves	20 %			Probably reduced
	- advanced measures	30-40 %			Probably reduced
After treatment	Selective catalytic Reduction	90-99 %			25-40 %
	SO_X				
	Scrubber		90-95 %		80-85 %
(Alternative) fuels	Low Sulphur Fuel 2.7 %S to 0.5 %S		80 %		20 %
	Both NO_X and SO_X				
	LNG	60 %	90-100 %	0-25 %	72 %
	Onshore Power Supply (in harbour only)	90 %	90 %	Depending on energy source	90 %

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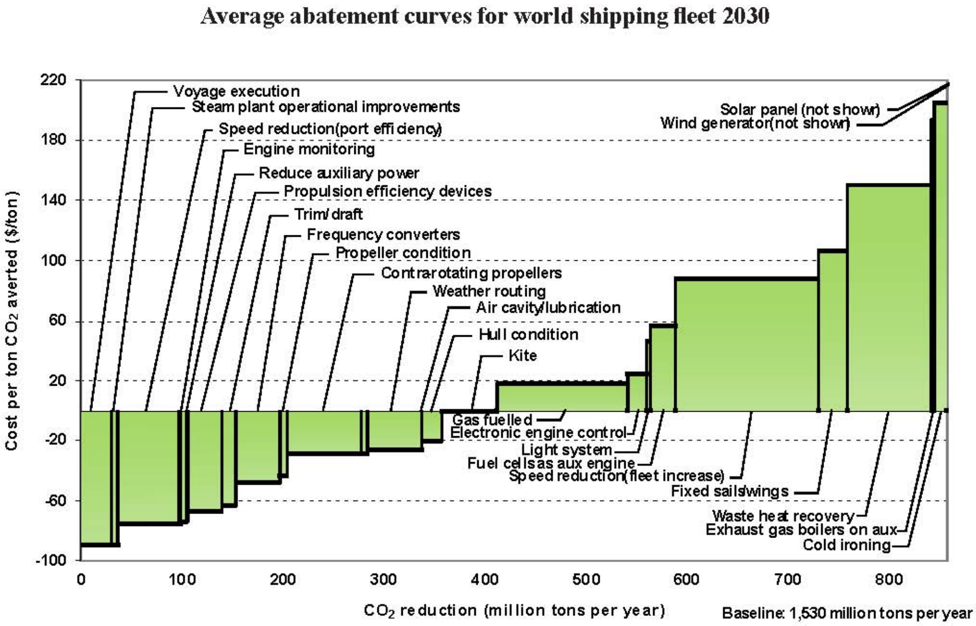

Figure 8: Overview of potential measures and reduction costs (DNV, 2010)

potential is shown. Not every technology is fully developed and ready to be applied on a large scale. Some technologies are still expensive to install or face practical barriers. Figure 8 also shows the CO_2 reduction potential of the 17 technical and 8 operational measures, including the cost of CO_2 reduction.

Currently, 18 partners across the countries around the North Sea region are involved in a project called Clean North Sea Shipping (CNSS). The aims of project are:

- Reduction of air pollution and GHG emission from shipping
- Research and application of existing and new technologies, methods and infrastructure
- For cost-effective and cleaner energy supply and usage for ships

The outcomes of this project are:

- To inform regional policy building - promote "clean shipping" Technology.
- To provide input to the implementation of EU, national and regional regulations.
- The promotion and implementation of Environmental Ship Index and incentives for "Clean Shipping Technology".

4.3.3 Energy Efficiency

As already mentioned above, MEPC made further progress in developing measures to improve the energy efficiency of ships in order to reduce GHG emissions from international shipping.

Currently IMO has developed two technical and operational measures for the primary assessment (and eventual control) of emissions from shipping, the Energy Efficiency Design Index (EEDI); and the Energy Efficiency Operational Index (EEOI) which assess the design and operational performance of a ship against a curve of achievable performance generated from the existing ship population.

The EEDI establishes a minimum energy efficiency requirement for new ships depending on ship type and size and is a robust mechanism to increase the energy efficiency

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of ships in the future (IMO, 2009a,b). The EEDI is a non-prescriptive, performance-based mechanism that leaves the choice of technologies to use in a specific ship design to the industry. As long as the required energy-efficiency level is attained, ship designers and builders would be free to use the most cost-efficient solutions for the ship to comply with the regulations. Thus EEDI will stimulate innovation and technical development of all the elements influencing the energy efficiency of a ship.

However, as is common practice in all IMO technical standards, EEDI will affect only new buildings and therefore, as the economic life of a ship can be 25–30 years it may take decades for the policy to sort any effect on the sector's GHG emissions (Faber *et al.*, 2009).

On the operational side, a mandatory management tool for energy efficient ship operation, the Ship Energy Efficiency Management Plan (SEEMP), has been developed by IMO (IMO, 2009c). The SEEMP establishes a mechanism for a shipping company and/or a ship to improve the energy efficiency of ship operations. The SEEMP provides an approach for monitoring ship and fleet efficiency performance over time using the EEOI as a monitoring tool and serves as a benchmark tool (IMO, 2009d). The SEEMP urges the ship owner and operator at each stage of the plan to consider new technologies and practices when seeking to optimize the performance of a ship. The Second IMO GHG Study 2009 indicates that a 20 % reduction on a tonne-mile basis by mainly operational measures is possible and would be cost-effective even with higher fuel prices than those currently experienced.

Development of the technical and operational measures is a very important step in ensuring that the global shipping industry has the necessary mechanisms to reduce its GHG emissions. However, these measures would not be sufficient to satisfactorily reduce the amount of GHG emissions from international shipping in view of the growth projections of world trade. Therefore, market-based mechanisms have been considered by MEPC.

A market-based mechanism would serve two main purposes: 1) off-setting in other sectors of growing ship emissions (out of sector reduction); and 2) providing an economic incentive for the maritime industry to invest in more fuel-efficient ships and technologies and to operate ships in a more energy-efficient manner (in sector reductions).

At present, several market-based measures are under discussion within MEPC, recently analyzed by Miola *et al.* (2011). In particular ten proposals for market-based measures have been discussed in MEPC 61on the basis of an assessment carried out by an Expert Group that has evaluated the proposals on the basis of nine criteria such as environmental and cost-effectiveness, impacts on trade innovation and technological change, etc (IMO, 2010). However, no decision was officially taken. The IMO GHG Working group will report on its conclusion on market-based measures during the MEPC 62.

5 RECENT DEVELOPMENT OF THE IMO GOAL BASED STANDARDS (GBS)

5.1 Present State of GBS Implementation at IMO

5.1.1 Goal Based Standards for Tankers and Bulk Carriers

During the work of this committee the discussion of GBS continued at the Maritime Safety Committee (MSC) of IMO. The progress will be described in the sequence of MSC sessions.

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During MSC 86 (IMO, 2009e) the process of verification of rules, as defined under Tier III, for their compliance with the goals was discussed. First discussion of the related guideline and the assignment of responsibilities took place during that session. Further possible consequences regarding costs of the verification process, the resource implications of the process were discussed. In this context a legal aspect raised in (IMO, 2009f) is worth to be mentioned. Who will be responsible for the rules? It is mentioned that rule developers might shift their responsibility for the rules towards the IMO after IMO have approved the rules being compliant with the GBS which were developed by IMO. This leads to another supporting argument that IMO should only assess the self-assessment and the rule developing process of the rule developers in the course of an audit.

Further the possible content of the Ship Construction File is a matter of concern regarding the intellectual property rights; see (IMO, 2009g). The intention of the ship construction file (SCF) is to provide information about the design of the ship to ensure a safe operation and maintenance of the ship during the ship's lifetime and the information shall be available in case of emergency situations. As this information possibly give an insight into the design criteria of the shipyards including their approach how to design the structure including the load assumptions and their calculation methods the shipbuilders during the discussion raise concerns that their intellectual properties might be violated if too many detail information would be available on board. To take care of the concerns a workgroup was formed to balance the interests of the industry stakeholders. The document provides a progress report on a cross industry project that may assist the finalization of Guidelines for information to be included in a Ship Construction File, taking into consideration the protection of intellectual property. A future guideline for the SCF shall be based on following principles:

- The SCF is a mandatory set of documents linked to the ship from delivery until the recycling.
- Ship owners must have access to documentation for safe operation of the vessel, including maintenance, repair and for emergency situations.
- The concept of property (with regard to intellectual property), its importance and impact shall be recognized.
- The SCF provisions must address safe operation of the ship and the concept of property, as above.
- All necessary structural safety information shall be available throughout the lifetime of the vessel, along with the obligation of respecting the IP protection principles.
- Availability of supplementary structural information, not related to the safe operation, maintenance and repair of the ship may be subject to commercial agreements.

During MSC 87 the GBS for oil tankers and bulk carriers were adopted (IMO, 2010d). Accordingly newly-constructed vessels will have to comply with standards conforming to functional requirements developed by MSC. This is the first time that IMO has set up standards for ship construction. The GBS were formally adopted as an amendment to SOLAS, the new regulation II-1/3-10.

During the same session MSC adopted guidelines that establish procedures to be followed in order to verify that design standards or classification rules of recognized organisations submitted to IMO conform to the GBS (IMO, 2010e). The verification process consists of two elements: self assessment of the rules by the submitting or-

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ganization, followed by an audit of the rules and the self assessment, carried out by experts appointed by IMO.

In continuation of the discussions at MSC 86, MSC 87 approves the Guidelines for the information to be included in the Ship Construction File (IMO, 2010f) aiming at providing additional guidance on the application of the requirements in SOLAS regulation II-1/3-10. For details of the discussion of intellectual property rights see also (IMO, 2010g,h)

According to the guideline the SCF should remain with the ship and, in addition, be available to its classification society and flag State throughout the ship's life. Where information not considered necessary to be on board is stored ashore, procedures to access this information should be specified in the onboard SCF. The intellectual property provisions within the SCF should be duly complied with.

The appendix of the resolution lists all the information to be included in the SCF related to 14 Tier II functional requirements of the GBS. Among those are requirements regarding design, construction, in-service considerations. The information regarding structural strength of the ship is listed in Table 5 and gives an impression of the degree of detail. With this IMO for the first time have set standards on the information to be kept on board

5.1.2 Safety Level Approach

This section gives an overview of developments related to the Safety level approach in a wider sense. First the status of the ongoing IMO activities on goal based standards is described. Because risk based designs and their approval can be seen as part of the safety level approach and formal safety assessments (FSA) are mentioned as possible methods to determine the risk level of a given system and to evaluate the effectiveness of risk control options both will be described under this section.

Preceding the adoption of the GBS for Tankers and Bulk Carriers which are of prescriptive nature there was a discussion of the safety level approach (SLA) as a possible alternative to the prescriptive GBS. At MSC 87 it was agreed to continue working on the GBS and to further develop the SLA.

Proposals how to develop the SLA were made by Germany and Korea by submitting two papers to MSC 88 (IMO 2010i,j)) which supplement each other. Both papers propose to continue the work on the SLA and describe the importance of the determination of the current safety level of existing rules and regulations, determination of target safety levels for future regulations and the monitoring thereof. Formal safety assessment and structural reliability analysis are seen as tools to support the development of safety level based regulations. Continuation of the work of MSC shall lead to Guidelines for GBS to a degree suitable for the preparation of regulations for future safety-level based standards within current or future review processes (definition of goals and functional requirements, etc.), taking into consideration recent experiences, e.g., in the discussions of the IGF Code and the International Code of safety for ships operating in polar waters. Further it is to be clarified how the acceptable safety level should be specified and to specify the model to determine the safety level of standards. In this context target safety levels for all the failure modes of ship structures, limit state equations for their failure modes are to be defined and probabilistic characteristics of random variables and guidelines for defining the characteristics of random variables.

MSC 88 also acknowledged that this would be a longer term project during which a number of unresolved issues needed to be considered, such as the role of FSA in the

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Table 5: Content of the SCF (IMO, 2010f)

Tier II item		Information to be included	Further explanation of the content	Example documents	Normal storage location
3	Structural Strength				
3.1	General Design	• applied Rule (date and revision) • applied alternative to Rule	• applied design method alternative to Rule and subject structure(s)	• SCF-specific	on board ship
3.2	Deformation and failure modes	• calculating conditions and results; • assumed loading conditions • operational restrictions due to structural strength	• allowable loading pattern • maximum allowable hull girder bending moment and shear force • maximum allowable cargo density or storage factor	• capacity plan	on board ship
				• loading manual	on board ship
3.3	Ultimate Strength			• trim and stability booklet	on board ship
3.4	Safety Margins			• loading instrument instruction manual	on board ship
				• operation and maintenance manuals	on board ship
		• strength calculation results • gross hull girder section modulus • minimum hull girder section modulus along the length of the ship to be maintained throughout the ship's life	• bulky output of strength Calculation • plan showing highly stressed areas prone to yielding and/or buckling	• strength calculation	on shore archive
				• areas prone to yielding and/or buckling	on board ship
				• general arrangement	on board ship
				• key construction plans	on board ship
		• gross scantlings of structural constituent parts • net scantlings of structural constituent parts	• structural drawings • rudder and stern frame • structural details of typical members	• rudder and rudder stock	on board ship
				• structural details	on board ship
				• yard plans	on shore archive
				• dangerous area plan	on board ship
		• hull form	• hull form information indicated in key construction plans	• lines plan	on shore archive
			• hull form data stored within an onboard computer necessary for trim and stability and longitudinal strength calculations	or equivalent	on board ship

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Table 5: Content of the SCF (IMO, 2010f) – continued

Tier II item		Information to be included	Further explanation of the content	Example documents	Normal storage location
4	Fatigue life	• applied Rule (date and revision) • applied alternative to Rule	• applied design method alternative to Rule and subject structure(s)	• SCF-specific	on board ship
		• calculating conditions and results; • assumed loading conditions	• assumed loading conditions and rates	• structural details	on board ship
		• fatigue life calculation results	• bulky output of fatigue life Calculation • plan showing areas prone to fatigue	• fatigue life calculation • areas prone to fatigue	on shore archive on board ship
5	Residual Strength	• applied Rule (date and revision)		• SCF-specific on board ship	

context of GBS, the availability of relevant data and statistics and the expansion of the scope beyond structural requirements. A GBS/FSA Working Group is established to discuss the development starting from a summary of the preceding discussion of SLA at various MSC meetings (IMO, 2011).

As a result of this discussion MSC 89 approves generic guidelines (IMO 2011a) that for the first time provide a process for the development, verification, implementation and monitoring of goal-based standards (GBS) to support regulatory development within IMO. In addition to the agreed system of tiers of the GBS the guideline clearly describes the scope of the verification process and the scope of documentation necessary for the verification process. Further a system of monitoring the effectiveness of goals and requirements is introduced together with the responsibilities for their monitoring.

There will be two monitoring processes, the monitoring of the effectiveness of single rules/regulations on the one hand and the monitoring of the effectiveness of the goals (Tier I) and the functional requirements (Tier II) on the other hand.

According to the guideline the monitoring responsibilities should be assigned as follows: For Tier I, the monitoring (including data collection), the analysis lies with the IMO the evaluation with the committees. For Tier II the monitoring (including data collection), analysis and evaluation lies with the Sub-Committees. For Tier IV the responsibility for monitoring and analysing the Rules and requirements lies with the rule maker under supervision of the IMO. Requirement under Tier IV developed by IMO will be monitored and analysed by IMO/Sub-Committees. The Monitoring will be based on the collection and evaluation of statistical data that are representative for the maritime industry.

With this guideline a unified structure for future regulations developed by IMO is introduced for the first time. Possible differences in the structure may be regarded as editorial difference only. However, in order to achieve a homogenous structure of future goal-based regulations, a section is added to the Guidelines providing generic guidance for the revision or development of IMO regulations, in particular considering the generation of goals and functional requirements as well as a generic structure.

Earlier in this discussion a guideline on approval of risk based ship designs was sub-

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mitted to MSC (IMO 2009h) which can be seen as the first document comprehensively describing the process of the risk analyses and the approval. It presents a high level process which can be well adjusted to the individual type of analysis. The document considers all parties involved as there are shipyard, producer, owner, risk analyst and the flag state, it describes their tasks and it gives advice at which step of the process each party should be active in the process. It recommends that flag state and design team clearly specify the scope of the risk analysis based on a first design review. Experience with risk analysis projects shows that this recommendation had not been followed with negative impact on the result and acceptance of the analysis. Further the guideline gives support on how to estimate the scope of the analysis depending on the degree of innovation of the proposed design. The guideline generally assumes that a risk analysis consists of two parts (one for the first design, the second for the final design) and that the design team (shipyard, owner, producer, risk analyst) do a hazard identification and a quantitative risk analysis.

In practical application of the process some times one of the steps might be omitted. However, that seems to be not a problem for the proposed process. The process described in the guideline seems to be flexible enough to cover such kind of deviations, thus one can say the process is sufficiently robust to be adjusted to individual analysis tasks.

During the previous period of this committee 5 FSAs, one each for Container Vessels (IMO, 2007b), LNG Carriers (IMO, 2007c), Cruise Ships (IMO, 2008b), Ro-Pax Ships (IMO, 2008c) and Crude Oil Tankers (IMO, 2008d) were submitted to MSC and MEPC for their consideration. An extensive FSA on General Cargo Ships followed in 2010 (IMO, 2010c). Following the submission MSC established the FSA Expert Group in which three members of this committee participated. The Expert Group, according to the following terms of reference, had to

- consider whether the methodology was applied in accordance with the FSA Guidelines and the Guidance on the use of HEAP and FSA;
- check the reasonableness of the assumptions and whether the scenarios adequately addressed the issues involved;
- check the validity of the input data and its transparency (e.g., historical data, comprehensiveness, availability of data, etc.);
- check whether risk control options and their interdependence were properly evaluated and supported by the assessment;
- check whether uncertainty and sensitivity issues have been properly addressed in the FSA study;
- check whether the scope of the assessment was met in the FSA study; and
- check whether expertise of participants in the FSA study was sufficient for the range of subjects under consideration.

The Expert group comes to the result that the FSA were done in accordance with the guidelines in general and show no major deficiencies. However, it can be observed that the recommended risk control options are similar in each case regardless of the ship type and mainly recommend improvements of the navigational equipment or training of personnel. As a consequence the discussion of the Expert Group is dominated by a discussion of the quality of available casualty data which form the basis of the hazard identification. Major concern is raised regarding the documentation of the root causes of accidents. Further to the above the degree of detail of the documentation of the risk analysis or the selection of experts participating in HAZID sessions are a matter

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of discussion. The report of the Expert Group (IMO, 2010k) finally recommends that a revision of the FSA guidelines should cover the following matters:

- description/discussion of experts participation in FSAs (i.e. expansion of specification for 10.1.5 of the FSA Guidelines);
- description of the structure, selection and composition of the project team, HAZID team and any other team, if established for taking any decision making (i.e. expansion of specification of 10.1.5 of the FSA Guidelines);
- information and analysis on root causes and details of casualties, with a view to obtaining RCOs focused on prevention rather than mitigation;
- development of risk models;
- unification of terminologies;
- reporting the method and justification for the final selection of RCOs;
- indices for cost-benefit analysis for risks other than safety of life;
- clarification on the use of NCAF and GCAF;
- methodologies to analyse possible side effect of RCOs;
- methodologies for sensitivity and uncertainty analysis;
- consideration of the human element (to have more detailed and specific guidance);
- methodologies to reach the consensus or agreement as well as reporting the degree of agreement, or concordance;
- how to present reports; and
- how to review FSA studies.

Following this report MSC establishes a Correspondence Group which work is still progressing at the time this report is written.

5.2 IACS Implementation of GBS (Ongoing Development)

The members of IACS are currently working on the harmonisation of the Common Structural Rules (CSR) for Oil Tankers and Bulk Carries. The CSR published in 2006 have been two sets each to be individually applied for Tankers or Bulk Carriers. In the context of the development of GBS this can be seen as a first step towards a single set of Rules that contain the basic principles for both ship types together with the individual requirements for both ship types. According to the five tier approach of GBS these rules have to be verified for compliance with the goals and functional requirements as defined as defined under tier 1 and 2. The Rules will be submitted to IMO for verification by the end of 2013 together with a set of background documentation describing the compliance with the GBS. An audit team consisting of experts nominated by the IMO member states will then carry out the review until May 2016. Finally the GBS will enter into force and will have to be applied for new designs of tankers and bulk carriers of 150 m in length and above:

- For which the building contract is placed on or after 1 July 2016;
- In absence of a building contract, the keels of which are laid or which are at a similar stage of construction on or after 1 July 2017; or
- The delivery of which is on or after 1 July 2020.

5.2.1 Ultimate Hull Girder Strength

In order to ensure sufficient structural safety for a ship structure throughout the lifetime, it is necessary to carefully identify all the threats the ship may encounter (IACS, 2006b, Sect. 2). A systematic review is carried out to identify hazards that may cause structural failure or lead to increased chance of additional hazards and

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progressive collapse. In risk based rules the proper balance between probability of failure and consequences of failure is sought for. High consequences of failure call for a low probability of failure whereas low consequences allow for a higher probability.

Failure of the hull girder, which is the top level of the ship structural hierarchy, is the most critical failure mode for a ship, and an explicit check of the hull girder ultimate strength is therefore included in the CSR. It turns out that in most cases sufficient hull girder strength is already obtained after the local strength requirements for structural elements at lower levels in the hierarchy are met, including fatigue. However, with increasing ship lengths and/or changes in the design, a verification of the hull girder check is clearly important.

The hull girder check was calibrated by the use of structural reliability analysis (SRA), ref. (IACS, 2006b, Sect. 9.1). This was done to:

- Ensure a consistent safety level for the ships designed according to the rules; i.e. minimise the scatter in safety level between ships
- Support the choice of design equation; i.e. the formulation of strength being greater than the load effects
- Support the specification of the characteristic values in the design equation; i.e. wave moment, still water moment and the ultimate bending moment capacity with its calculation procedure.
- Support the magnitude of the partial safety factors applied to the characteristic values, so that the associated uncertainty is properly reflected and the desired structural safety obtained.

The absolute value of the failure probabilities is a nominal value, and will generally not reflect the frequency of failure. The target failure probability used in the rule calibration was therefore mainly taken from that of existing ship structures, were in-service experience had proven satisfactory strength. In Horte *et al.* (2007b), the target failure probability from a cost benefit analysis was also evaluated, and confirmed a similar target.

5.2.2 Residual Strength

Residual strength checks are included in certain classification societies' rules, such as ABS and DNV, while the hull girder check in CSR is at present limited to failure of an intact ship in bad weather. Following the implementation of GBS, IACS identified the residual strength of a damaged ship as one gap in the CSR versus GBS, and it was decided to include a residual strength criterion in the new, harmonized CSR rules. Damages in this context are due to collision or grounding. This was studied by IACS using SRA in 2011 which will be published with the technical background of the harmonized CSR, following the principles as outlined in the following.

The failure of an intact ship in open sea occurs if the loads in terms of wave and still water bending moment exceed the hull girder ultimate bending capacity. Damage will lead to changes in these parameters, see Figure 9:

- The still water bending moment may increase or decrease, depending on location of damage and flooding or outflow.
- The wave bending moment is likely to be significantly lower than for unrestricted service in North Atlantic conditions due to short exposure time and lower waves where most damages take place.
- The ultimate bending moment will be reduced at the location of the damage; however, note that damages near the ship ends will not reduce the capacity amidhips.

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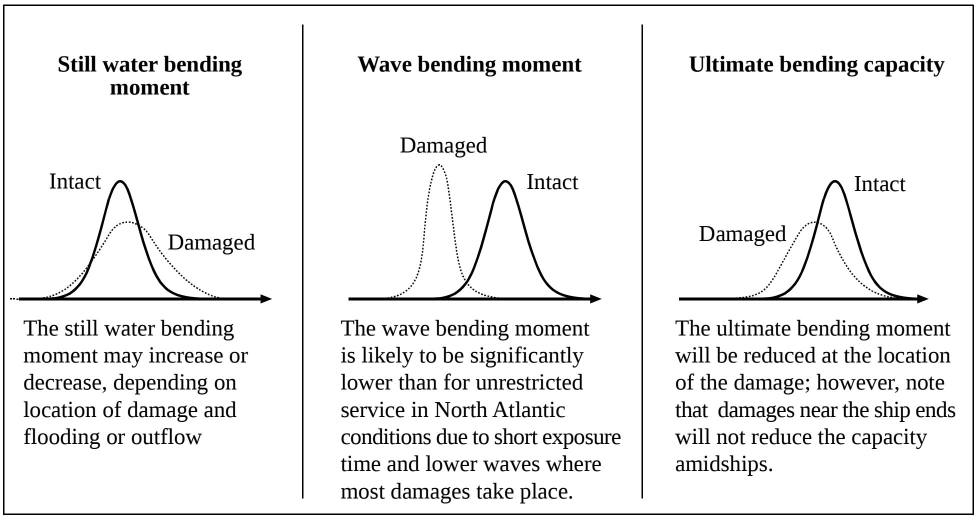

Figure 9: Effect of damage on loads and capacity

A qualitative criticality evaluation with these considerations in mind was made, and failure of a bulk carrier in sagging after collision damage was used in a case study.

5.2.3 Uncertainty Modelling

The uncertainty model for the intact case is reported in (IACS, 2006b, Sect 9.1) and Horte *et al.* (2007a). Here the differences between the uncertainties for the intact versus damaged cases are described.

- Still water bending moment in the damaged case was conservatively assumed to increase by a deterministic value corresponding to the still water moment increase from flooding of the most unfavorable compartment. This was considered conservative since the chance of hitting the most unfavorable compartment was then effectively set to 1.0, and so was the probability of flooding of an empty hold.
- The wave bending moment was significantly reduced due to short exposure time (assume one week after collision) and lower waves since these events are more likely in costal areas and not in the North Atlantic environmental conditions. World wide conditions were used, with sensitivity results using observed wave conditions at collision events taken from (Rusaas, 2003).
- The ultimate bending moment capacity was reduced due to the damage. This reduction in strength was implemented as a deterministic function of the damage size, where the damage size was modeled as a random variable.
- Finally, the probability of the collision event to occur was taken as 0.01, which is somewhat conservative compared to IMO (2010c).

The structural reliability analysis was used on a comparative basis between hull girder failure of intact ship and hull girder failure of the ship following a collision or grounding damage. The following analyses were made, see Figure 10:

- Calculate the failure probability of the intact ship; and use this as the target failure probability
- Calculate the conditional failure probability for the ship, given that the damage event has occurred

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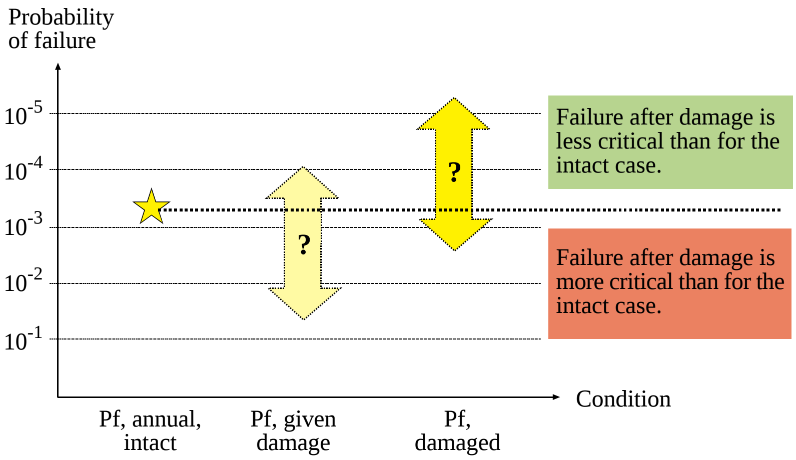

Figure 10: Illustration of comparative approach

- Calculate the failure probability for the damaged case, accounting for the probability of the damage event to occur; i.e. the conditional failure probability times the probability of damage occurrence

For the selected case, the probability for the damaged case was found to be lower than of the intact case. This could be taken as an indication that the residual strength criterion is unnecessary, i.e. not dimensioning. However, irrespective of the comparison between the intact and damaged failure probabilities, the SRA was used to support the specification of a residual strength criterion. This was done as follows:

- First the intact ship strength was modified so that the failure probability in the damaged case became equal the target failure probability from the intact case.
- Then the "design point"; i.e. the most likely value of all the random variables in the SRA that give failure was examined. The purpose of this examination was to see if a proposed residual strength criterion would be reasonable compared to what one would expect to be the most likely failure situation in real life.

The "design point" from the SRA showed fairly good correspondence with the product of characteristic values and partial safety factors as well as the damage size specified in the proposed criterion. The criterion was found to be on the conservative side, hence providing lower failure probabilities for the damaged case than for the intact case. However, even with this conservatism compared to the intact case it is unlikely that the criterion will be dimensioning and cause any increase in scantlings for conventional designs.

5.3 Potential for Success Associated with GBS

At the very beginning of the discussion of GBS at MSC there were two approaches, the prescriptive and the safety level approach. With regard to tankers and bulk carriers the more prescriptive approach has been chosen. However the discussion and development of the safety level approach continues at MSC.

As evidence for the success one can mention the decision of IMO to develop new regulations in the sense of GBS. Recent examples are the development of the code for life saving appliances, the Polar Code and the IGC. The decision at IMO to use formal safety assessments as a tool to develop the justification for new requirements supports this.

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The GBS for tankers and bulk carriers under Tier 3 require a verification of classification rules for compliance with the functional requirements laid down under Tier 2. This is a new situation for the classification societies. At first sight it seems that classification societies lose their independence to some extent as they have to repeatedly submit their rules to the expert group of IMO for verification after changes of the content of the rules.

Yet it is not clear how often and after what kind of modification the rules have to be submitted. The present practice of classification societies foresees a yearly update and improvement of their rules based on experience and damage analysis. These amendments to their rules have been carefully developed and discussed in the governing bodies (namely the technical committees) of the classification societies which consist of representatives from the industry stakeholders. This procedure already assured a development of the technical requirements taking into account the weighted interests of the stakeholders.

If these regular rule developments should be submitted to IMO in any case, continuation of this practice would cause extensive effort for the IMO on the one hand and changes to the procedures of classification societies on the other hand, namely extended lead times before publication of new rules which in turn might impair the up-to-dateness of rules. As for the time being the classification societies and IMO discuss how to deal with this. Publications regarding this are yet not available. The maritime community shall carefully observe how this new regime affects the progress of rule development.

6 APPROACHES IN OFFSHORE INDUSTRY AND AVIATION INDUSTRY

6.1 Design Criteria for Ice Action on Offshore Wind Turbines

Because the present report mainly deals with aspects of sustainability of the maritime industry and how the maritime industry can contribute to a sustainable use of the maritime environment the focus of this section is put on offshore wind turbines and related developments.

There is an immense global potential for wind generated electrical power (Lu *et al.*, 2009, Leung and Yang, 2012). Because of considerations such as space usage, adjacency to population centres and favourable wind speeds, developments of offshore wind farms are on the rise world-wide (Bilgili *et al.*, 2011, Markard and Petersen, 2009, Musial and Ram, 2010, and Zhixin *et al.*, 2009). The offshore oil and gas industry has of course for many years dealt with harsh ocean environments with some hard-earned lessons, particularly in the Arctic (Blanchet *et al.*, 2011, and Ghoneim, 2011). The development of offshore wind energy structures will have similar challenges to overcome with coupled forcing from ice, winds, waves and currents now influenced by turbine dynamics and other forces (Graveson *et al.*, 2001, Hacıefendioğlu and Bayraktar, 2011 and Volund 2003).

In 2001, the Danish Energy Agency (DEA 2001) issued recommendations for approval of Offshore Wind Turbines (OWT) with considerations for static and dynamic ice loads. In 2010, Germanischer Lloyd published a revised edition of the Guideline for the Certification of Wind Turbines (Woebbeking, 2010), which updates their 2005 guidelines (GL, 2005a) and complements their 2005 Guideline for fixed offshore installations in ice infested waters (GL, 2005b). Also in 2010, the American Bureau of Shipping (ABS, 2010b) Standard "Offshore Wind Turbine Installations" was released

18th International Ship and Offshore Structures Congress (ISSC 2012) - W. Fricke, R. Bronsart (Eds.)

in December. Det Norske Veritas issued its new Offshore Standard in September, 2011 (DNV, 2011b). These new standards refer to criteria established in the American Petroleum Institute's Recommended Practice 2N (API, 1995), the International Standard ISO 19906 (Karna *et al.*, 2011), the Petroleum and natural gas industries - Arctic offshore structures (ISO, 2010), and Annex E of IEC 61400-3:2009 (IEC, 2009). These standards establish design considerations for static and dynamic ice loading which, for the most part, were developed for Arctic offshore oil and gas structures.

Static ice forces or actions on offshore wind turbines to be considered, as commonly mentioned in the standards, are normally generated by temperature fluctuations or changes in water level in a fast ice cover. Dynamic loads are caused by moving ice interactions with the support structure as the ice impacts, fails, and clears around and past the structure.

Quoting from the new ABS Guide (ABS, 2010b):

> "For an offshore wind turbine intended to be installed in areas where ice hazards may occur, the effects of sea ice or lake ice on the Support Structure are to be taken into account in the design. Depending on the ice conditions at the site, the Support Structure may encounter with moving ice and fast ice cover… Statistical ice data of the site are to be used as the base for deriving the parameters such as ice thickness, ice crushing strength and pack ice concentration, etc., which are required for determining the ice loads. Impact, both centric and eccentric, is to be considered where moving ice may impact the Support Structure. Impact of smaller ice masses, which are accelerated by storm waves and of large masses (multi-year floes and icebergs) moving under the action of current, wind … is to be considered in the design. The interaction between ice and the Support Structure produces responses both in the ice and the structure/soil system, and this compliance is to be taken into account as applicable."

For lower speeds, forces slowly build until the ice strength is reached and ice fails resulting in a "quasi-static condition" where the frequency of the forcing is about an order of magnitude lower than the response of the structure (Eranti *et al.*, 2011). For intermediate speeds, the ice failure response can be coupled with the structural response, resulting in a "lock-in" response where the ice feature failure period and the response period of the structure coincide (Huang and Liu, 2009, Hetmanczyk *et al.*, 2011). A third important response regime occurs at high speeds of encounter in which brittle fracturing of the ice feature in contact with the structure occur in a more or less random pattern which results in random vibration excitation of the structure (Karna *et al.*, 2010).

These three conditions are specifically addressed in the ISO standard 19906:2010 for consideration in the design of offshore structures. A special consideration of lock-in vibrations is required due to the detrimental effects of such response with regard to fatigue and foundation/soil response. Additional conditions are also of importance for transitional depth structures which may have multiple and battered piles: sloping structures may allow the ice feature to fail in bending, rather than crushing; and, multiple piles add additional complexity of ice pressure distribution and non-simultaneous failure. A final important consideration is impact of drifting ice floes encountering the platform with a sudden increase in forces which results in high-amplitude transient vibrations of the structural system.

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For compliance with the ISO standard 19906:2010, the following conditions should be considered: quasi-static actions, where inertial action effects within the structure can be neglected; dynamic actions due to level ice, where inertial action effects within the structure are influential; and impacts from discrete features such as first-year ice features.

Also according to ISO standards, the following limiting mechanisms shall be considered for global ice actions:

a) Limit stress, which is the mechanism that occurs when there is sufficient energy or driving force to envelop the structure and generate ice actions across its total width.
b) Limit energy, which is the mechanism that occurs when the interaction is limited by the kinetic energy of the ice feature and is generally characterized by the absence of surrounding ice.
c) Limit force, which is the mechanism that occurs when the interacting feature is driven against the structure the actions are insufficient for the ice to fail locally and envelop the structure.

Furthermore as specified in the ISO standard are considerations for:

For *local ice actions* consideration must be given to the design of sheet piling, plates, stiffeners, and frames and bulkheads.

For *dynamic ice actions*, the time-varying nature of ice actions and the corresponding ice-induced vibrations shall be considered in the design. The potential for dynamic amplification of the action effects due to lock-in of ice failure and natural frequencies shall be assessed. Particular attention shall be given to dynamic actions on narrow structures, flexible structures and structures with vertical faces exposed to ice action. Structural fatigue and foundation failure as a consequence of dynamic ice actions shall be considered.

It is quite natural for structural design of offshore wind turbine structures to initially turn to the successes of offshore oil and gas industry and land-based turbines. Certainly the lessons learned in that regard are to be valued, however from a structural analysis standpoint, the offshore wind turbines are dynamical systems by routine. A thorough description of the structural response of the blades, tower, substructure, and foundation requires an integrated, dynamical systems approach (Petrini *et al.*, 2010). An OWT is subjected to wind, ice, and wave loadings of approximately equal severity rather than predominantly wave forcing for oil and gas platforms and predominantly wind for land-based units. A key factor is of course water depth, and while there is proven success at shallower water depths using concrete gravity and steel monopile structures, there are greater challenges for establishing economical designs in deeper waters when construction, operation and maintenance costs create additional system optimization challenges in cold regions (Zaaijer, 2009).

6.2 Approaches to Safety the Aviation Industry

The committee would like to make specific reference to the publication (De Florio, 2011) which provides a single reference on the subject of Aircraft Certification.

The committee has used the book to highlight issues of interest to the ISSC on the systematic aviation industry approach to flight safety, safety assessment and fatigue strength. The book is a comprehensive review of airworthiness requirements, type certification and production of products, certificates of airworthiness and continued airworthiness and operations. Approaches to sustainability and the regulatory environment in the aviation will not be further described

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6.2.1 Flight Safety

The publication specifically deals with safety related to aeronautical activities, starting by considering what has been defined as the main conventional flight safety factors. These are: man, the environment and the machine.

1. *Man* is intended as an active part of the flight operations, i.e. after the aircraft is designed and built, e.g. the pilots, maintenance manpower, air traffic controllers and others.
2. The *environment* covers all the external factors that can have an influence on the flying of an aircraft, meteorological conditions, traffic situations, communications, correct meteorological information, rules for the vertical and horizontal separation of the aircraft, suitable aerodromes, and so on.
3. The *machine* refers to a "project" i.e. the aircraft, its sound construction and its efficiency in relation to the operations to be carried out. Also, as with the Maritime Industry, National States entrust special public bodies with the responsibility of assuring that the aircraft (project) construction, and the operating instructions comply with flight safety requirements.

The three safety elements above act in series and not in parallel. They are three links of a chain representing flight safety. The failure of a single link is sufficient for an accident to happen. E.g. a pilot's error can put the best aircraft in jeopardy, and the best pilot cannot compensate for a serious failure in an aircraft.

6.2.2 Safety Assessment

The book presents the following rationale of how the aviation industry identifies an acceptable safety level. The definition of an acceptable safety level implies the definition of an acceptable accident rate; this cannot be defined as abstract wishful thinking, but on the basis of what is practicable. What is practicable for the future can be forecast by the analysis of past accident rates. Starting from the arbitrary hypothesis that a commercial large aircraft could present some 100 hazards (potential failure conditions) leading to a catastrophic effect, it follows that, for each system, the acceptable probability of a catastrophic failure is less than $1 \cdot 10^{-9}$ flight hours.

Failure conditions
Failure conditions are defined as effects on the aircraft and its occupants, both direct and consequential, caused or contributed to by one or more failures, considering relevant adverse operational or environmental conditions. Failure conditions are classified according to their severity as follows:

Minor: Failure conditions that would not significantly reduce aircraft safety and which involve crew actions that is well within their capability.

Major: Failure conditions that would reduce the capability of the aircraft or the ability of the crew to cope with adverse operating conditions to the extent that there would be, for example, a significant reduction in safety margins or functional capabilities, a significant increase in crew workload or in conditions impairing crew efficiency, or discomfort to occupants, possibly including injuries.

Hazardous: Failure conditions that would reduce the capability of the aircraft or the ability of the crew to cope with adverse operating conditions to the extent that there would be (a) A large reduction in safety margins or functional capabilities (b) Physical distress or higher workload such that the flight crew cannot be relied on to perform their tasks accurately or completely, or (c) Serious or fatal injury to a relatively small number of the occupants.

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Table 6: Categories of failures for a large aircraft

1	Minor failures	Become	Probable	
2	Major failures	Become	Remote	$P = 1 \cdot 10^{-5}$
3	Hazardous failures	Become	Extremely remote	$P = 1 \cdot 10^{-7}$
4	Catastrophic failures	Become	Extremely improbable	$P = 1 \cdot 10^{-9}$

Catastrophic: Failure conditions that would prevent continued safe flight and landing.

As an example: A single aircraft might fly a total of $5 \cdot 10^4$ hours and a large fleet of 200 aircraft (same type) might then accumulate a fleet total of $1 \cdot 10^7$ hours.

1. A catastrophic failure condition (at worst $1 \cdot 10^{-9}$) would be unlikely to arise in the whole fleet's life.
2. A hazardous failure condition (at worst $1 \cdot 10^{-7}$) might arise once in the whole fleet's life.
3. A major failure condition (at worst $1 \cdot 10^{-5}$) might arise once in an aircraft's life and would arise several times in the whole fleet's life.
4. A minor failure could arise several times in the aircraft's life.

The safety assessment of equipment, systems, and installation is a very important part of aircraft design. It is of paramount importance to start the assessment from the very beginning of the design. A late assessment could bring result in expensive design changes.

6.2.3 Fatigue Strength

The airworthiness standards essentially consider two types of structure:

1. Single load path structures, where the applied loads are eventually distributed through a single member, the failure of which would result in the loss of the structural capability to carry the applied loads.
2. Multiple load path structures, identified with redundant structures in which (with the failure of an individual element) the applied loads would be safely distributed to other load-carrying members.

In the first case, the structure must result in *safe-life,* that is, be able to sustain a certain number of events such as flights, landings, or flight hours, during which there is a low probability that the strength will degrade below its design ultimate value due to fatigue cracking. In the second case, the structure must be of damage-tolerance design, that is, be able to retain its required residual strength for a period of unrepaired use after the failure or partial failure of a principal structural element due to fatigue, corrosion, accidental damage, and bird strikes. Such a structure is defined as *fail-safe.*

For large aircraft, the relevant airworthiness standards require *fail-safe* structures, unless this entails such complications that an effective damage tolerant structure cannot be reached within the limitations of geometry, inspection, or good design practice. Under these circumstances, a design that complies with the *safe-life* fatigue evaluation requirements is used. A typical example of a structure that might not be conducive to damage tolerance design is the landing gear and its attachments.

In the case of loads and loading spectra, the assumptions made for fatigue assessment are as follows for large aircraft. The principal loads that should be considered in establishing a loading spectrum are flight loads (gust and manoeuvre), ground load and pressurization loads. The loading spectra are based on measured statistical data derived from government and industry load history studies and, where no sufficient

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Table 7: Relationship between probability and severity of failure conditions

Effect on aircraft	No effect on operational capabilities or safety	Slight reduction in functional capabilities or safety margins	Significant reduction in functional capabilities or safety margins	Large reduction in functional capabilities or safety margins	Normally with hull loss
Effect on occupants excluding flight crew	Inconvenience	Physical discomfort	Physical distress, possibly including injuries	Serious or fatal injury to a small number of passengers or cabin crew	Multiple fatalities
Effect on flight crew	No effect on flight crew	Slight increase in workload	Physical discomfort or a significant increase in workload	Physical distress or excessive workload impairs ability to perform tasks	Fatalities or incapacitation
Allowable qualitative probability	No probability requirement	Probable	Remote	Extremely remote	Extremely improbable
Allowable quantitative probability	No probability requirement	$< 10^3$	$< 10^5$	$< 10^7$	$< 10^9$
Classification of failure conditions	No safety effect	Minor	Major	Hazardous	Catastrophic

data are available, on a conservative estimate of the anticipated use of the aircraft. In assessing the possibility of serious fatigue failures, the design is examined to determine probable points of failure in service. In this examination, consideration is given, as necessary, to the results of stress analysis, static and fatigue tests, strain gauge surveys, tests of similar structural configurations and service experience.

Fatigue test programs for large aircraft can last years; hence, it is not generally possible to complete them before the aircrafts' type certification is issued. It is therefore required that at least 1 year of safe operations must be demonstrated when the type certificate is issued. Subsequently, to maintain the validity of the type certificate, the fatigue life substantiation must always exceed the number of cycles/flight hours reached by the "oldest" aircraft (lead aeroplane).

7 CONCLUSIONS

During the period of this report the committee focussed the report on questions regarding sustainability with regard to economic consequences of the shipping industry and the industry's impact on the environment and human life. Analysis methods of the impacts are presented in four subsections. The section regulatory approaches to sustainability and safety in the maritime industry presents methods, set up by several bodies, how to control the adverse impacts be it of random or systemic nature.

According to the mandate the committee spent time to discuss the present state of the development of the GBS and their implementation by both IMO and IACS classification societies. It lies in the nature of things that the present implementation of GBS focuses the prescriptive character of the GBS. The development of the safety level approach is still in progress at IMO and the future committee should investigate and document its implications for the work of classification societies and their respective rule development. It is recommended that the future committee should spend time to further document the progress on the implementation of risk based methods

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in ship structural design, which might have impact on design methods and on rule development.

Unfortunately the committee lacked of persons having sufficient expertise in the offshore sector of the maritime industry. For that reason the section deals only with the very specific issue of design requirements for offshore wind energy plants. There must have been significant development especially in the field of offshore energy production during the last three years. This may be the case for the offshore installations themselves but also for the ships necessary to install the offshore installations in great numbers. With regard to wind turbine installation vessels there have been several concepts developed lately which have to prove their practicability. It can be expected that during the following three years more publications will be available which should be reviewed by the future committee.

A comparison with the aviation industry is presented very briefly focussing on design criteria only. It was found worth to present the hierarchy of failure consequences and their associated levels of probability. This is a well established approach in the aviation industry. Future committees should discuss whether a similar systematic approach could be adapted to shipbuilding. For the sake of keeping page limitation of this report the regulatory environment of the aviation industry was not presented here.

The committee formally met once in Newcastle and two times in Hamburg, two informal meeting were held in parallel to PRADS in Rio and at MARSTRUCT conference in Hamburg.

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COMMITTEE IV.2

DESIGN METHODS

COMMITTEE MANDATE

Concern for the synthesis of the overall design process for marine structures, and its integration with production, maintenance and repair. Particular attention shall be given to the roles and requirements of computer-based design and production, and to the utilization of information technology.

COMMITTEE MEMBERS

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KEYWORDS

Ship design methods, computer tools, computer aided design, computer aided engineering, lifecycle management, databases, PLM, integrated tools, multi-level optimization, surrogate modeling.

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CONTENTS

18th International Ship and Offshore Structures Congress (ISSC 2012) - W. Fricke, R. Bronsart (Eds.)

18th International Ship and Offshore Structures Congress (ISSC 2012) - W. Fricke, R. Bronsart (Eds.)

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1 INTRODUCTION

The Committee was very enthusiastic to address the mandate we received. For years, and may be centuries, ship design has been an independent activity taking place at the beginning of the ship's life. More recently, the data associated with the design and production steps carried out in the shipyard have been transferred to external bodies such as class societies or ship owners to allow a more efficient maintenance, repair and disposal of the vessel. Unfortunately today such data transfers are still done on a case by case basis and not globally standardized. The Committee is convinced that in the near future data integration will become a reality for the lifecycle of a ship, connecting shipbuilding and shipping companies. We do not envision this integration coming from the unreachable Nirvana of a single central database that is shared throughout the design phase and then exported outside the shipyard. We instead see this arising from a usable set of data, which will be soon made mandatory by the regulation, linked to one ship and that can be consulted and edited for the whole lifecycle of the ship by all the stakeholders (ship owner, repair yards, class society . . .). This upcoming transition is the reason why we decided to make Life Cycle Management (LCM) the central focus of this report.

From our point of view, any kind of industrial activity is strongly influenced by the cost. For LCM, a key principle is the overall product life cycle cost (LCC). This cost is divided into various components:

- its purchasing costs (often called capital expenditures or CAPEX);
- its exploitation costs (often called operational expenditures or OPEX);
- its disposal costs (included or not in the OPEX or CAPEX depending of the product).

Sometimes more detailed formulae may be used to identify various components. An example formula may be described as follows:

$$LCC = C_{ic} + C_{co} + C_e + C_p + C_m + C_s + C_{env} + C_d$$

with:

- C_{ic} = Initial cost (initial investment or CAPEX)
- C_{co} = Commissioning costs (often included in the CAPEX)
- C_e = Energy costs (included in the OPEX)
- C_p = Exploitation costs (personnel included in the OPEX)
- C_m = Maintenance and repair costs (included in the OPEX)
- C_s = Loss of income costs linked to a production stop (included in the OPEX)
- C_{env} = Environment related costs (included in the OPEX)
- C_d = Disposal costs

A ship owner is obviously facing a very competitive marketplace and must seek to minimize vessel LCC as much as possible. The onus to do so is in turn transferred not only to shipyards but also to all activities involved during the ship operation and disposal. So, what we term LCM in this report includes all the methods, tools and, procedures the shipping community (including all actors from the shipyard to the disposal yard, including ship owner and classification society) must employee in order to keep the overall LCC of a ship as low as possible. The cheapest ship is not obviously the one with the lowest initial sale price. It is the one that costs its owners the least amount of money from conceptual design to disposal.

As defined by the mandate we gathered data from both commercial shipping and navies. The drivers for LCM regarding state owned ships differ from those applied in

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private companies. Nevertheless, all ship owners apply a LCM framework to a certain extent and we hope that the mutual comparison will be useful to every reader.

We will introduce the needs and requirements together with the drivers for a life cycle oriented design which we called design for lifecycle. To achieve design for lifecycle, existing tools and methods must be employed along with some newly developed approaches. In this report, we present both the existing tools and methods as well as highlight remaining areas of conflict or future development. We demonstrate how these methods and tools can be integrated into practical and convenient solutions for the stakeholders. Finally we present some existing and, more or less integrated solutions together with the obstacles which currently prevent software vendors from offering more integrated solutions and suppressing the demand for lifecycle solutions from the end users of the tool.

The main problem we faced in developing this report was the lack of reliable and consistent information. The cost aspects are always touchy and it is very difficult to get realistic and useful data. Nevertheless, we decided to try our best to get enough data to display a realistic picture of what we are aiming to demonstrate in this report. To do so we used two common methods of obtaining data.

Our first source of data is a literature survey based on public data. This includes books and PhD theses, journals, congresses and conferences proceedings and web sites. It also comes from public data issued by public funded projects such as European Union projects. Recently, an extensive analysis of the outcomes of European maritime research projects in FP5 to FP7 has been carried out in the European project MARPOS (2011). This analysis includes Chapters on Competitive Ship Design Methods, Integrated Life Cycle Services and on Improving Safety by Design, which provide further information in relation to the scope of work of this Committee.

Our second source of information came from a new survey commissioned by the committee. We built a survey based on our experience and topics we were looking for more information from. Each member has been in charge of contacts located in his or her geographical region. We received 23 answers to the survey. Unfortunately, most answers came from Europe and the limited amount of data not enough to draw real "statistical" worldwide conclusions. In the framework of an ISSC Committee where we had to find volunteers to fill in the survey, the responses received were viewed as significant enough in number, and we decided to use the data coming from the survey. A comprehensive summary of the survey results is presented in section 9.

Finally, the Committee would like to express special thanks to two major contributors who helped a lot in this report edition by their contribution to chapters and management of the survey: Jean-David Caprace from University of Liège in Belgium and Martin Bergstroem from CMT in Germany.

2 DESIGN FOR LIFE CYCLE

2.1 Integrated Life Cycle Management

According to Fiksel (1996), Integrated Life Cycle Management (ILCM) can be defined as a comprehensive and flexible life cycle framework for making planning, design, and operating decisions, explicitly considering costs and other fundamental business metrics together with environmental, health, and safety factors. ILCM is thereby an overarching system of concepts, methods, and practices that can be used to effectively manage a ship from cradle to grave. The framework includes all actors at all stages of the production and operation of a ship. According to the Quality Associates (2011)

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the fundamental components of the system include the organization, resources and processes. Consequently, people, equipment and business culture are part of the system as well as the documented policies and practices.

The general objective of ILCM is to reach long term sustainability by combining human requirements (such as safety, usability, and comfort), environmental friendliness, and profitability. In other words, the specific goal is to minimize the environmental impact while at the same time maximizing the long term profitability. Sharma and Kim (2010) state that the key to retain efficiency and economy is to manage resources in a collaborative and integrated environment that synchronizes with various requirements of customers, design firm/unit, production (shipyard), rules and regulation (classification society), outsourced collaborators etc. By integrating all systems and processes into one framework, it becomes possible to find out how various factors affect each other etc., which enables optimization of the overall life cycle performance of the ship. Obviously, this provides significant benefits in comparison with an un-integrated management system that only would enable optimization on sub-system level.

It has already been mentioned that an ILCM system should involve all actors at all stages in the production and operation of a ship. Thus, and ILCM system should involve the following types of management systems (here the term management means the process involving performance monitoring, decisions making, implementation of adjustments if necessary, etc.);

- Environmental management
- Quality management
- Logistics management
- Maintenance management
- Health and safety management
- Social responsibility management
- Etc.

Obviously, to make the different systems properly integrated, effective linkages between various management systems are needed. In addition, to successfully adopt and implement a life cycle management approach, it is necessary to maintain a consistent life-cycle perspective. Obviously, this requires an open minded multi-disciplinary approach to all issues.

As mentioned, the ILCM framework should include all significant stages of the production and operation of a ship. Specifically, this means that at least following production stages should be included;

- Raw material acquisition
- Manufacturing of ship building material and components
- Transport of material and components to the shipyard
- Shipyard activities (energy for welding etc, emissions, waste)
- Ship operation (fuel consumption, emissions to air and water, waste, etc.)
- Ship maintenance (materials and energy consumption)
- Final disposal (recycling of materials, hazardous waste, etc.)

The operation phase is generally the most significant in terms of emissions and costs such as carbon dioxide (CO_2), sulphur oxides (SO_x), nitrogen oxides (NO_x), and particulate matter (PM). In addition, possible discharges into the water (such as oily bilge water, ballast water, untreated grey water, and dangerous substances from antifouling) do also primarily take place during the operation phase. However, to get

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the whole picture, the production and the end-of-life (recycling or disposal) have to be considered as well. The building phase is especially important in terms of use of material, while the demolition phase is important in terms of environmentally hazardous waste such as non recyclable composites, asbestos, halons etc.

ILCM is on product level executed by applying Product Life Cycle Management (PLM). According to Sharma and Kim (2010), PLM is the process of managing the entire life cycle of a product from its conception, to design and manufacture, to delivery, to maintenance and service, and to finally disposal. PLM integrates human resources, data, design, processes, and business systems. Consequently, PLM is not just about software and data management but is also a business strategy. In addition, Sharma and Kim (2010) point out that PLM describes the engineering aspect of a product and should therefore not be mixed up with for instance product life cycle management (PLCM), which refers to commercial management of a product with respect to sales measures etc.

Sharma and Kim (2010) states that to make a PLM system work, it has to be built on top of CAD/CAM/CAE, PDM, and enterprise resource planning depending on the type of the primary user. The conceptual development and the basic building concepts for a logic based PLM system for the shipbuilding industry were presented by Sharma and Kim (2010). The logic bases of the presented system consist of modularization, standardization, geographical zoning, and functional zoning. The logic bases of modularization and standardization are used in the ship design and production processes, and the logic bases of geographical zoning and functional zoning are used in "logically grouping" the on-board activities in the ship production process. According to Sharma and Kim (2010) an implementation of the system indicated that the system results in more streamlined and better planned and executed design and production processes.

2.2 Design Loop and Lifecycle Data Management

According to Grogan and Borthen (2010), late changes to a ship's design are recognized as the primary factor contributing to increasing ship construction costs. Thus, when the US Navy's Zumwalt class guided missile destroyer was designed, an integrated detailed design was implemented to get the design right before start of production. The integrated design progress was carried out using an Integrated Data Environment (IDE), which makes it possible to freely send and receive information (models, presentations, written documents, charts, and visual issues) in a secure manner while at the same time being able to access the information from any authorized computer at any time. The integrated system was used to maximize the number of stakeholder disciplines that reviewed and critiqued the design. All the reviewers were able to comment on weaknesses in the design. Thanks to the IDE system, production planners participated actively in the detailed design. According to Grogan and Borthen (2010), potential manufacturing difficulties were, thanks to this procedure, found early in the design phase, avoiding them after the construction had started.

Generally the new building process produce a lot of valuable information that later can be used for the optimization of operations, safety, as well as retro fitting and recycling processes etc. By improving the cooperation between all actors in the life cycle chain, this information could be more efficiently used to improve the overall LCP of a ship. In addition, it is well known that the actors in the new building process, i.e., designers, shipyards and equipment suppliers, are often the drivers of innovation and use of technological solutions and skills. Thus, an integrated life cycle data man-

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agement system could also increase the competitiveness of the repair and retrofitting yards etc. by providing them access to data concerning new technologies. However, Intellectual Property Right (IPR) issues, which of course have to be considered, may pose significant challenges related to this issue. For the balance between IPR and design transparency, a cross industry group included in the GBS Working Group at MSC 82/5/4 (2010) is developing the Ship Construction Files (SCF) Industry Standers supplementing the MSC guidelines. SCF is designed to be mandatory and includes all documents that are sufficient to provide structural and safety information for safe operation and for emergency situation satisfy the GBS functional requirements, and to stay with the ship throughout its lifetime. This concept makes a start of solutions on IPR protection although the GBS will be forced from 2016 only for Bulk Carriers and Double Hull Oil Tankers. More information on IPR in shipbuilding may be found in the European project Guardship web site (2009). Thus, to assure proper work and secure data exchange, the relationship between the shipyard and the maintenance and repair providers has to be confidential. The relationship is especially important when dealing with maintenance of ships featuring unconventional technologies and materials such as composite. Such innovative solutions offer significant operational benefits. However, they can cause problems (including safety problems!) in daily operation if maintenance staff and repair and retrofitting yards are unable to deal with them due to lack of information/knowledge about possible special maintenance/repair procedures etc. Thus, the potential of various innovations cannot be fully used if skills on how to repair and maintain the solutions are not available over the entire life cycle.

2.3 Drivers for an Integrated Life Cycle Management

Shipbuilders and ship operators will in the near future have to adopt more and more life cycle thinking. Sharma and Kim (2010) points out that the modern environment of high efficiency and economy and sustainable environment is demanding ship design that are energy efficient, disposable with minimum damage to the environment, and able to stay in service for longer durations. Obviously, to meet such demands, it is necessary to implement ILCM.

Various LC approaches have already become standard in a number of industries. However, within shipbuilding, life cycle approaches are still not among the established processes. This is likely to change since there are a number of strong drivers for an ILCM. Some of the drivers are purely economical while others are set by various agreements, rules and regulations. The main groups of drivers are listed and discussed below;

- *International agreements, rules and regulations;* The IMO's International Convention for the Prevention of Pollution from Ships (MARPOL) is the main international convention covering prevention of pollution of the marine environment by ships from operational and accidental causes. By taking possible future regulations into account, such as a CO_2 tax, it is possible to design ships with a better long term performance. IHM is another upcoming regulation to be considered, refer to section 4.1.3 for more details.
- *Regional and national agreements;* IMO has set general global limits for air emissions and determined some stricter rules for certain sensitive areas referred to as ECAs (Emission Control Areas) or SECAs (Sulphur Emission Control Areas). EU and HELCOM have regulations and recommendations covering sea areas within the EU and the Baltic Sea. The EU environmental legislation is mainly based on IMO's recommendations. However, EU has developed own legislation concerning ship fuels, antifouling paints, etc. In addition, there are

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rules covering special environmental areas such as Galapagos Island. Obviously, a ship designed to meet such regional agreements would be more attractive on the second hand market while it would be suited for a large variety of operations.

- *Initiatives taken by others*; Most of the classification societies offer some kind of Environmental Class Notation. In addition, there are emission based fairway dues to cut the emissions in certain area. For instance, the Swedish fairway system favors environmentally friendly ships by offering them a discounted fairway due. The discount is calculated based on the amount of NO_x and SO_x a ship produce per kWh. HELCOM has given a recommendation and proposed a structure for environment-related fairway dues to its member countries (HELCOM Recommendation 28E/13). Furthermore, some ports give discounts to ships based their environmentally friendliness. Such discounts are given by a number of Swedish and Finnish ports, SPC Finland (2009).
- *Sign of environmental leadership;* increasing public awareness on climate change and environmental protection have made especially passenger ship owners keen to demonstrate environmental awareness to their customers. This has led to ambitious greenhouse gas reduction programs etc.
- *Cost savings;* Better energy efficiency onboard the ship leads of course to fuel savings and furthermore to cost savings. An ILCM can be applied to improve the energy efficiency of a ship resulting in lower fuel costs and emissions. In addition, ILCM can reduce costs by improving maintenance routines. Improved maintenance routines would also result in improved environmental friendliness, and safety. Ships have a long service time and the majority of the total cost of ship ownership accrues during that phase. However, life cycle costs reducing technology is usually "high tech" and demands therefore generally a higher initial investment than standard technology. Thus, shipyards have to be able to demonstrate and convince the ship-owner of the long term advantages of LCC reducing investments.
- *Capitalization of product data*: Briggs *et al.* (2009) stated that the business drivers for IDM are both for the US Navy and for the US shipyards to reduce the costs of ownership and exploit the investment in product data created during acquisition and maintained through the life cycle. Thus, the IDM system must
  - Enable that ships have improved availability, reliability, maintainability, and lower costs if ownership.
  - Reduce IT costs and ensure longevity in use of information
  - Ensure that digital product data are treated as a valuable business asset.
- *Other drivers;* According to Briggs *et al.* (2009) shipyards are increasingly responsible for the life cycle support of ships, including maintenance and logistics data over the life of the ship. The same source points out that life cycle support, repair, maintenance and overhaul, ships operating, testing and training are all information- intensive processes. Hence, it has become important for shipyards to efficiently integrate acquisition product model data with the life cycle support product model data. In addition, the global nature of shipbuilding/shipping and the large number of subcontractors, service providers etc. involved in the building and operation of a ship can of course also be considered as a driver for ILCM. Especially, the building and operation of cruise ships demands integration of a large number of various branches. A typical need for life cycle data is illustrated by an industrial activity just in between shipbuilding and offshore industry. This is when a tanker is converted into an FPSO. The structure remains almost the

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same with some additions and subtractions of structural elements, but the main subject to deal with is the fatigue state of the hull to define what the plates to be changed are in order to reach the expected life cycle of the structure taking into account the load history prior purchase.

3 AVAILABLE DESIGN METHODS

3.1 State of the Art in Ship Design Methodology

Design methodology consists of a formal description of the design process, its premises, objectives and procedures. One of its essential foundations is the approach of systems analysis which became known and rapidly spread after the Second World War, Nowacki (2009).

The prevailing design procedure was well captured in the image of the famous design spiral, attributed to Evans (1959) and later also adopted by Hurst (1971) in its early computer systems. This schema correctly depicts the iterative nature of design, but overemphasizes an apparently prescribed sequence of design steps. In practice the procedure varies from case to case and is much more flexible, given that provisional assumptions permit starting subtasks independently. At a later stage when concurrent engineering was pursued, the design team actually endeavored to perform several design subtasks simultaneously. Nevertheless the design spiral served well as guidance in coordinating design activities.

By about 1970 the methods of systems analysis had matured in many other applications and began to make a profound and lasting impact on ship design methodology. Systems analysis serves as a decision-making approach in the analysis, design and operation of large, complex systems. It can equally well be applied to ships, their subsystems and to the fleet or transport system of which the ship may be a part, Andrews (2003).

The approach of systems analysis made a deep impact on ship design methodology, not only because of its greater rigor, but also because it facilitated a coordinated division of labor in the design team. The introduction of computer aids in design enabled each designer to perform a greater share of subtasks in the design process and thus necessitated a reorganization of the division of labor in design. The subtasks of design attained greater scope and granularity, increasing the responsibilities of the individual team member. But systems analysis also provides criteria and methods for harmonizing the results of subsystem design in consonance with overall system performance.

Thus the systems approach has been providing a common platform for many new developments and innovative design techniques for many decades. Many good synoptical papers and textbooks have appeared and have underscored the common denominator in this multitude of new elements in ship design methodology e.g. Rawson (1979), Schneekluth (1980), Erichsen (1982), Andrews (1986), Andreasen (2003), Lamb ed. (2003), Hosoda (2006), Andrews (2009, 2010). The degree of change in ship design methodology during several decades was significant and must be rated by the sum of many individual innovations in this general framework.

3.2 Goals, Achievements and Inefficiencies

3.2.1 Economic Efficiency

Economy remains with safety the most essential goals of commercial ship design. There is no doubt that significant improvements were made in the economic efficiency of

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ships. The economic assessment of alternatives has become a routine matter in early design stages. A detailed review of different cost assessment methods have been done in ISSC 2006 congress and have been presented by the committees IV.2 and V.3.

The computer made it even more feasible to get an immediate evaluation of economic performance for a proposed design. Design decisions thus have become more transparent and more rational. The sometimes superficially conflicting requirements of economy and safety can usually be reconciled by quantification. Several approaches exist for making these criteria more commensurable.

The future trends are the design for lower lifecycle cost, i.e., shipbuilding and operating cost as well as the design for better product quality, i.e., improved functionality, performance and reliability of the ship. The reduction of the lead time for design and production to achieve shorter time to market is obviously also an important issue.

3.2.2 Ship Safety and Risk Assessment

Ship safety requirements are as essential to shipping ventures as economic objectives. This concerns the safety of human lives, the risks of damage to or loss of ship and cargo, and the hazards to the environment. In fact it is the art of ship design to find solutions meeting both economic and safety requirements without compromising any safety principles.

For many decades the management of safety in design has been a matter of improving regulatory requirements in response to experience with fatalities, damage or loss, by conventions issued by international agencies and institutions such as SOLAS and IMO. This is still necessary to set standards and reach international agreement.

Probabilistic methods for risk assessment have now gained full acceptance and are in practice replacing older deterministic, safety factor based regulations. Calculation methods for predicting ship performance in critical situations, in a seaway or in collisions and groundings, have been further developed. Extreme catastrophes, say, by monster waves or tsunamis, are investigated and taken into consideration. Quantification of risks in early design stages is becoming more and more feasible, Papanikolaou (2009). Pursuing risk based design approach quantifying all hazards is the future trend.

From a regulatory point of view, Formal Safety Assessment (FSA) has been the primary approach to analyze the cost benefit of new or changed regulations. FSA comprise a systematic methodology to identify hazards, assessing the risks related to these hazards, and determining the cost/benefit of alternative risk control options. The result can thus be used to make better informed decisions on regulatory changes, balancing the benefits in terms of expected reduction in lives lost or reduced pollution, against the cost both for individual parties as well as the industry as a whole. Several FSA studies have been developed as input to the work in IMO MSC, Papanikolaou (2009), as well as in the EU funded SAFEDOR project.

From a design perspective, FSA is important for promoting goal based standards to support the design of new and innovative designs, as an alternative to prescriptive rules presupposing a specific technical solution. By explicitly defining the safety objective to be met, alternative design solutions meeting the same standard may be approved. This also opens up for risk based acceptance criteria, with classification societies using the FSA guidelines as basis for own rule development, Skjong (2009).

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3.2.3 Rationality and Probabilistic Modeling

Many influences on ship performance are uncertain at the design stage, in particular the hazards of loads and safety. The environment of the ship in an irregular seaway and the events involved in ship collisions and groundings are examples of random processes that need to be described in terms of probabilities. Fortunately some pioneering work has made these processes amenable to probabilistic modeling. Recent applications, e.g. in the compartmentation of double hull tankers, Papanikolaou (2009), in design optimization, Diez *et al.* (2010), Hamada (2010), Okasha (2010), are giving new significance to such models. Design for structural reliability belongs to the same category. Therefore in recent decades several computational methods have been introduced and have become routinely applied in ship design, where appropriate, to evaluate risks and contend with uncertainties.

3.2.4 Optimization

In the framework of the systems approach optimization methods have become the favorite design solution tool. Many of the principal stages of the design process have been approached by optimization, Nowacki (2003), Bertram (2003), and Vasudevan (2008). The approach is invaluable for innovative design tasks and may confirm and thus reassure the solutions to more conventional design applications.

The advantage of using optimization in design is not only the ease of finding the best possible solution(s) more or less automatically, but also having the assurance that improvements are no longer feasible by small changes in the design variables. It is an important result also to learn which constraints are governing the solution, sometimes in order to soften certain constraints.

The nonlinear optimization problem does not necessarily yield a unique solution, in multimodal cases several local optima exist. It is of value to know multiple optima if they exist. To enumerate several or all local optima necessitates a conscientious inspection of the whole feasible design space.

Problem formulations with multiple goal criteria have become popular in ship design. This tends to occur when economic and safety indicators are both taken into account as equivalent goals. One possible approach to this dilemma consists of Multiple Criteria Optimization (MCO). MCO methods, e.g. Pareto optimization, help to define the most suitable compromises. See more methods and examples in chapter 5.

3.2.5 Integration

It was one of the earliest dreams in CAD/CAM to have available an integrated, coherent software system that would support the entire design process, Roos (1967). This meant that a set of design methods would share a certain database and build up the product model in successive design steps, not necessarily in any prescribed sequence. Thus the methods would be interfaced by sharing data sets in the database. The designer would be able to perform design steps in any desired and meaningful order without unnecessary responsibility for input and output.

The demand for fully integrated systems is undiminished. In practice some external and even in-house interfaces remain heterogeneous. Chances for integration have improved by standardization (STEP) and by building neutral connectors. The idea of standardizing product model representations is helpful, too. Yet on a larger scale integration is not yet fully realized, Boesche (2010).

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3.2.6 Open Communication

The communication between heterogeneous CAD/CAM systems and subsystems is now recognized as a key prerequisite for digital collaboration between suppliers and customers. The standardization in STEP and similar standards shows an approach for neutralizing the interfaces. However open product model communication between distributed partners has not yet been fully achieved, especially if the systems differ in functionality, Bronsart *et al.* (2005), Guyt *et al.* (2005), Thomson (2010), Briggs (2009).

3.2.7 Versatility

In ship design the lot size is usually one. Changes will always occur before and during production. Thus CAD/CAM systems must be extremely versatile to contend with ever changing design requirements. CAD systems during several decades have certainly become more comprehensive in scope and hence more versatile. Some system vendors claim to cover the complete CAD-CAM-CIM cycle. Exceptions from this trend still occur with new floating structures such as offshore wind mills and features as well as unconventional design objectives. Simulation and visualization have added to system versatility. The trend is in the right direction.

3.2.8 Simulation and Visualization

Simulation and visualization together ("the virtual ship") are also increasingly used in early stage design to display the product model of the ship in three-dimensional views together with its operating systems in order to review the geometry, subdivision and structure, for investigating issues of production and operation or safety hazards and emergencies, the performance of lifesaving systems and many other operational scenarios, Kanerva (2002), Lödding (2011). More considerations on production simulation and virtual reality are presented in the committee ISSC 2012 V.3.

3.3 Design for X = Current Practice

Today ship design can be viewed as an *ad hoc* process. It must be considered in the context of integration with other design development activities, such as production, costing, quality control, etc. In that context, it is possible for the designer to work on a difficult product, requiring high material or labor cost, and containing some design flaws that the production engineers have to correct or send back a new design before production. Any adjustment required after the design stage will result in a high penalty of extra time and cost, Olcer (2004). Deficiencies in the design of a ship will influence the succeeding stages of production. In addition to designing a ship that fulfils producibility requirements, it is also desirable to design a ship that satisfies risk, performance, cost, and customer requirements criteria. More recently, environmental concerns, safety, passenger comfort, and life-cycle issues are becoming essential parts of the current shipbuilding industry.

With this paradigm, the selected design will be a producible, cost-effective, safe, clean, and functionally efficient design. This will enable shipyards to obtain great rewards, such as the reduction of construction time and costs, reduction of lead time, improving product quality, simplification of products, and gaining sustainable competitive advantages in the shipbuilding market.

Throughout the engineering disciplines, many "Design for X" (DFX) processes have been developed in order to correct the inadequacies of the designs during the ship design stages. DFX is the process of pro-actively designing products to optimize all

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the functions throughout the life of the product. This has been called "Design for X" where X is whatever the specific focus happens to be. So "Design for X paradigm" covers many areas such as Design for Production, Design for Manufacturing, Design for Assembly, Design to Cost, Design for Simplicity, Design for Maintenance, Design for environment, Design for Safety, Design for Life Cycle Cost, Design for Robustness, Design for Six Sigma, etc.

3.3.1 Design for Cost

Design to cost (DTC) is a management strategy and supporting methodologies to achieve an affordable product by treating target cost as an independent design parameter that needs to be achieved during the development of a product. DTC is an area which has attracted much attention recently. The objective with DTC is to make the design converge to an acceptable cost, rather than to let the cost converge to design, Rush (2000), Ou-Yang (1997). DTC can produce massive savings on product cost before production begins. The basic concept of DTC is to estimate the manufacturing cost during the conceptual and early design stages in order to achieve the following objectives:

- To identify the model parts that might cause high manufacturing costs.
- To provide an environment to estimate alternative cost for comparative design models.

The general approach is to set a cost goal, then allocate the cost goal to all the elements of the product. Designers must then confine their approaches to set alternatives that satisfy the cost constraint, Michaels (1989). The control of costs to meet these objectives is achieved by practical trade-off involving mission capability, performance and other schedule objectives.

However, this is only possible once cost engineers have developed a tool set that designers can use to determine the impact of their decisions as they make them. Caprace (2010) presented different developments to help the designer analyze the impact of their decisions on the ship cycle.

A detailed analysis of the concept of design for production, design for manufacturing and design for assembly is available in ISSC 2012 V.3.

3.3.2 Design for Maintenance

Consideration of product maintainability and reliability tends to be an afterthought in the design of ships. The design of the support processes needs to be developed in parallel with the design of the ship and not after. Parallel design can lead to lower overall life cycle costs and a product design that is optimized to its maintenance processes. Maintenance characteristics of the design and particularly unplanned maintenance are very important mainly because they lead to a reduction in operability, and hence profit in the case of commercial vessels or the ability to complete the desire mission in the case of naval vessels.

Engineering techniques can be applied to systems design to minimize the time and effort required to perform periodic preventive maintenance as well as unscheduled maintenance. Some recommendations can be given to achieve higher quality, better reliability, lower operating cost, and better maintainability. For instance, Kenneth (2007):

- Reduce the number of parts to minimize the possibility of a defective part or an assembly error

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- Reduce the complexity and time of the assembly/disassembly process
- Improve the accessibility for testing or inspections of the components of the product
- Apply DFA to minimize non-value-added manual effort during the assembly of the product
- Use modular design for components with greater probability of replacement to facilitate assembly/disassembly
- Utilize standard parts to minimize the amount of spare parts
- Provide self test and self-diagnosis as more as possible
- Ease piping connections (i.e. flange connection)

3.3.3 Design for Environment

Design for environment (DFE) is a relatively new field, developed in parallel to pollution prevention. The aims of DFE are to minimize raw material consumption, energy and natural resource consumption, waste/pollution generation, health and safety risks, and ecological degradation over the entire life of the ship, Barentine (1996).

DFE integrates environmental considerations into the design of ships with a better environmental performance over the ship's entire life cycle. Decisions made about the types of materials and other resources, as well as manufacturing processes to be used during production, affect the environmental performance of the ship. Following the finished design, the ship's environmental attributes are generally fixed and cannot be changed (Olcer, 2004). Therefore, a systematic integration of environmental considerations into the earlier stages of design is essential to achieve increased environmental performance. Incorporating DFE attributes into ship design has some benefits, such as reduced energy and material use, reduction of emissions and waste, focus on material selection issues: design for recycling, design for disassembly, management of toxic materials, and evaluation of environmental attributes.

The reader may find more details regarding the design for environment approach by referring the section 4.1.3.

3.3.4 Design for Safety

Rather than waiting for an accident to happen and then act in haste to set up new rules, all pertinent knowledge deriving from such accidents could be analyzed and stored to improve the safety as early as possible in the design process. Today, it is widely accepted that rules provide minimum standards on average and in some areas there are not even rules to provide minimum standards of safety. Consequently, Design for safety (DFS) should systematically integrate risk analysis in the ship design process with prevention/reduction of risk (to life, property, and the environment) embedded as a design evaluation attribute.

DFS is a real opportunity for ship owners to have ships customized to their needs while maintaining the same safety levels. However, DFS is a very expensive and time consuming approach, Birmingham (2000). Indeed, the resources required for additional safety during the design stage will inevitably have a cost. It is from this background that the marine DFS emerged. The key drivers of the philosophy are to keep safety as an important functional characteristic of the design and to speed up the process of risk and cost analysis, so that the process itself becomes more usable. IMO, MSC, SOLAS, ISO, IACS, and MARPOL are continuously improving and implementing the safety requirements in the shipbuilding industry. In particular, the IMO Maritime Safety Committee MSC recently adopted a new philosophy and a working approach

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for developing safety standards for passenger ships, Papanikolaou (2009). In this approach, modern safety expectations are expressed as a set of specific safety goals and objectives, addressing design, operation and decision making in emergency situations with special attention paid to flooding survival analysis and fire safety analysis.

3.3.5 Design for Retrofitting and Refurbishment

Retrofitting and refurbishment are significant cost factors in the life cycle of a ship. Retrofitting and refurbishment is being carried out mainly for the following reasons:

- To adopt ships to meet upcoming safety and environmental regulations, e.g. related to double hull structures for inland waterway ships or to meet new regulations in regard to gas emissions;
- To adopt the interior of passenger ships to varying passenger needs and comfort requirements and
- To adopt ships to new operational tasks, e.g. the conversion of tankers into FPSO etc.

For complex ships, the cost related to refurbishment can reach the order of magnitude of the original investment, i.e. of the production cost. Even if retrofitting is in many cases not driven by structural aspects, the structure of a ship is often affected by changes in the outfitting part. Methods for an efficient "Design for Retrofitting" are therefore important to consider in this report.

The European Integrated Project BESST (2011) includes, among other aspects of life cycle performance improvements for passenger ships a specific work package on Design for Easy Refurbishment. Two European projects started in 2011 are looking into refurbishment and related design methods for improving the hydrodynamic performance of ships GRIP (2011) and the overall energy efficiency RETROFIT (2011). The project MOVE-IT is looking into refurbishment of existing inland waterway ships both to comply with new structural regulations and to improve energy efficiency MOVE-IT (2011). Another European project is looking to establish current practice in particular on smaller European shipyards ECO-REFITEC (2010).

Basing on the projects mentioned above, the following challenges are being addressed with regard to Design for Retrofitting:

- Availability of Data for Retrofitting: a focus of research is to ensure consistency of data from the new building phase, which can form the basis of retrofitting. As its must be assumed for different reasons, that in many cases geometrical and other data needed to design and plan retrofitting will not be available, projects are focusing on measurement systems and the integration of measured information into CAD models for retrofitting.
- Decision Making Tools for Retrofitting: focus of research is put to develop tools helping ship owners and other stake holders to assess the benefits and feasibility of retrofitting. Those tools aim to balance the cost of retrofitting (components and production) versus the life cycle benefits (fuel cost etc.).
- Modularization appears to be the way to promote Design for Retrofitting. It will provide standard interfaces in structures as well as in outfitting (supply of energy and media) and provide the necessary balance between economy of scale (standard components) and flexibility to cope with customer needs by combining those standard components.
- Planning of Retrofitting Processes: Time is a critical factor for retrofitting. It not only influences the direct cost of retrofitting, but mainly reduces the earnings

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of the owners. Research is therefore focusing to develop tools which will improve the planning of retrofitting processes, based on the limited amount of information and considering the variety of processes and work operations.

3.3.6 Design for Robustness

Robustness is defined as insensitivity (or stability) with respect to uncontrollable parameters and is becoming a standard concept, particularly for innovative designs. Many input parameters (e.g. loads, material data, thickness, etc.) held constant during the optimization process, are subject to uncertainties causing variations of the values in the criteria set and/or violation of constraints (infeasible design). They can also be costly to control. One way is to introduce safety margins on the constraints, but this leads to a reduction of the design space. Robust design has been developed with the expectation that an insensitive design can be obtained (robust means that the product or process performs consistently on target and is relatively insensitive to factors that are difficult to control).

The robustness measure η, developed by G. Taguchi, Ross (1988), Montgomery (1991), Cho (2006), is the ratio of the mean of the attribute value μ to the standard deviation σ resulting from uncertain parameter values. In fact it is the ratio of predictability versus unpredictability.

The robust design method greatly improves engineering productivity, Isixsigma (2009). Variation reduction is universally recognized as a key to reliability and productivity improvement. There are many approaches to reducing the variability, each one having its place in the product development cycle. The robustness strategy provides the crucial methodology for systematically arriving at solutions that make designs less sensitive to various causes of variation. It can be used for optimizing product design as well as for the manufacturing process design.

4 AVAILABLE MODELLING AND ANALYSIS TOOLS

4.1 State of the Art

The current state in the development of tools for the design of marine structures is characterized by increased scope, integration and the transfer of advanced analysis tools into the early stages of design. Design tools tend to continuously add functionality, covering additional aspects of technical, economic, environmental, risk and safety related performance of the vessel to be designed. Advanced types of analyses, using finite element analysis and computational fluid mechanics, are slowly moving from being used from the detail design stages into early design. This additional functionality is more seamlessly integrated into a common design package, either by relying on a common design representation, or by the efficient translation and exchange between multiple file formats.

4.1.1 Naval Architecture Packages

Naval architecture software tools are ranging in functionality from relatively simple calculations of hydrostatics, to advanced packages with integrated support for the analysis of multiple ship performance aspects.

Traditionally, a preliminary naval architecture design package will comprise the following functionality

- Hull definition, with various levels of lines manipulation and parametric hull form definition

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- Internal geometry and compartments
- Basic hydrostatic and stability calculations
- Hull resistance estimation based on empirical methods, speed and power prediction
- Simple methods for sea keeping and maneuvering

In addition, such a package may contain simple weight and cost estimation functions, sometimes combined with required freight rate (RFR) calculations.

In recent years, additional aspects of overall ship performance have been integrated into these tools. This includes computational fluid dynamics (CFD), probabilistic stability calculation, risk based design methods, and environmental analysis.

CFD analysis has so far mainly been used in the detail design of the hull, both for optimizing a given hull form for resistance, hull-propeller interaction and sea keeping, and for verifying the final design towards contractual speed and powering requirements. In the early design stages, characterized by a wider search through the design space for preferable design solutions, CFD applications have been less used. The primary reason for this has been the high cost, in terms of time and computational effort, for the evaluation of each design alternative. Contrary to what should be expected, computational times of CFD analysis have increased over the years due to the demand for meshing detail and flow complexity increasing at a faster pace than the growth in computational power, Peric and Bertram (2011).

However, even if computational time *per* se in many cases has increased, the total effort involved in CFD projects has decreased, mainly as a result of more efficient preprocessing stages. Recent developments with respect to modeling effectiveness through seamless integration with shipbuilding CAD have paved the way for CFD based analysis also in the early stages. This has been supported by many of the commonly used naval architectural design packages either by offering CFD calculations internally, for instance for wave resistance calculations, or by providing an integration mechanism for exporting the hull description with an external CFD tool, Lee *et al.* (2010), Korbetis and Georgoulas (2011), and for the import of the resulting performance data to be stored as part of the CAD model. Examples are NAPA and Friendship Systems.

We have also seen a continuous development of the scope and functionality of CFD tools. Examples of this is the handling of very complex geometry, including moving parts, modeling turbulence, free surface effects and cavitation, motion of floating bodies and fluid structure interaction. This development can be expected to continue, as well as integrating these types of analysis into the overall ship design process.

The integration of environmental analysis into existing ship design tools has mainly centered around the Energy Efficiency Design Index (EEDI), integrating the automatic calculation of this index to be used as a criteria for identifying energy efficient design solutions, Hagen and Grimstad (2010), Harris *et al.* (2011). Alternative approaches has been the use of life cycle analysis (LCA) as a means to capture the total environmental impact of a given vessel design, Ellingsen Fet (2002), or by explicitly considering both present and future emission regulations as part of an optimization model, Balland *et al.* (2010), Balland *et al.* (2011).

We have also seen examples of economic measures of merit integrated into the early stages of the ship design process. Typically this will focus on minimizing the RFR for transport vessels, Harris *et al.* (2011). For non-transport ships, such as offshore support vessels, the RFR is less relevant. Here, the income earning potential of a

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particular design should rather focus on its appropriateness towards future contract scenarios, Erikstad *et al.* (2011).

Another important development trend is risk-based design, Papanikolaou (2009), which is moving from the realm of research into naval architecture design packages. The concept of risk-based design covers all aspects of the ship design process where probabilistic risk and safety criteria are key drivers in the process, where quantifiable risk levels are used to meet given safety performance requirements. The primary focus so far has been on probabilistic damage stability calculations. This has contributed to a higher degree of design freedom, by allowing alternative vessel arrangements given that the overall safety level can be proved to be equal or above the level corresponding to what is required from deterministic stability regulations. At the same time the application of a risk-based approach has increased the total workload in the design process. Thus the need for efficient tool support has been imminent, and the major providers of ship design applications has responded by integrating support for probabilistic stability calculations in their naval architecture design packages.

An area that has received considerable attention in recent years is the design of ship arrangements. This can be seen as part of a wider process of configuration-based design, placing emphasis on the early design conceptual layout of the design solution. The building-block approach developed by UCL, Andrews and Pawling (2007) has been central to this development, allowing for a more creative, flexible development of multiple conceptual solutions based on alternative configuration of a set of modules derived from the ship's functional specification. The motivation has not only been to improve the result of the ship design process as such, but also to provide insight into the main design tradeoffs that has to be made between multiple conflicting objectives. This supports what is termed a "requirements elucidation" process, addressing the question about what the design specification should be in the first place. The building-block approach has been implemented as part of the GRC Paramarine CAD system. Practical applications have been mainly naval vessel, but the method as such has also been applied to commercial vessels.

Another approach towards ICT support for ship arrangement design has been through a "packaging" algorithm, Oers (2011). The application will here automatically generate a large number of feasible design configurations, combined with decision support functionality to aid in the identification of preferable solutions. A set of pre-defined modules derived from the functional specification is used as input. These modules are subsequently packed according to spatial and logical rules, and then wrapped within a suitable hull form. The primary design context is also here naval ship design, but it has been tested on other ship types as well, including offshore drill ships. A similar approach has been developed at the University of Michigan, called the Intelligent Ship Arrangement (ISA) system. This tool is intended to be used as part of the US Navy *Advanced Ship and Submarine Evaluation Tool (ASSET)*. The ISA system will capture the design rules, regulations, best practices and intent of the US Navy, quantify and compare alternative general arrangements, support the improvement and optimization of the general arrangements, and provide trade studies across a large number of possible solutions, Daniels *et al.* (2011).

The traditional software tools used in the naval architecture activities of the shipyards are obviously still active. Along those we must refer to:

Auto-Ship Systems Corporation produces a number of ship design software packages, including Auto-Ship for hull-form design, Auto-hydro for hydrostatics and stability,

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and Auto-structure for design of components and management of the production process. These tools act as a suite, with common data formats and interoperability. A range of parts, hull-forms and even entire ship designs are available to download from the companies' website. Auto-ship Systems also produce a cargo management tool for control of the logistics chain and cargo stowage arrangements. The tools are offered as a customized system, based on the specific user requirements.

The *NAPA group* provides a series of products and services for ship design, analysis and manufacture. They use a central ship model, which is accessed by a set of standard and add-on subsystems for analysis. The design starts with the definition of the hull-form using a Coon's patches method. The system can accommodate multi-hulls and asymmetric hulls, as well as offshore platforms. The geometry subsystem allows the design to be worked up to a detailed general arrangement. Further subsystems allow the analysis of stability in intact and damaged conditions and launching. Additional subsystems exist to analyze hydrodynamic performance, grain carriers and container ships. The latest developments in the software include a structural analysis subsystem, NAPA Steel, and on-board NAPA. The latter is intended for loading calculations and stability analysis on-board the vessel in operation.

The *MAESTRO ship structural design codes* available through DRS Technologies provide a very comprehensive preliminary ship structural design analysis capability and are used by more than 90 organizations in 23 countries. In particular, they include a ship modeling capability and limit state assessments and enable structural design of marine structures, ships, submarines, and foundations, and provide a structural optimization capability. NAPA and MAESTRO have created a NAPA/MAESTRO (2010) interface to bring more efficiency to the early stage ship structural design, analysis, and evaluation. The intent is to adopt a single product model for NAPA rather than translate it as may be required for design limit state evaluations and to create drawings suitable for classification society review and approval. This effort underlines the trend in ship design tools to adapt for commonality and facility exchange in support of enterprise life cycle data management requirements which continue to evolve.

4.1.2 CAD Systems (General Purpose and Specialized)

Throughout the history of CAD applications in the maritime industry, a special characteristic has been that the specialized shipbuilding CAD solutions have maintained a strong position. Many of the large generic CAD systems, having the ability to distribute the high development cost of new basic CAD technologies among a very large user community and across many industries, have also tried to get a foothold within the shipbuilding industry by providing shipbuilding variants of their packages. Many of those large actors have failed in this attempt. Shipbuilding CAD is a very specialized area, with a high degree of complexity and the need for a tight integration of many diverse, specialized disciplines. Those who have succeeded have typically either merged mature ship CAD functionality on top of a generic CAD/PDM system, or have integrated the shipbuilding specific functionality and process support on a very basic level. Among those CAD tools, we can refer to:

Dassault Systèmes CATIA has been used extensively in the automotive and aerospace industries. Its surface rendering capabilities have helped design a many cars and aircraft. One of their latest products is a single, open, and web-based scalable platform ENOVIA LCA PLM V6 enables real-time collaboration and online-enabled design that fully engages global collaborative innovation practices and integrates abilities for project life cycle management (PLM). It has extensive capability for the design

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definition of structures, distributed systems, parts management, manufacturing and specialized analysis. As a relatively new entry into the ship industry however, it has a limited user base. The preliminary design module is referred to as "Structure Functional Design" and the detail design module is named "CATIA Ship Structure Detail Design." The preliminary design module saves the model in one or many CATIA parts, and the detail design is then driven by the parts generated in the preliminary design stage, however many of the tools for ship design are still in beta form and the STEP protocol is not complete, Brennan (2011).

The *CADDS5 system* from PTC offers a full suite of capabilities for product development and manufacturing with a specific applications module related to all phases of the ship design process. All preliminary design data including hull surface, coordinate reference, seam and butt lines, frame lines, etc. are saved in a single CADDS part consisting of different layers. The detail design module is called "Advanced Structural Modeling." When doing the detail design, a user has to use the preliminary design part as a reference and create a detail structural member based on the data in the preliminary design model. The single preliminary design model and the collection of detail design models can be used for FE analysis. Surface design, outfitting, cabling, piping, advanced assembly, human product interaction as well as Enterprise collaboration capabilities are available to support ship design.

Unlike other, general-purpose CAD systems, Tribon was developed specifically for ships and provides tools that cover the entire ship design process. The *AVEVA Tribon* based system has the largest user base in the ship industry and arguably remains the world's principal ship structural design software tool. AVEVA Enterprise provides enterprise solutions for information management while AVEVA Marine provides a mature ship design capability based on the legacy Tribon system now at version M3.

ShipConstructor Software Inc. (SSI) is gaining widespread use in the ship CAD industry. Recent versions of the code have incorporated a Database Driven Relational Object Model (DDROM) technology that provides a relational-CAD capability whereby objects, through their relationships to other objects, are automatically updated to reflect modeling changes. This feature provides great utility for preliminary design since common structural changes can be quickly made and the model automatically updated through the DDROM mechanism. ShipConstructor is an AutoCAD based shipbuilding computer aided and manufacturing system that provides detail design and modeling tools for production engineering of marine structures. It enables the designer to define and generate hull forms, structures, distribution systems including piping, HVAC, ships equipment and can create production instructions for NC machinery for fabrication. It utilizes a Marine Information Model (MIM) as well as a single relational database residing on a Microsoft SQL-Server database that can export standard CAD formats including STEP, IGES and ACIS/sat.

FORAN was developed by the Spanish company SENER. A central database called the "Full-ship Product Model" is used to store the design. Spatial features within the model can be given numerical or topological links, to maintain the design style. Hull-form generation is accomplished using a Non-uniform rational basis spline (NURBS) implementation. NURBS is a mathematical model commonly used in computer graphics for generating and representing curves and surfaces that offers great flexibility and precision for handling both analytic and freeform shapes. The software can describe mono-hull or multi-hull vessels with symmetric or asymmetric hulls. The hull-form developed can then be used for naval architectural analysis and further design work. Modules are included to estimate the hydrodynamic performance of the vessel. A

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notable feature of the FORAN system is the accommodation design module, which works in both 2-D and 3-D and can produce arrangement drawings for the interior fittings of the accommodation. FORAN includes modules to develop the production model, including tools to break the vessel into blocks and to draw up a build strategy. Both FORAN and Tribon now use an ORACLE database for the product model.

Graphics Research Corporations' *Paramarine* software uses the Parasolid kernel developed by EDS of Cambridge and is an object-oriented code with the user inserting and linking objects designed to assess or describe specific features of the ship design. The software is particularly suited for rapidly developing the early stages of the design definition. The use of the standard kernel allows flexibility in the defined geometry. A multi-user version of the software is under development. In addition to the extensive ship design capability, tools are under development to facilitate life-cycle management.

Intelliship, developed by the Intergraph Corporation is intended to cover the ship design process from initial design to operation. It can incorporate and evaluate the effects of distributed engineering, work sharing and lifecycle data management. Intelliship is now re-branded as Smartmarine 3D and was built using foundation based systems that are more representative of plant and processing industries than shipbuilding. Its primary marine customers are the USN and Samsung Heavy Industries in South Korea. It supports the concept of a "phase 1" geometric definition, which is represented as 3D surfaces defined by thickness rather than 3D solids. This makes the phase 1 geometric much easier to process and create global finite element meshes.

The *Nupas-Cadmatic ship design software* provides a very capable ship design package and includes features for product model interchange, development and visualization capability intended for the life cycle product management. Their ship design software was developed through a joint venture between Cadmatic Oy and Numeriek Centrum Groningen B.V. Their CAD/CAE/CAM design software is intended to improve the efficiency, design and production of shipyards and ship design offices. Their system allows for basic ship design using 3 modeling techniques and allows for complete structural design using intelligent structural topology. This method enables automatic structural component adjustment in way of hull design changes. The design model is then rapidly transformed into a production specification report complete with materials lists, panel inventory management and creation of 2D AutoCAD-like drawings for production purposes. Other modules include machinery layout, piping, outfitting, build strategy and global engineering connectivity.

A general trend for some years has been the extension of shipbuilding CAD towards integration with Product Data Management (PDM) and Product Lifecycle Management (PLM) solutions. PLM is often used to describe a comprehensive management approach to combine different perspectives with corresponding tools towards sustainable products, Nagel (2011). This may comprise Life Cycle Assessment (LCA) focusing on environmental impact, Life Cycle Costing (LCC) to assess the complete costs over the product life time, Life Cycle Performance (LCP) focusing on life cycle performance, and Cost Benefit Analysis (CBA) for decision support.

We have also seen a development towards extending the CAD model into a Virtual Reality (VR) model, Andrews and Pawling (2007); Lödding, Friedewald *et al.* (2011). This VR model can be used for design or assembly reviews, collision detection and is of particular importance for high complexity outfitting assembly. A challenge for using VR has been the model development time, given the time and resource constraints in a typical shipbuilding and engineering project, as well as handling the high number of

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design changes and late arrival of sub-models from suppliers. To meet these challenges, dedicated VR systems have been developed based on the specific characteristics of the shipbuilding process, Nedess *et al.* (2009). By concatenating the data imported from the CAD model with metadata derived from the PDM, PLM or ERP system, a rich VR model can be developed that allows for the interactive filtering and navigation based on ship specific model concepts rather than general geometric constructs. Further, by adding assembly sequences and manipulation logic, immersive dynamic sessions can be created.

4.1.3 Tools to Manage Inventory of Hazardous Material Data

The international convention for the "Safe and Environmentally Sound Recycling of Ships" was adopted by the IMO in Hong Kong, (2009). This convention is primarily focused on the safe and environmentally sound recycling of ships. A key requirement is the Inventory of Hazardous Material (IHM), which is also known as the ship's "Green Passport". Even though the convention is not expected to be ratified before the 2013–2015 timeframe, many shipyards and ship owners have already started to implement compliance with the convention. The last available data from IMO on IHM may be found in the Resolution MEPC 179(59) (2009).

For ships in service, the classification societies typically provide simple tools for the superintendent to support the compilation of the hazmat inventory, to serve as a basis for the verification and certification by the class. For new builds, this is typically done by the shipyard, and followed up by class throughout the construction survey process.

The tools range from simple templates to be filled out, to more comprehensive packages containing libraries of material data. One example of the latter is the PrimeShip-Inventory provided by ClassNK, centered on a large database of material declarations from ship suppliers.

4.2 Current Practice out from the Survey

This section deals with an analysis of the survey results from a tools oriented point of view. For a more comprehensive analysis of the results, please refer to chapter 8.

4.2.1 CAD Tools

AutoCAD is used by almost companies which answered the survey. This is mainly related to the exchange needs of the shipyard with providers and sub-contractors. It is obvious that AutoCAD must not be regarded as the major CAD system used in the shipyards. Depending on the design phase the usual tools remain in a dominant position. These tools include NAPA, AVEVA/TRIBON, FORAN, CATIA, and others more recent tools as RHINO.

4.2.2 Class Society Tools

Regarding the classified ships (excluding navy vessels), the answers to the survey came mainly from Europe and Asia. As expected, ABS Safehull, BV Mars 2000 and GL Poseidon, which are usually requested by ship owners, have been referred to by a large majority.

4.2.3 General Purpose Structural Analysis Tools

Three software tools have been proposed in the survey: ABAQUS, ANSYS and NASTRAN. No other tool has been proposed by the answering companies. It is noticeable that FEM tools are used in the design loop sooner and sooner. Fifteen years ago, FEA were used only during the Detailed Design Phase and often sub-contracted. Today, these calculations are made in house, and some shipyards answered that they use them even in Preliminary or Basic Design phases.

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4.2.4 Computational Fluid Dynamics

Calculations with CFD tools are more confidential and still subcontracted mainly to model basin companies. This appears to be linked to the difficulty of use of such tools compared with linear FEA calculations, the need for highly specialized engineers to run the tools, and the high computational power and time requirements of the CFD tools. The shipyards in most cases are not equipped with computer platforms with the needed computation power to carry out CFD analysis in support of day-to-day design.

5 OPTIMIZATION AND DECISION SUPPORT TOOLS

Inside a comprehensive life cycle management set of tools, optimization tools are needed. Those tools play obviously a significant role during the design process but are also required during the ship operation as decision support tools to find out the best alternative for ship repair tasks.

For instance, to compare the impact of technological innovations on ship system level onto the life cycle performance in a holistic way, the European Integrated Research Project BESST, Roland *et al.* (2011) is developing a tool, which intends to compare design alternatives in view of life cycle cost, safety, environmental impact and public perception. While the focus of the tool is on complex ships build in Europe, the concept will also be applicable in other areas, e.g. to compare the environmental impact of different transport modes. At the end of the BESST project, the tool will be applied to assess the technical project results for three different “Virtual Ship Models” comprising passenger ships and ferries.

5.1 State of the Art

5.1.1 Overview of the Tools

The decision support methodology for the concept and preliminary design of complex ship structures (e.g. multi-deck, multi-hull, warships) requires hybrid solvers, multiple models and adequate computational resources. In reports of ISSC’2003 (TC IV.2), ISSC’2006 (TC IV.1 and 2) and ISSC’2009 (TC IV.1 and 2) basic definitions, models and the practical examples of progress of the profession (including aerospace) have been reported. It has showed the maturing of the design process and inclusion of decision support problems enabling designer faster and better decisions.

The modern multi-criteria, multi disciplinary design problem has to be solved as a multi-stakeholder one with the support of the ship-owner; the Classification Society/Navy and the shipyard. Besides those requirements, as mentioned in the previous Chapters, we need to include societal losses based on the risk analysis (ISSC’2009, TC IV.1) and complex economical calculations including uncertainty to cover LCC and other complex requirements. Direct calculation paradigm established in the seventies, Evans (1975), Hughes *et al.* (1980), applied the assumption that linear response models, augmented with nonlinear adequacy models are fast enough for the task. With the full introduction of the ultimate strength criteria into the design process as well as reliability based calculations (multi-point, direct), parallel processing power was needed, Thoft-Christiansen, Murotsu (1986), Zanic *et al.* (1993).

The demands today are even more stringent with introduction of e.g. collision/stranding load cases that require non-linear solvers, Paik and Melchers (2008), Hughes and Paik (2010), ALPS/HULL (2010), as well as a complex load cases definitions, Diez *et al.* (2010), complex responses for design optimization, Amatuli *et al.*

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(2010), Remes *et al.* (2011) and the multiplicity of load cases as required by the new IACS CSR-H Harmonized Rules. Note that proper definition of design load cases is of paramount importance for design optimization since optimistic loads lead to unsafe structures whereas pessimistic ones lead to the inefficient structure regarding cost, weight etc. The size of the models (measured in degrees of freedom), required by those demands is also large.

However, the models can be successfully generated semi automatically (for the mesh size required for the problem at hand) through CAD to FEM interfaces in NAPA Trident, Tribon, etc. as described in Chapter 4. To handle the required large problems in the acceptable time, the techniques of surrogate (meta) modeling are used in the decision support problems. For very large problems, as well as for the integrated multi-disciplinary models, the problem decomposition and coordination techniques are often applied with or without surrogate models. Both techniques are described in the following subsections.

To handle these complex requirements in a tractable way, for the objectives defined in Chapter 3 with multiplicity of tools as defined in Chapter 4, an applicable taxonomy is needed for basic data sets, functions, associated modules and the basic optimization problems.

The design problem taxonomy, see Table 1, is defined using design descriptors and the necessary mappings from design space to the attribute space (direct or normalized) and to the selection spaces. In structural design, the mappings are implemented as computational modules for analysis (AM: response, adequacy, quality) and synthesis (SM: GUI, optimization solvers, surrogate solvers).

Those modules are integrated for solving complex problems and the design procedure flow, the design problems definitions and the generic and full ship models (example) are given in Table 2. Problems are solved via the Multi Criteria Decision Making (MCDM) techniques i.e. by its MADM or MODM variants (Problems 1A and 1B - see col. 2 of the Table 2). Filtering (Problem 2) to get non dominated solutions (Pareto frontier) is needed to enable interventions of stakeholders in subjective decision making (Problem 3).

Integration of all those modules is a complex task particularly for the large scale decomposed problems. It requires the efficient GUI and the problem sequencers for controlling the flow of data and processes. It is also important the final selection of the preferred design.

To gain the speed of the design process, the optimization process has to follow designer's data availability and provide fast answers with adjusted models. This rules out the standard optimization procedures as inoperable, and requires development of new approaches to the decision support problem for the complex ships.

Development of such novel and efficient multi step procedures is needed in order to solve the complex topology optimization problem with interwoven scantling/geometry optimization when e.g. number of decks or web frames, openings in side structure, etc., are elements of the design variables set. The general approach has to combine three design steps (see Table 2, col. 1):

Steps 1 and 2 usually use the generic/simplified concept design models (see Table 2, col. 3) for the fast generation of design variants regarding topological, geometrical and scantlings variables. The example of the concept phase optimization block is given in Table 1 for the efficient description of applied modules, surrogate modeling or decomposition techniques.

The 'full ship' model in Step 3 used for the preliminary design level optimization and analysis of the preferred design is given in Table 2, col. 3. Selection block, between two design phases, is also shown between models.

Note: RoPax ship, used here as an application example, was developed during the EU FP6 project IMPROVE and was described in the Report of ISSC'2009 TC IV.2. Novel process includes surrogate modeling with parallel processing and partial problem decomposition and is currently in phase of extensive testing, Prebeg (2011).

5.1.2 Large Scale Optimization Techniques - Surrogate Modeling,

As stated before, the analysis methods of contemporary complex engineering systems, like nonlinear CFD or FEM, can be computationally very demanding and despite of steady advances in computing power; the expense of repetitive running of analysis codes remains nontrivial. A single analysis of one design solution can take from a few minutes to hours or even much longer for e.g. non-laminar and non-stationary 3D CFD problems. Due to these characteristics, direct use of some analysis methods is not possible in optimization because the optimization algorithm may require the computation of several hundreds or even thousands of single analysis cases. An application of surrogate modeling as an approximations (or surrogates) of expensive computer analysis codes can result in significant savings in both the number of analysis and the total time in which satisfactory optimal solutions are obtained. One another important aspect of surrogate based optimization is easier parallelization of optimization process.

Surrogates also offer insight into functional relationship between design parameters and design criteria which is one of the obstacles in understanding the behavior of numerical models.

One of the most cited handbooks with detail overview of designs of experiments methods (DOE) for classical (physical) experiments is Montgomery (2001) while the overview of surrogate modeling for deterministic computer experiments (DACE - Design and analysis of computer experiments) can be found in Fang *et al.* (2006).

The main difference between "classical" and computer experiments is nonexistence of random error for deterministic computer experiments which leads to conclusion that surrogate model adequacy is determined solely by systematic bias and that the classical notions of experimental blocking, replication and randomization are irrelevant.

Steps necessary for generation of surrogate models includes: planning of experiments or sampling, execution of simulations with original analysis methods, generation or creation of selected surrogate model and validation of surrogate model adequacy.

After selecting an appropriate experimental design according to given criteria, Goel *et al.* (2008) and performing the necessary computer runs, the next step is to choose a surrogate technique and corresponding fitting method. Many alternative methods exist, and there is no clear answer which is better. The selection of appropriate surrogate method depends mostly on characteristic of physical phenomenon that is approximated.

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Table 1: Basic taxonomy for integration of complex decision support models

DESIGN DESCRIPTION (SETS AND SPACES)

$\boldsymbol{d}, \boldsymbol{d}^0, \boldsymbol{d}^-$	= n-tuple of (all, basic, remaining) design descriptors
$\boldsymbol{d}$	= $\{d_i\} = \boldsymbol{x}, \boldsymbol{d}^-\}; \boldsymbol{d}_i = \{d_{iMEAN}, statistics_i\}, i = 1, \ldots, n$
$\boldsymbol{D^k}$	= design variant k (or project $\boldsymbol{P}^k$) = $\{\boldsymbol{d}, \boldsymbol{y}, \boldsymbol{m}, \boldsymbol{l}\}^k$
$\boldsymbol{m}$	= n_v-tuple of normalized attribute values; point $\boldsymbol{m}^k$ in $\boldsymbol{M}$
$\boldsymbol{M}$	= metric attribute space spanned by attributes m_i
$\boldsymbol{l}$	= n_v-tuple of composite attribute values; point $\boldsymbol{l}^k$ in $\boldsymbol{L}$
$\boldsymbol{L}$	= selection space spanned by composite attributes l_i
$\boldsymbol{x}$	= n_x-tuple of design variables x_i, $i = 1, \ldots, n_x$; point $\boldsymbol{x}^k$ in $\boldsymbol{X}$, $\boldsymbol{x} = \{\boldsymbol{x}^{Topology}, \boldsymbol{x}^{Geometry}, \boldsymbol{x}^{Material}, \boldsymbol{x}^{Scantlings}\}$
$\boldsymbol{X}, \boldsymbol{X}^{\geq}, \boldsymbol{X}^{ND}$	= design, feasible, nondomin. spaces spanned by x_i,
$\boldsymbol{y}$	= n_y-tuple of design attribute values; point $\boldsymbol{y}^k$ in $\boldsymbol{Y}$
$\boldsymbol{Y}$	= attribute space spanned by design attributes y_i
$\boldsymbol{z}$	= set of load effects (stresses, displacements from FEM response analysis) or economy data for given $\boldsymbol{d}^{\Phi}$ and $\boldsymbol{d}^{\epsilon}$

MAPPINGS

$\boldsymbol{c}$	= n_c-tuple of design criteria functions (mappings) $\boldsymbol{c} = \{c_i\} = \boldsymbol{g}U\boldsymbol{a}$ $c_i : (\boldsymbol{d}, \boldsymbol{z}) \rightarrow q_i$ (quality measure)
$\boldsymbol{a}$	= n_a-tuple of design attributes fn's (obtained from $\boldsymbol{c}$) $a_i : (\boldsymbol{d}, \boldsymbol{z}) \rightarrow y_i$
$\boldsymbol{g}$	= n_g-tuple of design constraint functions(obtained from $\boldsymbol{c}$) $g_i : (\boldsymbol{d}, \boldsymbol{z}) \rightarrow I_{gi}$ (pass-fail indicator), $\boldsymbol{X}^{\geq} = \{\boldsymbol{x} \mid I_{gi} = pass, all\, i\}$; ${}^i_j\boldsymbol{H} = n_{ss}$-tuple of mappings (subsystem i to j) ${}^i_j\boldsymbol{H} : (\boldsymbol{d}, {}^i\boldsymbol{z}) \rightarrow^i_j \boldsymbol{z}(\equiv {}^i_j\boldsymbol{h})$
$\boldsymbol{o}$	= n_o-tuple of design objective fn's o_i = manipulated/simplified a_i, u_i, l_i
$\boldsymbol{p}$	= n_p-tuple of probabilistically based $\boldsymbol{c}$ functions e.g. REL: $\boldsymbol{g}(\boldsymbol{d}, \boldsymbol{z}) \rightarrow p_{failure}$; ROB: $a_i(\boldsymbol{d}, \boldsymbol{z}) \rightarrow$ robustness measure
$\boldsymbol{r}$	= n_r-tuple of design response fn's (e.g. 3D FEM) $r_i : \boldsymbol{d} \rightarrow \boldsymbol{z}^i$
$\boldsymbol{u}$	= n_u-tuple of subjectively normalized attribute functions $u_i : (y_i, \boldsymbol{P}^u) \rightarrow m_i$; $\boldsymbol{P}^u$ = designer inter/intra attribute preference data
$\boldsymbol{v}$	= n_v-tuple of value functions $v_i : (\boldsymbol{m}, \boldsymbol{P}^v) \rightarrow l_i$, alternatively: $v_i(\boldsymbol{u}(ROB(\boldsymbol{a}(\boldsymbol{d}, \boldsymbol{z}), \boldsymbol{P}^u), \boldsymbol{P}^v) = l_i$; e.g. $v_i = L_p = \Sigma|\boldsymbol{m}^* - \boldsymbol{m}|^p)^{1/p}$ $\boldsymbol{m}^* \subseteq \boldsymbol{D}^{target}$ or $\boldsymbol{m}^{ideal} = \boldsymbol{m}^* = \{m_i^{max}\}$

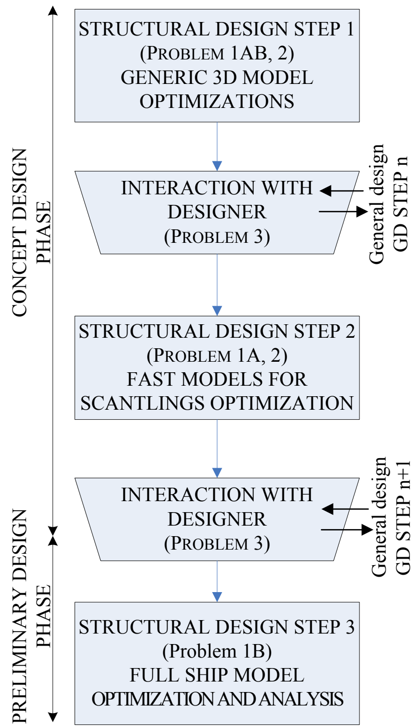
COMPUTATION MODULES AND THEIR APPLICATION TO DECISION SUPPORT PROBLEM

$\boldsymbol{\alpha}$	= adequacy meta-system; subset of modules in the analysis model (AM) containing safety (e.g. class. Rules) constraint functions/mappings g_i. Output: $\boldsymbol{I}_{gi}$, $\boldsymbol{g}$-values.
$\boldsymbol{\Gamma}$	= set of synthesis modules (GUI) in synthesis model (SM) for optimization (using $\boldsymbol{P}^u$,$\boldsymbol{P}^v$ data for subjective definition of $\boldsymbol{u}$ and $\boldsymbol{v}$), designer interaction with the design process, filtering of designs and visualization of $\boldsymbol{X}, \boldsymbol{Y}, \boldsymbol{M}, \boldsymbol{L}$ spaces. Output: $\boldsymbol{m}, \boldsymbol{l}$.
$\boldsymbol{\Delta}$	= set of modules for the synthesis (optimization) problem definition (selection of variables $\boldsymbol{x}$ and criteria fn's $\boldsymbol{a}$ and $\boldsymbol{g}$, problem decomposition and coordination)
$\boldsymbol{\epsilon}$	= environment/economy meta-system (loads, costs, etc.); subset of modules in AM with data generators E: $\boldsymbol{d}^{\epsilon} = \{\boldsymbol{d}^{pressuresLC}, \boldsymbol{d}^{accelerationsLC}, \boldsymbol{d}^{masses}, \boldsymbol{d}^{costs}\} = E(\boldsymbol{d}^0) \subseteq \boldsymbol{d}$
$\boldsymbol{\Phi}$	= structural (physical) meta-system; subset of modules/modelers in AM/SM with data generators F: $\boldsymbol{d}^{\Phi} = \{\boldsymbol{d}^{topology}, \boldsymbol{d}^{geometry}, \boldsymbol{d}^{material}, \boldsymbol{d}^{scantlings}\} = F(\boldsymbol{d}^0) \subseteq \boldsymbol{d}$
$\boldsymbol{\pi}$	= reliability/robustness meta-system; subset of AM containing modules based on **REL/ROB** ($\boldsymbol{d}_{MEAN}$, $\boldsymbol{statistics}$, $\boldsymbol{z}$) functions. Output: $\text{prob}_{\text{failure}}$, robustness measures
$\boldsymbol{\rho}$	= response meta-system; subset of AM, containing modules for FEM procedures r_i. Output: $\boldsymbol{z}$ (load effects).
$\boldsymbol{\Sigma}$	= set of optimization solvers (e.g. Seq. Linear Programming- (SLP), Fractional Factorial Experiments (FFE), Multi Objective Particle Swarm Optimization (MOPSO), Multi Objective Genetic Algorithms (MOGA), Evolution Strategy-Adaptive Monte Carlo (ES - AMC), etc.) generating Pareto frontier $\{\boldsymbol{x}^k, \boldsymbol{y}^k\}^{ND}$ by filtering designs in $\boldsymbol{X}^{\geq}U\boldsymbol{Y}^{\geq}$ based on objectives $\boldsymbol{o}$.
$\boldsymbol{\Xi}$	= surrogate solvers (e.g. Response surfaces (RS), Kriging, Radial Basis Functions (RBF), etc.) Input : set $(\boldsymbol{d}, \boldsymbol{z})^k$ from fn c_i, output: quality measure q_i for any $\boldsymbol{d}, \boldsymbol{z}$; e.g. $q^{RBF} = c_i^{RBF}(\boldsymbol{d}, \boldsymbol{z})$, ($q^{RBF} \equiv y_i, m_i, l_i$ or z_i)
$\boldsymbol{\Omega}$	= design uality meta-system; subset of AM/SM containing functions/mappings a_i. Output: $\boldsymbol{y}$.

Example of Optimization PROBLEM 1A, 1B, 2	
$\boldsymbol{x}$	$\boldsymbol{x}^G = F(\boldsymbol{d}^{0G}), \boldsymbol{x}^T = F(\boldsymbol{d}^{0T}), \boldsymbol{x}^S = F(\boldsymbol{d}^{0S})$
$\boldsymbol{y}$	$\boldsymbol{\Omega}^{cost}, \boldsymbol{\Omega}^{mass}, \boldsymbol{\Omega}^{VCG}$
$\boldsymbol{g}$	$\boldsymbol{I}_g = \alpha^{BV} (= \alpha^{MAESTRO})$
$\boldsymbol{AM}$	$\boldsymbol{d}^{\epsilon} = E(\boldsymbol{d}^{BV\ Loads}), \rho^{MAESTRO}$
$\boldsymbol{SM}$	(a) $\sum^{DOE,\ ANOVA}(x^T, x^G)$, (b) $\sum^{MAESTROSLP}(x^S)$
$\boldsymbol{Res}$	6 Topological/Geometrical Variants

Table 2: Large scale design procedure

<table>
<tr><th>DESIGN PROCESS PHASES</th><th>DECISION SUPPORT PROBLEMS</th><th>MODELS AND SELECTION BLOCK</th></tr>
<tr><td>



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PROBLEM 1A - Multi Attribute Decision Making (MADM) solution. Solved by $\boldsymbol{\Sigma}$ optimizers (may include surrogate solvers $\boldsymbol{\Xi}$). Generate set of designs $\boldsymbol{y}^k = \{\boldsymbol{a}(\boldsymbol{x}^k, \boldsymbol{d}^-), \boldsymbol{p}\ (\boldsymbol{a}(\boldsymbol{x}^k, \boldsymbol{d}^-))\}$ for $\boldsymbol{x} \in \boldsymbol{X}^{\geq}$

PROBLEM 1B - Multi Objective Decision Making (MODM) solution. Solved by $\boldsymbol{\Sigma}$ optimizers (including surrogate solvers $\boldsymbol{\Xi}$).
Extremize $y_i = \{a_i(\boldsymbol{x}, \boldsymbol{d}^-), \boldsymbol{p}(a_i(\boldsymbol{x}, \boldsymbol{d}^-))\}$ for $\boldsymbol{x} \in \boldsymbol{X}^{\geq}$
Extremize $l_i = v_i\ (\boldsymbol{u}\ (\mathrm{ROB}\ (\boldsymbol{a}(\boldsymbol{d}, \boldsymbol{z}), \boldsymbol{P}^u), \ \boldsymbol{P}^v)$ for $\boldsymbol{x} \in \boldsymbol{X}^{\geq}$

PROBLEM 2 - Using $\boldsymbol{\Sigma}$ modules filter the nondominated (Pareto) solutions $\boldsymbol{D}^{\mathrm{kND}}$, from designs generated in PROBLEM 1, based on direction of quality improvement for each objective. Appl. as second part of MADM or for multiple MODM runs.

PROBLEM 3 - Using $\boldsymbol{\Gamma}$ modules select the preferred design $\boldsymbol{D}^{\mathrm{FIN}}$ on Pareto frontier (PROBLEM 2). Apply:
(1) normalized attribute functions set
$\boldsymbol{u} = \{u_i\} = \{w_i\ (\boldsymbol{P}^{\mathrm{u\ AHP}}) \cdot U_i(y_i, \boldsymbol{P}^{\mathrm{u\ fuzzy}})\}$
enables mapping of $\boldsymbol{y}$ to normalized values $\boldsymbol{m}$ using:

- inter-attribute preferences $\boldsymbol{P}^{\mathrm{u\ fuzzy}}$, defined interactively, containing coefficients of each fuzzy function U_i.
- intra-attribute subjective preference matrix $\boldsymbol{P}^{\mathrm{u\ AHP}}$, defined interactively, that allows calculation of the importance factors $\mathrm{w} = \{\mathrm{w}_i\}\|\boldsymbol{\Lambda}\|$, ($\boldsymbol{\Lambda}$ is an eigenvector corresponding to the largest eigenvalue of the problem ($\boldsymbol{P}^{\mathrm{u\ AHP}}$ - $\boldsymbol{\lambda}$ I) w = 0).

(2) subjective value of each design defined using functions $\boldsymbol{v}$ ($\boldsymbol{m}^k$) for the design variant k based on e.g. distance norms $\boldsymbol{v} = \{L_p\}$, p=1,2 or ∞; used with respect to the specified target design $\boldsymbol{m}^*$.

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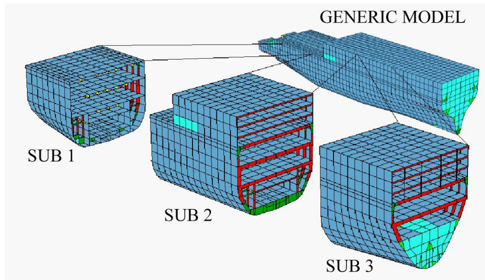
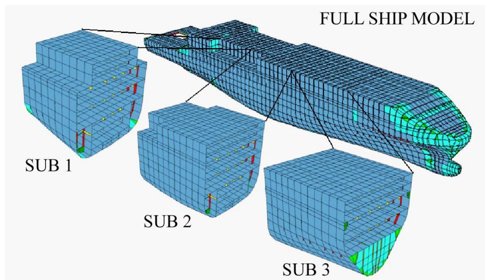


Interaction With Designer – PROBLEM 3
$\boldsymbol{\Omega}$ WGT, PRCST, MAINT, FUEL, LCC, ROBPRCST, ROBLCC
$\boldsymbol{\Gamma}^{\mathrm{AHP,\ Fuzzy,\ Lp\ metrics}}$, $\boldsymbol{\Gamma}^{\mathrm{DeView}}$
Res: Prefered Design



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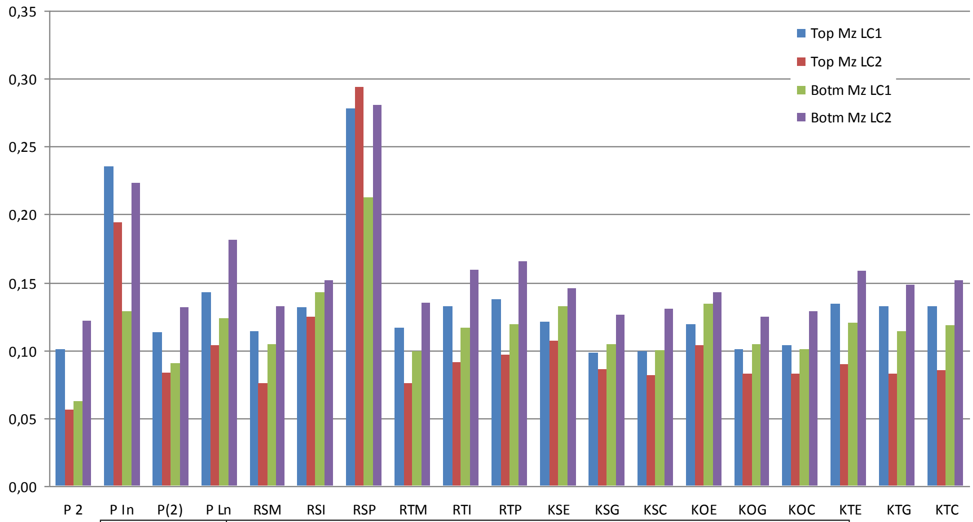

Abbrev.	Description
P2	Full second order polynomial surrogate
PIn	Polynomial with interactions
P(2)	Pure quadratic polynomial surrogate
PLn	Linear polynomial surrogate
RSM	Simple RBF, Multiquadratic basis function
RSI	Simple RBF, Inverse multiquadratic basis function
RSP	Simple RBF, Thin plate spline basis function
RTM	Trend RBF, Multiquadratic basis function
RTI	Trend RBF, Inverse multiquadratic basis function
RTP	Trend RBF, Thin plate spline basis function
KSE	Simple Kriging, Exponential variogram model
KSG	Simple Kriging, Gauss variogram model
KSC	Simple Kriging, Cauchy variogram model
KOE	Ordinary Kriging, Exponential variogram model
KOG	Ordinary Kriging, Gauss variogram model
KOC	Ordinary Kriging, Cauchy variogram model
KTE	Trend Kriging, Exponential variogram model
KTG	Trend Kriging, Gauss variogram model
KTC	Trend Kriging, Cauchy variogram model

Figure 1: Normalised RMS error for the tested surrogate models for the girder bending moment in top (deck) and bottom of the barge structure for two load cases - sag, hog (Prebeg, 2011)

Probably the most widely used surrogate method are response surfaces (RS) that approximates criteria functions using low order polynomials, mostly simple linear and quadratic or some specific polynomials like orthogonal Legendre polynomials. RS' popularity for modeling of deterministic computer experiments, besides their good characteristics for certain type of problems, is due to the fact that surrogate modeling itself evolves from classical Design of Experiments theory where RS was used for the description of physical phenomena. Some of the applications in engineering includes: ship structural optimization, Prebeg (2011) and Pareto front generation, Goel *et al.* (2007).

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Another surrogate modeling method that evolves from statistics, in this case geostatistics, is Kriging modeling which was originally developed to estimate mineral concentrations over an area of interest given a set of sampled sites from the area. A Kriging model is a generalized linear regression model that accounts for the correlation in the residuals between the regression model and the observations. Kriging offers a good flexibility to approximate many different and complex response functions and it is a good choice for approximating deterministic computer models because it interpolates the observed data points. Kriging models have been used in a variety of applications including conceptual design, structural optimization, multidisciplinary design optimization, aerospace engineering and mechanical engineering.

Radial basis functions (RBF) (surrogate method) have been developed for scattered multivariate data interpolation. The method uses linear combinations of a radially symmetric function based on Euclidean distance or other such metric to approximate response functions. Like Kriging, it is also interpolation based technique and it is a good choice for approximating deterministic computer models. Other surrogate models used in engineering includes: Artificial Neural Network (ANN), Support Vector Machine (SVM), Splines (linear, cubic, NURBS), Multivariate Adaptive Regression Splines (MARS). Comparison of different surrogate models for girders in a barge structure is presented in Fig. 1 based on Normalized RMS error measure.

5.1.3 Large Scale Optimization Techniques - Decomposition and Coordination

Complex engineering systems can typically be considered a hierarchy of coupled subsystems. The total performance of such complex systems is a combination of responses evaluated at each of subsystems. A standard optimization approach that does not take into account this behavior usually treats the total system, or some part of the total system, as one integral element with one optimization sub problem. Another approach is to treat the total design problem as a group of non-coupled optimization sub-problems with their local objectives, not taking into account the influence that such changes have on the overall design, while system design objectives are not translated into subsystems/sub-problems criteria.

As stated in the overview by de Wit and van Keulen (2010), the field of multi-level optimization and multi-disciplinary optimization is concerned with developing efficient analysis and optimization techniques for complex systems that are made up of coupled subsystems (components). Multi-level or multi-disciplinary optimization methods rely on a decomposition of the optimization problem into individual optimization problems that are coupled. Thus, it is attempted to incorporate design variables, objectives and constraints originating from different levels and/or disciplines into the design.

Unlike some other overviews that handled either multi-level optimization or multi-disciplinary optimization, de Wit and van Keulen (2010) focuses on the general steps of methods that belong to either the field of multi-level optimization or the field of multi-disciplinary optimization. According to that work the coordination approaches that handle decomposed problems can be classified according to the Figure 2.

Some of the existing coordination methods includes: Optimization by Linear Decomposition (OLD), Concurrent Subspace Optimization (CSSO), Linearized multi-level optimization (LMLO), Collaborative Optimization (CO), Bi-level Integrated Systems Synthesis (BLISS), Analytical Target Cascading (ATC), Analytical Target Cascading with Lagrangian Coordination (ALC), Quaziseparable Decomposition (QSD), and Inexact Penalty Decomposition (IPD).

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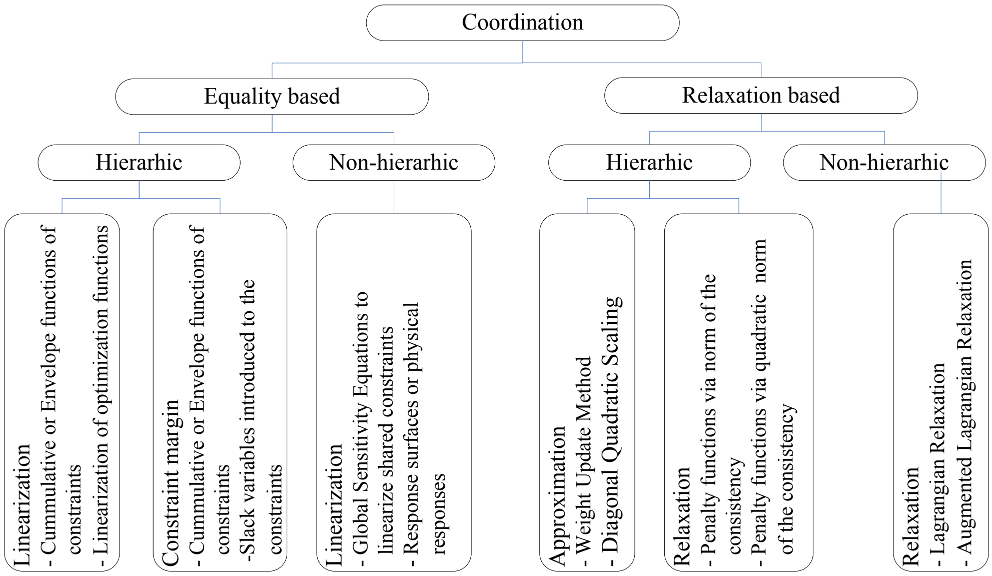

Figure 2: Classification of coordination approaches

Several basic properties for some of the mentioned multilevel optimization methods are given in Table 3 based on Agte *et al.* (2010).

Flowchart of BLISS, based on Agte, (2005), is given in Figure 3 as an example of tool that includes multilevel optimization in combination with surrogate modeling and selection of appropriate surrogate modeling technique with respect to the relevant accuracy criteria.

In one of the recent panel discussions from this research area, Agte *et al.* (2010) two perspective directions or categories for future advancements has been identified.

The first category, so called horizontal, encompasses developments that improve on the capabilities already established toward greater dimensionalities of the applications and extend the application spectrum, e.g., to include the life cycle, economic factors, uncertainty, and reliability.

The second category, or so called vertical, identify developments that are conceptually and qualitatively new, for instance optimization of entire families of products for cumulative return on investment. The two orthogonal growth directions are expected to symbiotically reinforce each other into a “dream growth” delivering capabilities that are both qualitatively new and powerful in terms of the size of the problems they will solve.

Table 3: Overview of basic aspects of multilevel optimization methods

	CO	CSSO	BLISS	ATC
System-level analysis required	×	✓	×	×
Subspace sensitivity analysis required	×	✓	×	×
Number of levels	2	2	2	2+
Subspace optimization influenced by targets	✓	×	✓ (indirectly)	✓
Autonomous subspace optimizations	✓	✓	✓	✓

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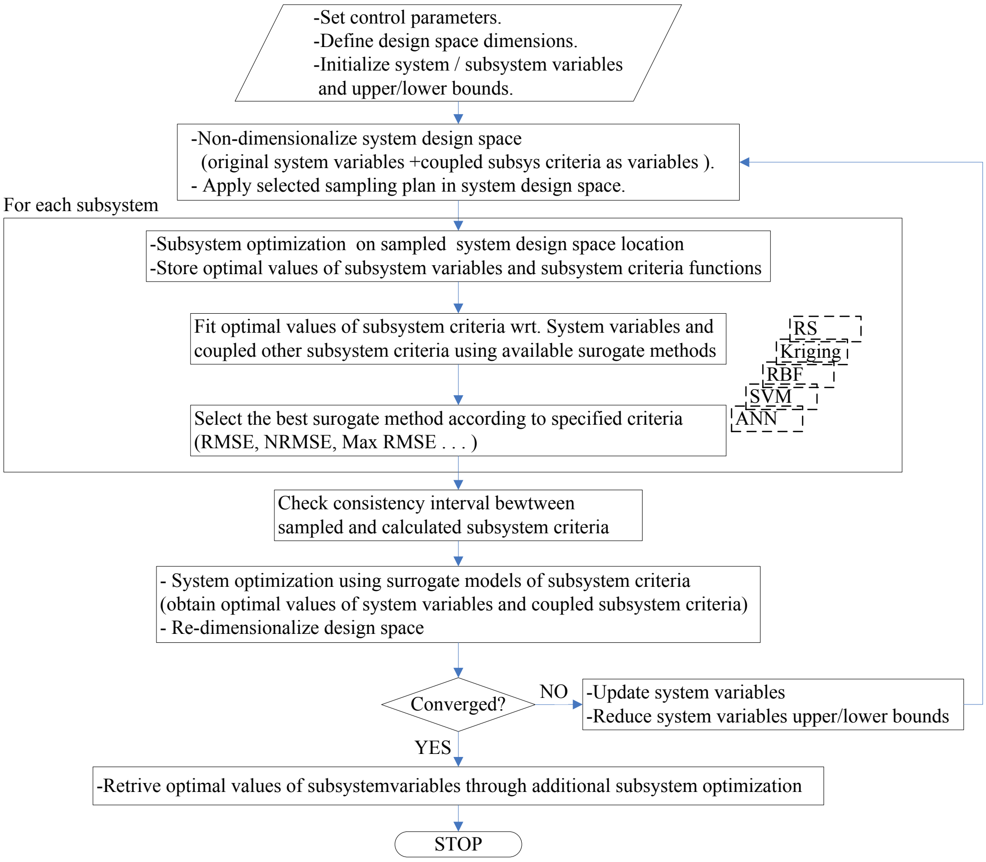

Figure 3: Flow chart of BLISS - multi-level optimization method with surrogate modeling used for subsystems

5.2 *Current Practice and Future Trends*

5.2.1 *Optimization for Design and Production*

Classical design paradigm: 'cost vs. safety in the available time' is also in the background of the modern design procedures. One of the major drivers of expected achievements are novel design methodologies that have to closely join two collaborating design systems (general ship design and structural design) as well as the basic stakeholders in the paradigm (Owner, Yard/Designers, Regulatory institutions) through formulation of Decision Support Problem for rational decision making. Multi-stakeholder approaches achieved through an interactive design environment (GUI) enables stakeholders to discover their subjective preferences and may improve the quality of decisions. It was confirmed in the EU FP6 projects IMPROVE and DeLight that the primary role structural designers is to generate a Pareto frontier of non-dominated structural designs. This frontier is then used for higher level decision making (general design) to multiply the benefits from the structural optimization.

Ship-owner's profit can be significantly increased due to reduction in fuel consumption (better propulsion and ship hull form, reduced weight, etc.), increase in payload and better LCC performance. It is also very important to acknowledge that reduction of fuel consumption can significantly reduce CO2 emission, thus increasing environ-

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mental friendliness and also ensuring that requirements related to the pollution would be easier satisfied in the foreseeable future.

Regarding cost competitiveness, the new methodologies give shipyards and owners the possibility to select competitive design solutions by following the paradigm: better ship for the shipyard production and more profitable ship for the owner. Modern designs presented in many recent papers and the associated design attribute values prove that gains from this paradigm, as well as the efficiency of the modern methodology (design and IT), is driving the design process towards such optimization approaches.

Hamada *et al.* (2011) propose a new design system discussing uncertainties in the product information. The system newly, introducing an optimization method named Wildcard GA, has been applied at the initial design stage whose decisions extremely influence the cost and performance, and when the detailed information on the ship is not available. From the viewpoints of optimization and convergence of solutions, superior performance by Wildcard GA compared to general optimization methods is also reported.

Nakamori *et al.* (2010) report an optimal structural design of midship sections with rearrangement of compartments and investigate the influence of the design variables in the structural optimization of the midship sections of bulk carries showing the material and assembling costs of the optimized structural design by using their own developed structural optimal structural design system with a genetic algorithm. The developed system is connected with the 3D product model.

The features of the tool and the related methodology, as well as the Key Performance Indicators used to do the assessment is described in more detail by Nagel (2011ab).

Regarding safety: In the Proceedings of ISSC, 2009, TC IV.1, Section on 'Defining the principles for acceptance criteria', the owner's and societal interests are contrasted. Owner's basic economical consideration (y) can be, somewhat simplified, summarized as:

y =	net gain with running costs subtracted	–	sum of calculated expected loses i.e. risks
		or	
y =	(p)	–	(r)

with y > 0, where the second term r represents the sum of N considered unwanted events, quantified by product of i-th event frequency ($\boldsymbol{\lambda}_i$) and the associated expected loss for the owner. Note that r can be subdivided into risks related to serviceability (r_{service}) and collapse (r_{ultimate}) criteria due to different associated costs, related to maintenance and loss of ship respectively. The inequality can be applied for any time horizon, and corrected for the related ship condition, interest rates, etc. that the owner considers applicable for his vessel.

The owner should provide added value to society (GBS/Tier 0) and assure that activity is the corporate-socially responsible, Ditlevsen (2004). This constraint can be expressed as:

y · (societal factor (fraction) signifying the part to be asset to society)	>	(sum of societal risks)
	or	
y · (t)	>	(s)

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where the right hand side term represents the sum of N considered unwanted events, quantified by product of the event frequency and expected loss for the society in excess of owner's compensation and his own loss.

Therefore, the implementation of social responsibility constraint in the owner's considerations is a process taking place at IMO, possibly leading to new ship designs, that meets the new technological demands.

This contemporary philosophy certainly leads towards better ships of the future, although the data for societal constraint is hard to obtain and may require specific country dependent considerations. It still gives a clear direction of societal objectives that will be enforced in the future. Since ships are products with a long lifespan, a realistic design approach that will be in line with the foreseeable societal responsibilities, is needed now.

However, to be implemented in practice, the procedure has to be followed by the practically applicable method leading in the same direction but free, if possible, of dubious considerations.

After problem identification, the Decision Support Package (DSP) problems are usually manipulated into a mathematically equivalent formulation but solvable within the available solution strategies and accompanying techniques.

It is obvious that the problem may be, in general, manipulated into at least three formats: In the first format the owner's gain is maximized along the different (dependent on i) acceptable risk (or λ_i) contours. In the second format the risk is minimized along the different acceptable owner's gain contours. The third formulation will produce the Pareto frontier of non-dominated designs making DSP transparent and suitable for techniques of subjective decision making by the stakeholders (owner, yard, regulatory organizations). The mathematical requirement is that the order of designs regarding the applied quality measure is maintained i.e. the monotony of both: the simplified measure of design quality and the full formulation.

If (s) and (r) can be replaced with the simplified deterministic or robustness safety measures, the selection of quality designs will be largely simplified related to the largely philosophical ISSC TC proposal. In the third problem, the definition is still entangled with disputable parameters such as cost of life, etc. Those considerations are excluded from the Blocks for generation of the Pareto frontier (see Table 2) and transferred to the Blocks for selection of the preferred design on the generated hyper surface of no dominated designs.

It is only now that complex requirement, given before as $(p(x, d) - r(x, \lambda, d)) \cdot t > s(x, \lambda, d)$, has to be included, but only as a filter on the small set of generated Pareto designs. Subjective considerations still lie with the stakeholders (designer, owner, society, politics, etc.) but they are applied to the specified Pareto designs. It seems to be a substantial step forward in the inclusion of safety in the design process, at least in selecting the design with required gain but with simultaneously maximized safety or the safest design for the required/selected gain - see Thoft-Christiansen and Murotsu (1986), Zanic *et al.* (2010). Basic conclusion is that we are required to include safety considerations, not only as design constraints but also as a design goal if we want the maximum gain for the given investment from the owners' and societal point of view.

For those reasons, the research and applications area is currently very active and some recent references on the related topics are provided in this paragraph:

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Recent methodology is presented in Cui *et al.* (2008), Fach *et al.* (2009), Gillespie *et al.* (2010), Tosserams *et al.* (2010) with interesting approach to metrics in Caprace *et al.* (2010).

Ship general design is given in Vasconcellos (2010), Clauss *et al.* (2010), Balmat *et al.* (2009), while conceptual structural design is discussed in Amrane *et al.* (2011), Andric *et al.* (2010). Detail design problems are presented in Zimmermann *et al.* (2009), Frank *et al.* (2010).

Reliability related methods are presented in numerous works e.g. Wang *et al.* (2010), Kawamura *et al.* (2010), Rizzuto *et al.* (2010), Balmat *et al.* (2011), Okasha *et al.* (2010), Gang *et al.* (2011) with loads prediction in Eisen *et al.* (2009).

5.2.2 Optimization for Operation

Since synthesis methods and modules for the decision support problems are domain independent, (if analytical model is available) the methodology is applicable also in the optimal operations area. Some recent references on the related topics are given in the sequel:

Onboard operations are presented in Perera *et al.* (2011) where the prototype of an onboard decision support system for ship navigation under rough sea and weather conditions is under development (implemented on the Ro-Ro ship). For calibration and validation, the system is currently collecting data (motions, strains) as the ship operates. The time series of the values of the strains at these sensors locations, are supposed to serve as the basis for training of a neural network, capable of quickly and accurately giving the expected loads at the present sea state and also the possible ship's courses and speeds.

Routing and operations based ship design is given in Eljardt *et al.* (2009) where a new approach to benchmark different designs, keeping a clear focus on the operation is presented. It has proved that it is possible to simulate a complete lifecycle of a projected vessel, using fore- and hind casted operation data (ship-specific and environmental). The use of an entire maneuvering simulation leads to a complete database of operational data. Using simulation it is possible to evaluate and optimize the design regarding operational efficiency, rudder design and also ship safety. In addition it is possible to reliably measure the savings/expenditures of design on a lifetime basis.

The paper by Egorov *et al.* (2010) presents the analysis models and criteria for two new Russian multipurpose Emergency Rescue and Response vessels (MPV) concepts, i.e. salvage vessel with icebreaker/high ice class functions. Complex combination of vessel's functions brings to mutually contradictory tendencies while defining hull forms, main particulars and other MPV properties, opening a stage for the multicriterial decision making.

The paper by Dolinskaya *et al.* (2009) presents the investigation of the optimal short-range routing of a vessel in a stationary random seaway. To obtain the fastest path between two points, the underlying structure and properties of the maximum mean attainable speed are analyzed. While the presented analysis is restricted to finding a path that minimizes the total travel time, the same results are valid for other path-optimizing problems e.g. finding a path minimizing the fuel consumption of a vessel, etc.

Energy efficiency is treated in the paper by Boulougouris *et al.* (2009) urging for the collaboration of all major stakeholders of shipbuilding and ship operations to efficiently address this complex techno-economical and highly political problem. Coordination

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of efforts of many maritime stakeholders, with often conflicting interests, and ultimately aiming at optimal ship design and operation solutions has been addressed within a methodology developed in the recently completed EU-funded project LOGBASED (Logistics-Based Design Procedure). Based on the knowledge base developed within this project, a new parametric design software tool (PDT) has been developed for implementing an Energy Efficiency Design and Management Procedure as the part of an earlier developed Holistic Ship Design Optimization Approach. It addresses the multi-objective ship design optimization problem. It provides Pareto-optimum solutions and a complete mapping of the design space in a comprehensive way for the final assessment and decision by all involved stakeholders.

Risk assessment is presented in Kaneko *et al.* (2009) for determination of the ship's global fatality risk level and environmental global risk level. They were obtained based on the estimation of number of regional collision hazards applied to a specific sea area. From the estimated number of collision hazards and the corresponding number of collision accidents, the collision avoidance failure probability was estimated. Since it represents a fundamental characteristic of a trained mariner, this value would be almost unique all over the world, making it possible to estimate collision frequency/ regional environmental risk of any sea area where observed data of ships' movement are available. It is also possible to estimate the regional risk of a ship which sails in only specific sea areas and to consider the effective safety measures for such ships.

6 PRODUCT LIFECYCLE DATA MANAGEMENT

Product lifecycle data management refers to the manner in which data is managed by shipbuilding projects that are following a recent trend towards adopting Product Lifecycle Management, or PLM methods for their business operations. This process is intended to manage the engineering development of products from cradle to grave and includes concept formulation, design development, manufacture, release into service, in-service maintenance, and disposal. This process is distinct from Product Life Cycle Management (PLCM), which refers to the management of product marketing in the commercial sense. The importance of a PLM-driven, extended enterprise platform is nowhere more apparent than in the shipbuilding industry. Appropriate implementation of PLM is expected to automate every aspect of a ship's entire lifespan and includes everything from configuration management through quality control and service. The fast-paced innovation required for naval and other leading edge shipbuilding projects can be better realized by streamlining its processes and managing product data in a controlled environment. Such a capability is intended to help shipyards improve productivity across a global network of suppliers and efficiently respond to a rapid design development. Appropriate product lifecycle data management will provide a seamless technology platform and enable optimizing the total enterprise performance throughout design development, production, and during the entire in-service phase of a ship or class.

In addition to the technical difficulty of the data management, obstacles towards a more integrated use of data and information throughout the life cycle phases include the management of IPR and aspects of work organizations and cooperation between the different stakeholders in the life cycle. The European project THROUGHLIFE (2011) is aiming to identify obstacles and potentials of a closer cooperation between new building yards, repair yards and ship owners. Based on this, the project is intending to develop innovative business models to facilitate closer cooperation of stake holders on one side, and innovative technical solutions with a higher reliability and

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more efficiency over the entire life cycle. The technical developments of the project will focus on alternative means to achieve structural durability: innovative means of corrosion protection versus the use of anti corrosive steels and composite materials.

6.1 State of the Art

A key factor in PLM is the need to define the product. The ship building industry has been developing specific Ship Product Models[1] (SPM) to support the design, analysis, construction, and management of commercial and naval vessels for nearly a decade, Brennan *et al.* (2011). SPMs facilitate unification of 3D CAD data models that incorporate hull structure, propulsion, steering, distributed systems such as piping, electrical, and HVAC, as well as all other components that allow defining an entire ship using a single database. Ship classification societies and navies, most notably the United States Navy's LPD 17 and DDG 1000 projects, continue to develop and apply efforts to bring SPM technology to its full potential.

For an SPM to be useful it must facilitate seamless data transfer between the various groups that require access to support the product at some stage in its lifecycle. While a specific single data standard remains to emerge, NAVSEAINST 9040.3 outlines the policy for ship design data exchange in United States Naval construction projects. The ISO 10303 standard outlines a methodology for model definition to enable data exchange. The LPD 17 project, which started in 1994, was the first United States Naval program to use such an Integrated Product and Process Development (IPPD), Keane *et al.* (2009). The IPPD process led the LPD 17 design towards improved producibility and helped integrate the government project design teams with industry and production. It provided a collaborative strategic infrastructure embodying data standards that supported the project business across geographically dispersed and heterogeneous organizations with the ability to electronically access, share, process, and analyze data throughout the program and its anticipated complete life cycle. The seamless environment linked the acquisition and logistics program teams and allowed single entry, manipulation, configuration management, maintenance and approvals processes and ultimately facilitated management, administration and program execution efforts.

Improved automation of computer aided design and engineering activity was needed to develop a ship product model (SPM) that could support appropriate data transfer and facilitate integration of engineering with production. A significant adjustment of mind-set was required but the efforts to enable extensive concurrent engineering activity ultimately allowed a robust product data management (PDM) capability. The modeling and simulation tools used by the IPPD needed features that enabled access by the various project operations using a distributed network design to provide necessary details of ship systems including auxiliaries, propulsion, electrical and ship structure as well as signature management and other capabilities. The development of an integrated product data exchange (IPDE) capability allowed the LPD 17 project to use a wide area network (WAN) that enabled effective data exchange across some 20 sites and could support up to 250 users.

The Canadian Navy has also sponsored development of an SPM based computer-aided ship data and analysis capability to improve the Life Cycle Management of its fleet during this same period. Much of this work was progressed by Martec Ltd., Brennan *et al.* (2011) who developed the Improved Ship Structures Maintenance Management (ISSMM) Technical Data Package (TDP) under contract to Defense Research

[1]SPM is used in the literature to refer to ship product model, smart product model and single product model. In most cases the meanings are synonymous

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and Development Canada (DRDC). They successfully demonstrated the feasibility and utility of an SPM concept by using the CAD-like database of the Canadian Navy's FFX330 class to perform integrated sea load and structural analysis and to determine the effects of structural damage on a vessel's ability to undertake intended operations. The ISSMM project and others in the Canadian system use the navy's Structural Inspection Database (SID) as well as the TRIDENT finite element analysis and modeling system. Various application interfaces (API) through the TRIDENT graphical user interface enable performing a complete set of ship design and analysis functions that, among other capabilities, provide an extensive set of software tools that address structural Life Cycle Management (LCM) issues. It is reasonable to expect that future Canadian naval vessels will be designed and built using SPMs.

There exists a strong global interest by ship owners, design agencies, and SPM software producers to extend their applications beyond design and construction and to apply Life Cycle Data Management (LCDM) techniques into shipbuilding projects. This integrated process is expected to avoid the time consuming and costly practice of producing individual models and analyses that need to be translated or otherwise revised to support the numerous activities and practices required for other in-service maintenance management requirements for naval ships, or maintaining classification for commercial ships. An effective capability is also expected to speed up design, design change, production definition and materials procurement and production. Earlier and more thorough access to the design process by all concerned parties will not only reduce project costs by shortening the development phase but also the time required to reach market and will allow an improved understanding of vessel, its systems and ultimately improve confidence in the vessels performance and its safety.

Liu and Zhang (2009) examined the computer aided design capability of Chinese shipbuilding and explain how important it is for Chinese shipbuilding, in way of the global financial crisis to take advantage of modern CAD/CAM technology to transform their philosophy and methodology to better consolidate their position in worldwide competition. The need for integrated hull, outfitting and integrated design and manufacture is vital and they recommend establishing integrated digital shipbuilding platform based on the PLM system to apply open CAD for the upstream design tool with the manufacturing process management (MPM) software system as the downstream, tool. They point out that ship design software is difficult to apply for Chinese shipbuilding unless it includes Chinese characters. They consider that adopting this technology will help speed up their process and facilitate improved high technology content for ship designs.

While LCDM techniques have achieved expectations in practice by the aerospace and automotive industries, a full-fledged implementation of LCDM remains under development as an emerging capability throughout most of the shipbuilding industry. In summary, LCDM requires a thorough review and understanding of the ship product business process, including all aspects of management, engineering, procurement, fabrication, quality control, distribution, and in-service support activity. Once the process is mapped, an optimization of each element is necessary to develop effective and appropriate standard operating procedures and to ensure that all program stake holders are able to fulfill their mandates efficiently. In some cases a reorganization of mandates or processes may be necessary. Following process optimization, a data access and retrieval method must be established, implemented, and maintained. Periodic reviews of the system and its efficiency will then be required to update and facilitate knowledge transfer as well as allow for back-use or re-application of perti-

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nent legacy information for future products. A particular difficulty remains with the means required to resolve the technical problem of data access and exchange. Many of the engineering design and analysis methods used for ship design evolved from unique sets of technology and tend not to share common formats, models, data structures, or methods for exchange. The review of recent literature in this filed offered in this chapter provide practical examples and reinforce many of these concepts.

6.1.1 Design for Life Cycle

As already introduced, cost is always an important issue in ship operation, which encompasses the entire product life from conception to disposal. Manufacturers usually consider only how to reduce the cost of materials acquisition, production, and logistics. In order to survive in the competitive market environment, manufacturers now have to consider reducing the cost of the entire life cycle of a product, called LCC, Hansen (2003).

Design improvement such that maintenance is easier and that ship problems are less frequent or less significant may certainly reduce the cost of exploitation and increase safety. Currently, the LCC is not yet the major concern for shipyards. This is an economic and strategic mistake. Integration of the LCC, including maintenance costs and operating costs in the design procedure, could be used by designers and shipyards as a huge selling argument. If the shipyard can show to the ship-owner that the proposed design satisfies the standard technical requirements and the usual ship-owner specifications but also considers maintenance and operation issues, the shipyard may get the order even if its offer is not the cheapest. Ship-owners want to minimize short term investment but above all maximize their profits. Some new solutions are currently in development, Nagel (2011), Renard (2009), Sharma (2010).

More considerations about Life Cycle Management are considered in chapter 2.

6.1.2 Overview of the LCDM

Lee *et al.* (2006) describe the overall structure and basic requirements for a typical ship product based life-cycle technical information management system. Their particular system was developed to evolve isolated engineering workstation based design, production, and management methods into a system that allowed full process collaboration between distributed groups of experts. This evolution is considered an essential step towards a more efficient shipbuilding product development and maintenance process. They analyzed ship design and build practice using the integrated computer-aided manufacturing language (ICAM) and integrated definition (IDEF) methodology, first introduced by Mayer *et al.* (1995). They then established an integrated system framework definition using the Unified Modeling Language (UML) to integrate applications and database functions within a concurrent engineering environment. They defined the Integrated Data Environment (IDE) capability to be the end goal of a continuous acquisition and life-cycle support (CALS) system implementation and explained how it relies on sharing information between servers and clients over a local or wide area network. Security management of such data is possible using various means such as privilege control and public key infrastructure (PKI) methods as well as more secure Military systems. A typical system combines various databases in a manner that allows users to access single product models and perform analyses, develop solutions, or establish production or maintenance activity.

A ship technical information management system must hence include a framework for development and application of a diverse set of necessary tools. It must provide the

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design support system and allow for document management. It must include project management and deal with knowledge management. Access and process requirements for these systems differ and must take into account the need for through life systematic and integrated management.

The requirements to build a common data model for total ship lifecycle data management were defined by Thomson (2010). He divided the ship lifecycle into five distinct phases that include the initial concept definition of a ship; the detail engineering and procurement phases of major equipment; the exchange of data with classification societies; development of design and production documentation and the final handover and operation phase. Each phase includes a diverse set of data management requirements that must become integrated to allow the many hundreds of diverse formats, applications, languages, and user access methods to work together seamlessly. A standard data access format seems feasible by complying with the ISO 15926 standard for product data files that include the engineering information and workflow model (EIWM) to represent data using a master class and attribute library (reference data library RDL) and finally, XML template files to capture the technical descriptions and associated data files, drawings, photographs and other related documentation, Thomson reports that the web based document and content management system, Microsoft Windows Sharepoint Services (WSS) provides a stable and suitable means to establish a global interchange with suppliers, ship owners, building yards and design offices when combined with specialized ship management software applications such as the AVEVA NET Ship Life Cycle Support.

To facilitate data access and translation, adaptive data models are required. The ISO standard 15926 for "*Data integration, sharing, exchange, and hand-over between computer systems*" is primarily used by the oil and gas industry but its principles cover the requirements for data transfer and apply equally well to the ship building industry. Such standards are necessary to facilitate efficient single product model management across enterprises in the global sense. Another similar standard, ISO 10303, "*Automation systems and integration - Product data representation and exchange*," defines the Standard for the Exchange of Product model data STEP. Kassel (2009) reports that, in keeping with the 2008 NAVSEA directive for the development of ship design and analysis tools, the United States navy is committed to the acquisition of intelligent 3-D product model data using the ISO 10303 ship AP protocols (e.g. AP215, AP216, AP218 etc) identified in the NSRP strategic plan. The various APs cover detail data standard requirements that define ship arrangements, ship hull forms, structures, distribution systems including, piping, HVAC, Cable trays, mechanical and electrical systems, equipment subsystems, parts and reference data libraries as well as a miscellaneous category that specifies requirements for finite element analysis, computational fluid dynamics and logistics.

The STEP standard file includes an integrated product structure, graphics, and data with parameterized components that have logical and geometric relationships. STEP standard graphics share a standard product structure and properties that maintain a linkage between product structure and graphics. While STEP reflects the state of the art that is achievable today, most commercial CAD systems still cannot process the STEP APs. Most APs remain under development with different prototypes being developed using different schema. Most importantly, shipbuilders have not embraced ship STEP protocols and have not demanded a ship STEP translation capability from their product model vendors. The NAVSEA migration strategy intends to use the more

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mature automotive STEP AP214 protocol that deals with Core data for automotive mechanical design processes to populate most of what is required for their ship models.

The NAVSEA "*Leading Edge Architecture for Prototyping Systems*" (LEAPS) is based on an extensible information meta-model designed to provide data to support modeling and simulation tools used by naval designers. The LEAPS product-modeling environment enables importing AutoCAD, Rhino, CATIA and SolidWorks models through the STEP/IGES protocol and provides input files for a variety of engineering analyses without the need to conduct additional pre-processing. The LEAPS product model database is intended to interact with modeling and simulation, various tools and allow full life cycle applications but will remain external to the ship product model (SPM)" (Sullivan, 2011). Efforts to encourage pervasive commonality and culture change to reduce the cost of naval programs argues for the need for a database search and mining tools that will make available to any designer or shipbuilder the full selection of components, but more important, could show designers which fittings, components, or commodity items are most commonly used on other platforms and allow for direct inclusion in the design process. Such a platform requires interlacing the various tools available today, from vendor database, to Internet tools, to 3-D product model integration, and finally the ability to include and translate CAD models from the more common types available to small contractors (AUTOCAD, RHINO, etc.) to load into the high-end product models (CATIA, Ship Constructor, Intergraph, etc.)

Brennan *et al.* (2011) describe a Data Interface Management Engine (DIME) which has been designed by Lloyd's Register (LR) to facilitate transfer of data from ship design offices into the Lloyd's Register Applications. DIME provides a toolkit which facilitates data transfer between ship modeling and analysis applications. The interface toolkit exposes a single Lloyd's Register data format to the outside world that is controlled by the Data Model or Data Schema, which can be extended if required as new functionality becomes available. Data elements have been consolidated across the current suite of applications resulting in a common data model. This allows a single instance of third party data the potential to be passed to numerous LCM and LR applications. DIME also includes a robust geometric kernel and the associated processing for the purpose of creating a geometric representation of the structure suitable for finite element meshing. The ability to create open format finite element models is essential to enable a practical application of ship design analyses.

The Data Interface Management Engine (DIME) is central to the Interface Toolkit. It has been designed exclusively to facilitate the transfer of data to the Lloyd's Register applications. DIME can support ship designers, administration and interface developers. In practice Lloyd's Register staff use DIME throughout Interface creation. When Interfaces are successfully implemented, the DIME performs the role of coordinating data flow, providing a view on the data and progress reporting to Engineers. DIME has a number of possible methods of operation. The desired state is to run in the background, providing relevant progress information as data passes between applications but alerting the user if there is missing/incorrect data. If the user chooses to enter the data in DIME at this time, the data will be stored and the user will not be prompted on subsequent data transfers. The DIME keeps a comprehensive transaction log with timestamp, source application, location, and target application information.

The DIME Interface Toolkit uses XML technologies including, the XML Schema Definitions (XSD's); the eXtensible Stylesheet Language Transformations (XSLT's); and SSX, the Ship Structure eXchange file (LR XML File). The XSLT's transform and filter XML to XML data, prior to transfer to the assessment applications. XSD's are

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also used in the DIME for filtering and display of data, they define the rules that the data held by an *.ssx file must adhere to. Flexibility is the key to the interface toolkit and DIME uses a modular architecture and the concept of plug-in functionality. The LR Update Manager allows quick and effective means to update components. The Updating of executable files, XSD's, imported driver dynamic link libraries (DLLs) and XLST transformation files is managed within the application and updates are provided as required from the LR website via the "Auto Update" functionality introduced firstly for DIME but now implemented in many other LR Engineering Software applications. The adopted interface approach ensures that LR applications retain their flexibility of information sources and can be used by different teams of people at different stages in the design. The Interface Toolkit has already been used to implement interfaces between LR applications and NAPA, AVEVA Vantage Marine (Tribon), Intergraph SmartMarine3D, AutoCAD (2D Section & Lines plan), IGES (Hull), and HecSalv applications.

A key element for any ship based life cycle data management system would be its model and data format translation tool. Such a tool must enable a seamless ability similar to DIME that will allow file import from supported third party ship design applications. The LR DIME is essentially an expert system that supports both end users and those developing interfaces to the LR applications. As a suitable system for such a purpose the data management system must be able to direct files simultaneously to the appropriate application. In the case of DIME, it simultaneously selects multiple LR applications such as RulesCalc, Ship-Right; SDA; SSC. Such a system must be able to adapt to Dynamic Updates as they are developed and posted on some central node. It must be able to check for updates and install latest drivers and import translators. It must provide a clear view of the imported data format with "traffic light" color coding to indicate correct or missing data as well as help text for all supported data items. It must create some form of an activity transaction log that shows file information, source application, time sent and etc. It must have the ability to import material, profile, and end connection data from designated resource libraries. It must include features to report system information to assist in troubleshooting and associate installed drivers and importer functionality with associated version; store missing data for subsequent data transfers; and customize the tree display and help text to other languages if needed.

Application Programming Interfaces (APIs) are modules that assist the creation of code that will enable developers and ship designers to extract data to the Interface Format file (*.ssx). The same API's are used by Lloyd's Register and 3rd party ship design/CAD suppliers in creating their code. With this approach Lloyd's Register does not have to initiate the implementation of interfaces, since using the API's allow third parties to create the SSX format that DIME can read and that subsequently can be processed in the usual manner by routing directly to any of the supported Lloyd's Register, Martec or Canadian Naval applications.

6.1.3 General Purpose Tools with a Ship-oriented Option

The Dassault Systèmes ENOVIA solutions are a suite of software packages, linked to CATIA, intended to support the design and lifecycle management of a product with communication via web-based portals and PPR (Product, Process and Resource) hubs for the exchange of information between the different members of a project team through their life cycle applications tool (LCA). Specific solutions developed for the shipbuilding industry include AEC hull design, structural design based on standard

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parametrically controlled parts and software to generate production information for the design. CATIA contains data management tools for use in the build process to track and manage parts. It can also be used to generate a Virtual-Reality (VR) environment of the ship, to assess human factors in the design and operation of the vessel. Their 3-D com tool enables collaborative product development through a common interface and provides access to the various applications and data sources.

IBM offers companies a consulting support capability using their Rational Team Concert to provide a lean collaborative lifecycle management solution. They have developed tools for both engineering design and Product Lifecycle Management, (PLM). For shipbuilding, they have established a strategic partnership with Dassault Systèmes and rely on CATIA for product modeling, DELMIA for their product assembly process detailing and validation and ENOVIA to support the global online collaborative environment for creators, collaborators and even consumers in the product lifecycle.

Team Center Siemens PLM software (2011) includes a variety of specialized tools among those we can find NX-Unigraphics, now version NX-8, the legacy CAD/CAM/CAE software package, but also the Parasolid solid modeler and the I-DEAS CAD software. They offer a range of life-cycle and process management tools. These are sufficiently generic that they can be adapted to a wide range of engineering applications. Examples are as diverse as the Joint Strike Fighter project, Alstom's Industrial Gas Turbines division and LEGO toys. In these cases, the company has provided design and management software to suit the customer's needs.

6.1.4 Ship Dedicated Tools

In combination with Tribon AVEVA offers a ship design software system which includes a Product Information Model, (PIM) that can be accessed by various modular programs to perform standard operations such as calculating hydrodynamic parameters, hydrostatics, hull lines and various structural details. The system defines surfaces, allows structural design, hull outfitting, design re-use as well as development of distribution systems including piping and ship systems in 3-D. Production and assembly data packages can be produced that also include ship construction and welding definitions. The system includes a Data Management module to handle configuration control and also maintain and track revision levels and a large inventory of standard equipment and parts that can be called up into the design.

Another interesting combination has been produced by Sener Marine, the makers of FORAN and in combination with the PTC Windchill product which combines the power and benefits of Windchill with the FORAN Design Environment. The Windchill Gateway for FORAN offers a powerful solution to help shipbuilders address their unique challenges in a distributed design engineering environment. The system allows shipbuilding designers to reliably and easily synchronize their FORAN FBUILDS structures, 3D graphics and attributes with Windchill thereby allowing the sharing of a single, synchronized, graphical view of the ship functional and build structures. The system has been shown to support lifecycle management of FORAN Documents in Windchill including FORAN Data files, FORAN Drawings and FORAN Schematics. A bi-directional exchange of FORAN Product information is possible and improves collaboration by integrating the FORAN design environment with the wider enterprise in terms of business processes and procedures. The data quality is improved by providing all relevant groups with accurate, up-to-date, relevant product content information that's held in a single location. Enterprise efficiency also increases by enforcing standard design processes across multiple design projects and organizations.

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The various Shipbuilding Templates allow for additional visualization capabilities and leveraging of Shipbuilding Part Types.

Like CATIA, the vendor of Intelliship provides an API, through which the data required by the LCM tools can be accessed and extracted. The system also uses a "Smart Product Model" of the ship, with rule-based automated systems for estimating the design at the initial stages. Parts are hierarchically linked, so that the effects of design changes will propagate through the model, reducing the delay in reworking of the design.

The open nature of the Nupas-Cadmatic software is intended to facilitate efficient concurrent and distributed design. The software automates many design processes and allows easy sharing of 3D project information between designers, project managers, owners and sub-contractors. The data publishing tool uses smart visualization techniques to quickly create 3D models and facilitate distribution through the internet. The Nupas-Cadmatic software uses a database-centric client server system where the 3D model and documents are all stored in databases and hosted by a database server. In a globally distributed project the data is updated between remote design sites via an online network connection such as the internet or by simply exchanging the file in an email attachment. It is easy to divide design work globally between several design offices with server replication and the addition of new design teams being reduced to a few mouse clicks. Their Internet-based Cadmatic eBrowser is a powerful data publishing tool that enables effective communication between all parties involved in plant investment projects by linking partners through the internet. Plant owners, designers, engineers, subcontractors and customers are all linked to a mutual 3D model allowing easy and concurrent project reviews and plant inspections, facilitated by the ability to virtually walk around the design area.

6.2 Current Practice

6.2.1 Industry-implemented Solutions

Caprace *et al.* (2010) state that available life cycle optimization tools that should enable selecting the correct design options for a given ship and system levels remain poorly applied. Better methods and tools are needed to connect technical design parameters with life cycle performance, and allow technical experts to better assess the impact of design options and parameters on the overall ship performance. An integrated view requires dedicated methods to compare production and operational costs, safety and environmental aspects. It also requires tools for life cycle optimization in the different design and production phases of a ship. The efforts to implement a more collaborative product development in shipbuilding such as the United States naval LPD 17 program have provided improved means within the industry to address such shortcomings, Keane *et al.* (2009). Such enterprise solutions will undoubtedly help reduce corporate amnesia and enable the type of knowledge transfer described by Formentini and Romano (2011) to avoid repeating similar mistakes from project to project.

This need is echoed by Park *et al.* (2007) who developed the DSME Engineering Wizard System that aims to accelerate process performance by managing design execution, promoting collaboration, and maximizing engineering data reusability using a workflow concept. They analyzed Marketing Design in the Korean shipbuilding context, to establish a unique workflow template to identify activities and help organize design experiences into a best practices guide so that tasks could be performed in the

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most efficient manner. Marketing design is that portion of work that covers the pre-contract award period of engineering performed in a shipyard. A key element required organizing an improved Engineering Data Management (EDM) capability. In most enterprises, the document management system is not harmonized with engineering work. Engineers typically search for data to perform individual specific tasks and are responsible for storing and managing data in addition to and apart from their primary engineering responsibility. Hence, effective document access, process definition, system maintenance, and process monitoring are essential solutions to improve industrial capability and can be implemented in a practical manner.

Specific application of the project life cycle model (PLM) is reported by Le Duigou *et al.* (2009). Their study audited several companies to better understand how digital and collaborative engineering was performed and to determine best practices using a benchmarking system to rate software tool capability and efficiency. They found that product improvements developed by designers due to user feedback, improved methods, and optimization or testing were not reproduced on other company products unless the particular designer was specifically involved in their production. They noted that the methods used for producing the Bill of Material (BOM) technical data definition was performed manually and was only updated when there was a major modification of the product design. They also noted inefficiencies in the retrieval of legacy product design information as well as references and specification and noted problems in the methodology for estimating raw material requirements. By developing an expert system that would construct a CAD file to describe the object based on its defined functional requirements and other constraining criteria, much like a mathematical spreadsheet, it was possible to automate the creation of the BOM, maintain it simply whenever a functional requirement was modified and enable storing it within the PLM database. It is possible to automate the various analysis required for the product from the BOM data file. The development of a standard methodology for common shipbuilding components is underway and expected to rapidly progress to enable more efficient product design development.

Nishiyama *et al.* (2010) introduce their approach of design quality improvements at initial and detail design stages, and applications of 3D design information at production stages by using the 3D-CAD MATES (Mitsubishi Advanced Total Engineering System for ships) developed on 1980's and functionally improved on regular basis.

Wu and Shaw (2011) propose a basic ship design knowledge model for information storage and retrieval using a knowledge-based engineering system. They analyze the design flow advantage of applying a document based KBE system. In current practice, ship design relies on using past experience and with reference to document based ship data information. The method presumes that the reference ships are actually optimal design solutions and that deviations from their designs are to be avoided. They propose that, by adopting a rule-based reasoning approach, an improved development of conceptual ship designs will be possible. They describe their information technique architecture as containing knowledge based engineering (KBE) that is coupled to design rules and an inference engine to provide an integrated framework for ship design knowledge. Their document management system allows development of specific vocabularies and exact meanings using standard xml format documents. In parallel, another system is developed to list the owners' functional requirements. Using standard methods, an initial design requirements document is formulated by applying the owners' requirements to the KBE database. As the design development continues, principle dimensions of the hull, the ships power, propeller design and other details are

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developed through a basic design graphical user interface following a logical sequence. They show that as design rules, performance requirements or other details arise, it is possible to rapidly and simply update the data model for immediate changes to all the related design details and analysis results. Such expert systems are thought to become more and more common in the industry to address various ship types. With time it is expected that standard libraries will be created to standardize the ship design and build process.

Li *et al.* (2011) discuss the merits of translation as compared to using a common standard to enable ready interchange of product models created using different modeling and analysis systems and report on a comparison made against Tribon and AVEVA PDMS. While it is expected that there should exist a single repository for information and as enterprises grow into a global network, and new software systems emerge, it is still necessary to exchange data among heterogeneous CAD systems and to migrate legacy data to next-generation CAD systems. Clearly, incompatible file formats prevent simple migration and it is not only time consuming to translate files but it is difficult to maintain sufficient translating capability as more efficient file formats are created by the industry and further complicated by operating system utility standards design. The authors report success with a method that creates repositories based on ISO 10303 AP277, the process plant configuration and ISO 15926, integration of life cycle data for process plants including oil and gas production facilities. They developed a ShapeDB, which is constructed to manage the geometry information of the product data model that refers to the equipment catalogue defined by ISO 15926. By designing the ShapeDB Schema in such a way, that Tribon is able to populate the necessary database as a neutral format conforming to AP227 and ISO15926, the PDMS is able to directly import the information by accessing the standard neutral format as well. This example reflects to a degree the difficulty that is prevalent thorough out the industry today and shows the difficulty of applying enterprise wide solutions.

Shao *et al.* (2009) report on progress made with design of ships machinery using an expert system for the computer aided conceptual design of ships engine room automation (ESACD). Their solution custom designed an application using an existing Ship Data Warehouse system, a configuration selection assistant (CSA), and the design scheme decision assistant (DSDA). Their process integrated the Fuzzy c-means algorithm (FCM) with Rough Sets Theory (RST) to assemble configuration rules from the existing database. Given the fundamental importance for the conceptual design of a ship's engine room, and its impact on the ship cost and performance, a design method based on more than designers experience is well justified. Their case study demonstrated the validity and utility of the expert system in the design of an engine room for a 50,000 DWT bulk carrier and effectively demonstrated. With improved knowledge of computer aided design methods, that such expert systems show great promise for improving the capability of future shipbuilding design toolsets

Whitfield *et al.* (2011) report on an approach for managing the exchange of engineering product data between geographically distributed engineers, designers, and analysts using a heterogeneous tool set for the through-life design of a ship. Their method followed the methodology outlined by the pan-European maritime project, VRShips-ROPAX 2000 that showed how information technology could be integrated into the design process. The methodology, file structures, and management systems are more generic however seem similar to those described for the LR DIME. The use of neutral ship product data based on STEP protocol and a common model within an integrated design environment (IDE) was maintained. Their demonstration started

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with an empty common model which was initially populated with a hull-form, decks and bulkheads uploaded by an engineer in France. The various users configured their design and simulation tools by linking them with tasks within the various process models and building a consistency map to be managed by the system consistency manager. In turn, the common model was populated by users spread across Europe using a closely-coupled approach. XML was chosen as the appropriate technology for the storage and communication of ship product data primarily due to its familiarity within the IT support community. The VRShips IDE approach was found to ensure that the correct data in the right form and at the right time was provided for the users and that the resultant design activity was timely and appropriate. The authors caution that as suggested by Gielingh (2008) that it is virtually impossible to create a single integrated information model that meets all industrial criteria, but rather that it is necessary to create a more pragmatic, bottom-up approach for and build in some dynamic capability to adjust for different ship types.

Maopoulos and Ceglarek (2010) report about practices for design verification and validation in product lifecycle. Their review of required processes show that virtual prototyping within the PLM construct enables design verification of dimensional and many other properties of product more effectively compared to conventional physical models and suggest that future trends will tend to rely less on prototyping and physical rather than digital model studies. In particular, performing assessments earlier in the product lifecycle helps industry reduce project risk and facilitates optimization of design options well ahead of design freeze deadlines.

Papanikolaou (2009) provides an introduction to a holistic approach to ship design optimization and defines the generic ship design optimization problem which can be solved using advanced optimization techniques that enable computer aided generation and selection of optimal designs. They describe typical ship design optimization problems with multiple objectives that can lead to improved cargo capacity, reduced powering or better safety or survivability. During the initial design phase of conceptual or preliminary design, conflicting requirements can be resolved, as can many other variables such as cost, weight, and speed. The PLM database will facilitate design optimization, particularly if it is close coupled to enable selection of alternate components and space reallocations. The more investment that is made to develop analysis methods to study the influence of design variables on the project, the greater will be the potential cost and schedule savings.

Olmos (2011) describes the data management method used by NAVANTIA S.A., Cartagena, since 2004 for the S80 Spanish submarine project. Their method is based in the PTC WindChill PLM system, which is linked to the FORAN design tool by means of the FORAN PLM tool set (FPLM) developed by Sener marine. The submarine was first defined in FORAN and separated into various "zones" and "systems". These were then translated into WindChill by a specific "Strategy of Construction" which allows WindChill to show every item in a constructive, functional or geographic breakdown. The database method allows access to more than 250,000 objects with complete drawings, specifications and 3D virtual reality modeling for distributed systems, structures, machinery and bills of material. The method presented in the paper covers the whole design and construction phases until the delivery of the ship to the owner. After delivery, NAVANTIA provides the owner with all the information needed to populate their own PLCM throughout their operation and maintenance phases. De Góngora (2009) provides more detail about the expert system module developed within the FORAN shipbuilding tool set that allows ship designers to design a complete HVAC

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distribution system using functional requirement criteria. The code automatically calculates duct sizing, routing layout, and bills of material down to the level of hangers and clearance dimensions, as well as a complete flow and pressure loss calculation report. Olmos and Valderrama (2011) report on the electrical cable system design methodology used for the design of the S90 submarine based on a relational database and automated system design capability. Automation was considered essential, given the large number of components and the need for precise routing and installation. In particular, they note that by programming a particular component correctly once, and including its connectivity, seating, and so on, it is possible to locate many of these items throughout a design by simply calling them up and pasting wherever required.

In addition to the efforts taken by shipyard engineering and code developers, some note should be made of Classification Society software solutions being developed for their customer base. The LR approach with their DIME system supplied as part of their Rules Interface Toolkit initiative is to allow ship designers ready access to Rule and procedural checking alongside their preferred design tools. Their RulesCalc software tool enables ship designers to quickly assess designs against the Lloyd's Register's Rules and Regulations for the Classification of Ships, the IACS Common Structural Rules for Double Hull Oil Tankers and the IACS Common Structural Rules for Bulk Carriers. The DNV approach with their Yard Package provides a more complete Enterprise solution. In addition to supporting model transfer and rules assessment support, the DNV Nauticus Early design and Brix Foundation package together with their legacy Nauticus Hull and Nauticus Machinery packages, the Environmental Performance System (EPS) and TenderSuite provide a near implementation of a product lifecycle capability. The Brix Project Manager provides a powerful mechanism for knowledge management and allows setting a common project space for all ship design project members. By implementing information workflow as an important technology, DNV Software helps existing and new customers find the right balance between emerging technologies and new ways of engineering and includes a full design and analysis capability in their suite to help comply with classification criteria.

6.2.2 LCDM Facts Book: How it works on a Day-to-day Basis

In addition to ship specific LCDM products, purpose built applications can be developed by service providers like IBM Global Business Services who provide consultation, integration and implementation services around the mySAP Product Lifecycle Management solutions. Typical implementations enable enterprise solutions access to developing and legacy information across their entire business chain to promote faster and more accurate decision-making. Collaboration capability for design management and product maintenance helps reduce design and production time. Product development capability is enhanced and time-to-market is reduced with additional benefits provided by improved market visibility and distribution. Improved production is facilitated by gaining control over planning, purchasing, operation, maintenance, upgrades, and replacements. Product quality improvements are made possible by integrating quality management across development, production, and maintenance. While the day-to-day processes that utilize the capability made possible by an implemented PLM and LCDM to an enterprise will vary, however, depending on the requirement, specific processes and methods will not vary. The methods for data access, retrieval, network sharing, model maintenance and process development will remain similar across many enterprises.

A typical mySAP Business Suite implementation of Product Lifecycle Management would include a scale able technology platform to integrate existing enterprise tech-

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nologies and enable establishing a new generation of cross enterprise processes. Components would include an enterprise resource planning module, a supplier relationship management component, an enterprise access module to manage enterprise data and provide content designed to address user roles, some means for allowing cross enterprise distribution and capture of information, and a means to maintain a knowledge bank for reference, training, and documentation.

In the modern economy, with scaled down operations and the need for competitive advantage, the requirement for a well-integrated application of knowledge and experience to win building contracts is more important than ever. The need to shorten the design cycle and improve its accuracy, particularly in the pre-contract stage, to better mesh with tendering constraints and avoid costly re-design requirements, will more than ever require ship yards to focus on more efficient and faster design analysis. While the basic shipbuilding process does not vary much between yards, customized coordination of design and procurement and the delivery of essential lifecycle data documentation remains a key constraint when, for example a typical cruise ship build is considered, that requires involvement of many hundreds of groups that include national authorities, regulators, consultants, turnkey suppliers, various engineering offices and subcontractors.

To staff such a volume of documentation for such a large group of stakeholders on schedule and without technical error or product design impact requires a significant and well thought out data management capability. Such a capability must rely on efficient automated data processing systems. According to Watt-Pringle (2011), large shipbuilding firms, including Hyundai Heavy Industries (HH) and STX-Finland Cruise Oy, are investing in various modern computer aided data management methods to streamline their shipbuilding process during the planning and design stages to maintain total control of the schedule and have the ability to respond to rapid changes in information that reduce risk at each stage of the process particularly in consideration that the principles of shipbuilding are based on concurrent design, engineering and installation.

6.2.3 Data out from the Survey

The survey statistics, albeit drawn from a small sample size of 23, confirm observations made by Caprace *et al.* (2010), that while the shipbuilding industry is allowing some free data access and using the advanced architecture of STEP or XML file systems only in certain cases, most practices prefer to use format data structures that are native to their legacy application tools and continue to operate closed and restricted data access systems. The respondents reported using various versions of the ship dedicated tools described in section 6.1.3, however there was little to no mention made concerning the use of open format enterprise wide LCDM or SPM methodologies or any mention given to any of the industry-implemented solutions that were discussed by section 6.2.1. Given that some progress was reported in the use of advanced design and analysis tools by the survey compared to ten years ago, and that certain major shipyards, who may not have participated in the survey are now to use LCDM and SPM, it is expected that, especially as economic pressures continue, companies will adopt the improved efficiencies afforded by a more widespread use of enterprise solutions for knowledge management using SPM and open architecture methods. Please refer to chapter 8 for more details on the survey.

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7 OBSTACLES, CHALLENGES AND FUTURE DEVELOPMENTS

7.1 The Impact of Regulations on Various Stages of the Ship Life

Faced with increased shipping activity and consequent potential increase in ocean disasters as well as the related impact on the environment and human health issues related to the management of the overall ship lifecycle, regulation authorities decided to publish new rules. Some rules have already been applied while the remainder will be invoked in the very near future. The following three documents provide examples of such new regulations:

- "Technical Guidelines for the Environmentally Sound Management of the Full and Partial Dismantling of Ships", the so-called Basel Convention, issued in 2002 by a UN Technical Working Group (http://www.basel.int)
- "Safety and Health in Ship Breaking: Guidelines for Asian Countries and Turkey" issued en 2004 by the International Labour Organisation (ILO) (http://www.ilo.org)
- "Guideline on Ship Recycling, Resolution A.962(23)" issued en 2004 by the International Maritime Organisation (IMO). Guidance of "best practice" for
  - flag, port, and recycling States
  - shipowners
  - shipbuilders
  - marine equipment suppliers
  - recycling facilities

  (http://www.imo.org)

A rather simple comparison of the scope covered by these regulations is presented in Figure 4 below.

Some efforts are made to ensure a better coverage of the various items by the regulations. More details may be found on the IMO web site.

7.2 Survey Analysis and Product Lifecycle Management

For more details on the survey, please refer to chapter 8. While limited by the number of participants and the geographical location of the participants, the PLM survey results do reveal some challenges in the application of product lifecycle management in the marine industry. Firm statistical conclusions cannot be drawn from the limited samples set, so this section will focus on several themes that appear in both the survey results as well as the literature reviewed by this committee.

The survey revealed that during the design stage a wide range of engineering tools are required. Other than AutoCAD, in-house spreadsheets and custom applications were the most frequently cited tools used. This may reflect both the focus of the European marine industries on specialized, one-off ships which require specialized

	IMO	ILO	BC
Role of stakeholders and other bodies	×	×	×
Design and construction of ships	×	×	
Operation and maintenance of ships	×	×	
Preparation for ship recycling	×	×	×
Occupational safety and health in ship scrapping operations	×	×	×
Environmentally sound management at ship scrapping facilities	×	×	×
Design, construction and operation of ship scrapping facilities	×	×	×

Figure 4: Comparison of the respective scopes of IMO, ILO and BC regulations

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engineering skills not supported by standardized tools, and the current fragmentation of the design process under "Design for X". "Design for X" may further fragment the types of engineering data and tools required for successful design depending if the yard and owner are primarily interested in cost, safety, environmental performance or etc. For such custom spreadsheets and tools, the end user is also the tool developer. Therefore, the end user would be required to maintain compatibility with neutral-format standards such as XML and STEP using their own investment of time and money. A further difficulty raised by Gischner (2006) is that the lifecycle of marine products may be up to 50 years, but the typical IT system lifecycle is only 10 years. This implies that many IT advances will occur over the vessel's lifetime and therefore the PLM data must be repeatedly moved to new systems via new investments.

While not confirmed by the limited data in the survey, the survey results would seem to suggest that the customer demand for data in these formats is not strong enough to encourage this investment. Further support for this assertion can also be found in the data transfer section of the survey, where scanned and native format transmissions of data were the most and second most popular means of moving data and little evidence of STEP or XML formats was found. Furthermore, most data transfers appeared to be between shipyards and subcontractors for either design or construction, with little data transfer to owners or other through-life actors. Moredo *et al.* (2009) have a slightly different take on the origin of this problem, noting many yards are not set up to make profit from after-delivery servicing and support, and that if more were, this might spur development of more complete data transfer and associated PLM solutions.

Notable as well is the wide adoption of general-purpose engineering tools for which the marine market is likely a minor component - indicating that marine-specific neutral-format export capabilities may not be a priority of the developer. AutoCAD, Excel, and Rhino all fit in this category, and during preliminary design were the first, third, and fourth most commonly cited tool respectively. Many of the classification societies have been pushing lifecycle support through extensions to their own custom toolsets (Safehull, BV Mars 2000, etc.) of which six were included in the survey. However, at this time, the survey revealed that the use of all six of these tools peaks during basic design, presumably for plan approval, and then falls off again. This pattern suggests that such tools are not capturing all aspects of the design necessary for complete PLM, although they may be more successful in supporting lifecycle class activities such as surveys.

While the survey does not reveal the exact reasons for the lack of neutral-format PLM solutions at the moment, recent literature has suggested some practical problems. Boesche (2010) noted that neutral-format files for machinery and outfitting components typically had the shortcomings of:

- Very large file size;
- Models were often too detailed for overall design integration purposes;
- Contours and surfaces may get tessellated during conversion with loss of quality;
- Important metadata and attributes are often lost.

Boesche presented an alternative, centralized parametric modeling capability that could directly produce native file format renderings for a variety of systems as an alternative. Authors and software vendors also push for a single, centralized repository solution. Recent progress in the U.S. Navy acquisition community has shown progress in using STEP, S1000D and neutral-format files as the basis of a PLM system for high-valued, specialized naval combatants, Briggs *et al.* (2009). In such cases, there

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is only one customer for the lifecycle of the vessel, and a small number of shipyards and vendors compared to the wider commercial shipbuilding world. However this experience suggests that the challenges associated with neutral-format data exchange can be overcome with a strong enough customer demand.

The ideal format of the PLM data structure is still being debated in the literature. As mentioned, Briggs *et al.* (2009) advocated a standard based on STEP and S1000D. Sharma and Kim (2010) advocated a modular structure to a PLM using both geographical and functional zoning, and suggesting neutral-format for data exchange. Donoghue and Cartwright (2009) provide an overview of a modular commercial system focused on product data as well as design requirements documentation and other process-related IP. Thomson (2010) presents a different commercial system based on ISO 15926 data modeling to associate components, data, and calculations, as well as universally unique identifiers (UUID) assigned physical design components to provide better granularity for change revision control.

Thus, at this time the survey and literature review suggests that the marine industry has not yet routinely applied robust PLM solutions for design and operation of vessels. Some standards, such as S1000D, via SHIPDEX, appear to be gaining widespread acceptance. This uptake may pave the way for future PLM advances. At the present time, identified key limitations for marine PLM are:

- The state of the art in the industry appears to be native file format transfers or scanned documents, and outside of shipyard and subcontractor ties, little data appears transferred.
- The product lifecycle (20–50 years) outlives the current IT system lifecycle.
- Customer demand and opportunities for shipyards to turn lifecycle support into revenue appear to be lacking.
- Continued research into the description of the ideal structure for marine PLM tools is still on-going, with both neutral-format and proprietary solutions still being proposed and debated in the literature.

7.3 Design Process and Optimization

As reviewed in Section 4, a key challenge with ship design and optimization remains the automated creation of 3-D FEA models and structural descriptions such that advanced optimization tools can be applied in at least a semi-automatic fashion. Many integrated software packages feature such tools, however, the use of such packages often preclude the use of custom or in-house optimizers to then drive the problem. Additionally, should a design based upon ultimate limit states be required, the nonlinear FEA models require additional information about residual stresses and initial imperfections in the structure, Benson (2009). This information is not typically stored or processed in the existing system. Given the complexity of such failure modes, the general desire to be able to address multi-objective optimization, and to include some measures of uncertainty such as reliability-based design optimization (RBDO), the use of metamodels and parallel processing is a growing area of interest. Kriging models and other surrogate modeling techniques have been explored in limited depth at the present time but clear recommendations on their use cannot yet be made, and more research on these topics is required, Purswani *et al.* (2010).

For a large passenger ship optimization, Caprace *et al.* (2011) were able to develop multi-objective Pareto frontiers successfully, but noted that the following research needs were still required:

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- Fast and reliable models for structural constraints such as fatigue and loads.
- An open interface/plug-and-play system for structural analysis modules is highly encouraged.
- Further integration of the structural optimization tools with the major CAD/CAM and FEA systems to allow faster and more automated optimization.
- Further use of multi-stakeholder, multi-objective solutions for more reliable industrial solutions from the process.
- Better integration of maintenance and lifecycle costing into the initial stages of design.

A further challenge for ship structural design remains the difficulty of changing or upgrading ship structure once constructed. In light of changing environmental regulations, the general ship design community is exploring what is necessary to include such uncertainty in the design process. However, many of these models rely on being able to design for upgradability or to switch out components later in the vessel's life, something which is difficult for structures, Niese and Singer (2011). Commenting on a design-stage model attempting to include maintenance and repair costs in the initial structural design decisions, Turan *et al.* (2009) noted that the current state-of-the-art had several shortcomings. The following challenges and future research areas were noted:

- Inability to obtain accurate repair cost and maintenance strategy data from ship-owners for design hampers what can be achieved today.
- Systems for advanced reasoning with vague and imprecise verbal knowledge of repair costs would be beneficial, as well as more study of advanced data regression techniques.
- More advanced lifecycle design models that include the repair approach of the owner would be beneficial.
- Ability to include uncertainty in the economic side of the picture (e.g. freight rates) would also make such models more useful.

The literature reviewed by this committee suggests that the research and industrial communities are actively seeking more advance structural design methods that can reliably trade between conflicting objectives of cost and through-life performance. Practical multi-objective frameworks including higher-fidelity structural models and through-life maintenance costs remain challenging. Such procedures are an active area of research and development with improvements being sought for both optimization frameworks as well as prediction modules to compute objective function values.

8 SURVEY ON IT TOOLS AND DATA EXCHANGE

To base the "state of the art" sub-chapters of the report on actual data, the Committee decided to distribute a web-based survey among shipbuilding stakeholders. The target bodies of the survey were shipyards, design offices, research centers, software vendors and universities. Each Committee member was in charge of contacting people in a specific geographic area. Despite an easy access and a few questions the Committee got answers from only 23 bodies. It is insufficient to draw statistics but it is representative enough to analyze and show trends.

8.1 Overview of the Results

Number of answers: 23

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Company profiles: Almost half of the companies (11) are shipyards. There were 4 design offices, 1 class society, various suppliers and no ship owner.

Company fields: Almost half of the companies (12) were acting in the capacity of merchant shipbuilding. Two companies were acting only in naval construction and 8 companies were acting in offshore but none exclusively for offshore as they were coupled with certain shipbuilding activity.

Company locations: Survey responses were obtained from three continents. The majority of responses came from Europe (15). Asian companies provided 6 answers while North American firms provided 2 answers.

Company sizes: Using an average value of less than 500 employees to define an SME, the responses were distributed at about half from SMEs and half from large companies and groups. One response came from a micro enterprise (1 to 5 employees) and 6 responses came from the largest category that was defined (e.g. more than 3000 employees).

Occupation of the contract in charge of filling in the survey:

Office Manager & Supervisor:	6
Computer & Information Systems Manager:	2
Research & Development Manager:	6
Design & Conception Manager:	7
Production & Manufacturing Manager:	1
Other:	1

Confidentiality issue: 6 persons chose not to complete the entire form due to confidentiality issues related to certain of the questions.

8.2 Utilization of IT tools

8.2.1 CAD Tools

The shipbuilding industry is included in the overall modern design and production process that involves many companies and needs standards. Therefore, it is not a surprise to find Autocad definitely at the first rank for CAD systems. Almost 75 % of the companies are using it whatever the size of the company is. Furthermore, Autocad is used all across the deign loop from preliminary design through basic design and up to detailed design.

8.2.2 Class Society Tools

Among the shipyards which answered the survey, ABS Safehull is mainly used in Asia while BV Mars 2000 and GL Poseidon are the favorite tools in Europe. As expected, these tools (whatever brand) are mainly used in the basic design stage where the sales price must be decided.

8.2.3 General Purpose Structural Analysis Tools

Three software tools were proposed in the survey: ABAQUS, ANSYS and NASTRAN. No other tool has been proposed by the answering companies. They are all used on an equivalent basis with a few more hits for NASTRAN in the basic design stage. With respect to equivalent surveys (ISSC 2003, WONDERMAR European project) carried out almost 10 years ago, it is noticeable that such tools are used all along the design loop and not only during the detailed design stage as it was previously. This means that the shipbuilders are facing more challenging projects (both from the technical and the economical point of view) and perhaps tuning is needed from the early beginning of the project even in a series of sister ships.

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8.2.4 Computational Fluid Dynamics

Four tools were proposed in the survey (Diodore, Fluent, Shipflow, ANSYS CFX). Fluent is clearly the best known product. These tools are still used in larger organizations but less often in smaller bodies and less used than structural analysis tools. The explanation for that is related to the more difficult access to these tools particularly given the necessary skills (required academic level for their appropriate application), the license pricing and the required resources for CFD analyses (computation and modeling times, computer power . . .). As expected, the stamping ground for CFD is primarily used during the preliminary design when critical choices involving hydrodynamics are made to define the main characteristics of the ship (hull shape, propulsion and other potential design drivers . . .).

8.2.5 Other Tools and non Listed Solutions

Almost half of the responders admitted using spreadsheets somewhere in their design loop. But the majority used in-house developed custom tools. These results clearly demonstrate a need for customization. Once more, innovation is an explanation but the complexity of the ship herself remains an issue difficult to be addressed by the software providers. At least a full integration is not possible in most cases, but various special tools are often needed to address the complete design process and in-house developments or macros are still required. It is interesting to note that the number of in-house tools decreases with the advancement of the design loop: the more finalized the project is the more integrated the solutions become. Nevertheless this trend remains marginal (In-house developments: PD: 13, BD: 12 and DD: 11). Several in-house developments are based on the open software community.

8.3 Data Exchange

8.3.1 Data Access

The current trend is to restrict access to the data. Among the partners of a shipyard the need to exchange data with subcontractors for manufacturing, suppliers, or other building yards, repair yards, or owners, the usual data exchange status is No "access" in most cases. Two particular cases have to be considered: Subcontractors for design have often a full access to the data (sharing CAD data bases, e-procurement . . .) and Class societies have often a "read-only" access for the approval of the drawings. The crew is usually not given an access to design data (outstanding examples exist in the Navy).

8.3.2 Data Exchange Media

The favorite media used in the day to day exchange is definitely e-mail. More integrated electronic means such as direct FTP, VPNs or direct connection to a database are seldom used. These integrated solutions are mainly used to improve the efficiency in the design stages (still sharing CAD data bases and e-procurement).

8.3.3 Data Format

The primary formats used are restricted to the "native tool format" and the "scanned document" format while advanced formats such as STEP or XML remain seldom. This situation implies specifications for PLM tools from both storage and retrieving point of view.

8.3.4 Ranking of Data Exchange

The panel was asked to provide the survey with a ranking (from 1 - worst to 5 - better) of the present data exchange they are using within their company. As is usual for such

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cases, the answers almost fit a normal distribution with mean value 2.98 and standard deviation 0.25. But when the survey is restricted to subcontractors, suppliers and class societies, the average rank is increases to 3.16 while the standard deviation reduces to 0.11. This last result clearly shows that in the day to day work, data integration is actual but not yet extended to many of the stakeholders that play a key role during the life cycle of the ship.

8.4 Overall Survey Conclusion

While the survey size of only 23 respondents is not sufficient to draw reliable statistics, and while the answers are not adequately spread throughout the world, some of the results help support expected conclusions. A real effort is required to better integrate data from the initial design to the final disposal stage. It is not obvious how to address such an issue but some advances have clearly emerged during the last decade.

9 CONCLUSION

The approach to ship design has become more systematic, more rational, more analytical, and more transparent in its justifications. The quality of the product ship and its safety and reliability have benefitted from this new approach that requires a concerted application of human creativity in problem formulation and application of methods for systems analysis and optimization, using the increasing abundance of computer-based technologies. These developments have been to the advantage of the marine industry and of its customers. Effective solutions in shipping provide the foundation for global trade and global standards of living. Automated monitoring systems are commonly fitted to many types of ships. A brief look into the future has shown that much work still lies ahead. The same methodologies are suitable to guide us further. The international community in ship design should be encouraged by its past achievements and should confidently face the new challenges ahead, Nowacki (2009).

The use of computer tools and electronic devices is now a reality within the overall ship lifecycle. From design to disposal through operation pertinent data are generated and stored. The larger data sets are produced during the design stage. Parts of these data sets are often open to external bodies (sub-contractors, class societies). The real challenge shipbuilding and shipping industries are facing now is to integrate all the available information and make it accessible during the whole lifecycle of the ship. In recent years, the need for cost effectiveness has led to:

- The anticipation of technical stops to minimize the loss of income using a rational preventive maintenance based on an up-to-date database (steel structures, outfitting . . .)
- A maximized value on the second hand market of a ship able to display its effective state
- A better brand image for the ship owner able to demonstrate a well driven management of the fleet from the safety side (safety of passengers and/or cargo, minimized risks of pollution . . .)
- A minimized impact on the environment for the whole life cycle: environment friendly building procedures, impact of maintenance activities, encouraging recycling instead of garbage collection during ship disposal, integrated ship design and management to minimize energy/fuel consumption . . .

This observation is not a single point of view, but presents a real trend that has already some effective examples in practice: GL Pegasus system and the last releases of BV

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Veristar Hull include the results from the European Project CAS (2008) to offer a database-oriented support for hull monitoring data.

The regulations will have, as usual, a noticeable impact on the behavior of both ship yards (building, repair and decommissioning yards) and ship operators.

Finally, the maturity of the software tools and the power and reliability of the hardware tools may facilitate the emergence of a more integrated solution that can handle a comprehensive set of data for the entire lifecycle of the ship in the short term.

10 ABBREVIATIONS

ABS	American Bureau of Shipping
ALC	Analytical target cascading with Lagrangian Coordination
AM	Analysis Module
API	Application Programming Interfaces
ATC	Analytical Target Cascading
BD	Basic Design
BLISS	Bi-level Integrated Systems Synthesis
BOM	Bill Of Material
BV	Bureau Veritas
CAD/CAM/CAE	Computer Aided Design/Manufacturing/Engineering
CALS	Continuous Acquisition and Life-cycle Support
CAPEX	Capital expenditures
CAS	Condition Assessment Scheme for ship hull monitoring
CFD	Computational Fluid Dynamics
CIM	Computer Integrated Manufacturing
CO	Collaborative Optimization
CSA	Configuration Selection Assistant
CSR	Common Structural Rules
CSSO	Concurrent Sub Space Optimization
DACE	Design and Analysis of Computer Experiments
DD	Detailed Design
DDG	Guided missile destroyer (US Navy)
DFA	Design For Assembly
DFC/DTC	Design For Cost, Design To Cost
DFE	Design For Environment
DFM	Design For Maintenance
DFP	Design For Production
DFR	Design For Robustness
DFRR	Design For Retrofitting & Refurbishment
DFS	Design For Safety
DFX	Design For X (where X stands for Production, Maintenance . . .)
DIME	Data Interface Management Engine
DLL	Dynamic Link Libraries
DNV	Det Norske Veritas
DOE	Design Of Experiments
DOF	Degree Of Freedom
DSDA	Design Scheme Decision Assistant
DSP	Decision Support Package
DWT	Dead Weight Tons
EDM	Engineering Data Management
EEDI	Energy Efficiency Design Index
EIWM	Engineering Information and Workflow Model
ERP	Enterprise Resource Planning

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EU FP(6 or 7)	European R&D Frame Program (6=previous, 7=on going)
FCM	Fuzzy C-means Algorithm
FEA	Finite Elements Analysis
FSA	Formal Safety Assessment
GBS	Goal-Based Standards
GL	Germanischer Lloyd
GUI	Graphical User Interface
HVAC	Heating, Ventilation and Air-Conditioning
IACS	International Association of Classification Societies
ICAM	Integrated Computer-Aided Manufacturing language
ICT	Information and Communication Technologies
IDE	Integrated Data Environment
IDEF	Integrated DEFinition
IDM	Integrated Data Management
IGES	Initial Graphics Exchange Specification (geometric data file format)
IHM	Inventory of Hazardous Material
ILCM	Integrated Life Cycle Management
ILO	International Labor Organization
IMDC	International Marine Design Conference
IMO	International Maritime Organisation
IPD	Inexact Penalty Decomposition
IPDE	Integrated Product Data Exchange
IPPD	Integrated Product and Process Development
IPR	Intellectual Property Right
ISO	International Standards Organization
ISSMM	Improved Ship Structures Maintenance Management
IT	Information Technology
KBE	Knowledge-Based Engineering
LCA	Life Cycle Analysis
LCC	Life Cycle Costing
LCP	Life Cycle Profit
LCP	Life Cycle Performance
LMLO	Linearized multi-level optimization
LPD	Amphibious Transport Dock (US Navy)
MADM	Multi Attribute Decision Making
MARPOL	International convention on MARitime POLution
MCDM	Multi Criteria Decision Making
MCO	Multiple Criteria Optimization
MODM	Multi Objective Decision Making
MPM	Manufacturing Process Management
MS WSS	Microsoft Windows Sharepoint Services
MSC	Maritime Safety Committee (IMO Committee issuing guidelines)
NURBS	Non-Uniform Rational Basis Spline
OLD	Optimization by Linear Decomposition
OPEX	Operational expenditures
PD	Preliminary Design
PDM	Product Data Management
PIM	Product Information Model
PKI	Public Key Infrastructure
PLM	Product Life Cycle Management
PPR	Product, Process and Resource
QSD	Quazi Separable Decomposition
RBF	Radial Basis Functions

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RDL	Reference Data Library
REL/ROB	Reliability/Robustness
RFR	Required Freight Rate
RMS	Root Mean Square
ROPAX	Roll On Roll Off also carrying passengers (PAX)
RS	Response Surfaces
RST	Rough Sets Theory
SCF	Ship Construction Files
SID	Structural Inspection Database
SM	Synthesis Module
SNAME	Society of Naval Architects and Marine Engineers
SOLAS	Safety Of Life At Sea
SPM	Ship Product Models
SQL	Structured Query Language (database handling language)
SSX	Ship Structure eXchange file (Lloyd's Register XML File)
STEP	Standard for the Exchange of Product model data
TDP	Technical Data Package
UCL	University College London
UML	Unified Modeling Language
UN	United Nations
VR	Virtual Reality
WAN	Wide Area Network
XML	eXtended Markup Language

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