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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

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S. Kar
T. Lindemark
T. M. Netto
A. Bollero
C. W. Rim
J. Romanoff
J. Rörup
Y. Tanaka
H. Zhuang

KEYWORDS

Quasi-Static Response, Strength Sssessment, Ship Structural Analysis, Finite Element Modelling, Fatigue, Corrosion, Ice Loads, Steel Sandwich Panels, Passenger Ships, Ice-Going Vessels, Container Vessels, IACS Common Structural Rules, Offshore Structures.

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1. INTRODUCTION

A ship is a complex and complicated structure designed and built to withstand a variety of loads, namely, wave and wind loads which are ever changing, cargo loads as a result of ballast, and full load operations 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*., 2006 and Aksu *et al*., 2007). Specifically, the report discussed the level of analysis in relation to design stages, such as simplified analysis, direct calculations, reliability analyses, and optimisation based analyses (including reliability). Reference was also made to rule-based and rational based designs. With regard to load modelling for the quasi-static response, load modelling for rule based versus rational based design, loads extracted from towing tank trials and loads from seakeeping and CFD codes, the effect of mass distribution were reviewed. In the area of finite element modelling, discussion was provided on time spent versus expected results, uncertainties in FE modelling due to material, as built versus as designed, residual stresses, etc., adaptive methods, mesh criteria. For the structural response assessment, the previous committee report focused on new computational techniques, uncertainties in calculations, and the development of naval-oriented post processing tools. With regard to safety, structural problems of aged bulk carriers and accelerated phase-out of single hull tankers were discussed together with new rules and regulations introduced by IACS and IMO.

The present committee report is organised in the following manner:

In Chapter 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 and collision analysis were discussed.

Chapter 3 forms a major part of this report where a comprehensive review of calculation procedures has been presented. First, load application methods such as rule formula loads, design wave loads and physical wave loads are discussed. Second, a discussion is provided on the compatibility between product models and models for numerical tools used for load and response assessment. In particular, the issue of inter-model data exchange is discussed. Third, the interaction between CFD and FEA is covered. Finally, recent studies in relation to improvements and new techniques for finite element modelling and analysis are discussed.

Chapter 4 was dedicated to composite structures, especially steel sandwich panels. Recent studies on steel sandwich panels have been reviewed, and deformation limits for steel sandwich panels with elastomer core have been discussed. Also, a review of composites, in general, has been provided.

The structural responses of specific ship structures, such as passenger ships, ice-going vessels, container vessels, and LNG/CNC vessels are reviewed in Chapter 5. With regard to safety, harmonization of IACS common structural rules and IMO's Goal Based Standards are also discussed. A case study is presented on the differences in scantlings based on the fatigue assessment using IACS common structural rules for tankers and bulk carriers.

In Chapter 6 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 Chapter 7.

2. STRENGTH ASSESSMENT APPROACHES

Although significant advances have been made in relation to complex and sophisticated analysis techniques for analysis of ship and offshore structures, simplified analysis procedures for the quasi-static response calculations are still often used and are of significant importance since they provide initial guidance during the early design stage. They are also used to evaluate results obtained from more complex numerical calculations. For most vessels, the use of simplified analysis where rule loads are applied to a structural model is still practiced by shipyards. Simplified analysis typically includes checks against yielding and buckling.

However, more and more direct analysis based on first principles approach are used for new and novel designs by designers, naval architects, and structural engineers. Direct calculation method offers the desired level of safety in vessel design to be considered explicitly, especially for vessels trading in harsh environments. Another aspect is that the classification society rules are based on the vast service experience that has been accumulated by the classification societies on existing ships. The rules contain implicit safety factors based on this past experience. For novel designs where past experience does not exist or is limited, direct calculation is the only reliable approach to achieve adequate safety.

Traditionally, the strength of a ship structure is assessed deterministically. Reliability analysis is used to measure the probability of structural failure by considering both the loads acting on a vessel and the resistance (strength) of the structure in probabilistic terms. Structural failure occurs when the load effect is larger than the resistance. In a reliability analysis of vessel design, there will always be a calculated failure probability; whether this failure probability is acceptable or not depends on the target safety level. Probability analysis can also be used to establish prescriptive criteria for rules that reflect target safety levels. In this way, a safety level can be met by the vessel designed according to the rules.

2.1 Quasi Static Modelling of Dynamic Problem

2.1.1 Loads

The adequacy of any ship design depends on the appropriate definition and application of loads. Virtually all ship structural analysis, whether rule based or based of first principles employ highly idealized load descriptions. The loads in classification society rules are often formulated starting from simple mechanics, for example, hydrostatic pressure on the bottom, and the dynamic effects and other complexities are implicitly included by the introduction of some form of a “coefficient”. In the past, it has been unrealistically expensive to measure or collect long-term loads acting on a ship and offshore structure or to determine these numerically with the required accuracy. Advances in the area of ship hydrodynamics have made it possible to determine more realistic definition of loads and apply those in more advanced analysis approaches. Also, advances in technology enable on-board load measurements to be carried out relatively inexpensively.

2.1.2 Response

There is a growing capability to calculate complex structural responses (linear, nonlinear, dynamic, long-term) that provides the ability to examine not only the behaviour of existing vessels, but also to consider novel designs and new construction materials.

In reliability analysis of plates and hull girder, analytical formulae for strength predictions, can be conveniently employed. The reliability methods such as first order and second moment (FORM) can be applied to this type of analysis since the limit state functions are explicitly expressed. For example, Monte Carlo simulation method can be integrated into progressive failure analysis for more accurate estimation of failure probability. For predicting the capacity of the plates using nonlinear finite element methods, the limit state function is in implicit form which makes the FORM not suitable. In this case, the response surface methods are considered to be more suitable. In a recent study, the Artificial Neural Network (ANN) approach was combined with response surface approach to form a Neural Network Response Surface (NNRS) (see Yan *et al*., 2007).

The input data in strength calculations (e.g., loads, geometry and material properties) may have different levels of certainty/uncertainty. In most cases, the level of certainty of results (e.g., stresses) is unknown. When the probabilistic distribution of the stresses is available, the level of certainty of any calculated stress can be determined. However, deriving this distribution is not always possible. Therefore, Yuen *et al*. (2008) proposed an approximate method for its assessment that does not require knowledge of the probabilistic distributions of the input parameters but it is based on the percentiles of the input parameters calculated from the statistical analysis of the sample of data for each input parameter. The proposed approach was applied for probabilistic assessment of residual plate thickness, hull girder bending stresses, and stresses derived by finite element modelling.

The US Ship Structures Committee recently published report SSC 446 (Kendrick and Daley 2007 and Daley *et al*., 2007a and 2007c). The aim of the report was to dissect ship structural rules to their essentials, show the rationales contained therein and illuminate where the rules contained their factors of safety. Two very illuminating findings arose from this review. One was that all the rules have been formulated on similar and relatively simple assumptions. Nowhere were found complex rule components to reflecting in-depth and sophisticated research of the type referenced in other parts of this report. This is not necessarily a bad thing, but it does suggest that there is far more known on complex ship structural behaviour than is captured in any design standard. The second finding was even more surprising though very clear. No obvious factors of safety were found where one might expect. The loads and elastic capacity appeared to be precisely formulated with little of even no reserve. Instead, a significant factor of safety was uncovered in the post-yield behaviour. The authors concluded that rather than applying factors of safety to current rule formulations, a better strategy may be to have the rules begin to reflect the real behaviour of ships. For example, Naar (2006) executed a detailed analysis on the structural behaviour of multi-deck vessels, knowing that present rule formulations are inadequate in reflecting their true capabilities and reserves. This required a sizeable analysis effort though it also led to the development of a better simple analysis tool for this type of vessel. This type of approach may be adopted in future ship structural standards. The importance of increasingly sophisticated analyses of increasingly complex vessels must be addressed.

Jia and Ulfvarson (2005a) presented an analysis and discussion on the static and dynamic behaviour of a high tensile steel deck designed with trapezoidal stiffeners. From a finite element model of the deck structure, the authors investigated the influence of support condition for the longitudinal girders, contact area between vehicle tyre and panel for different load conditions comprising of the unloaded and loaded deck, and the load type, i.e., cargo loads or vehicle loads (car loads or truck loads).

Fujikubo *et al*. (2005a) developed a simplified method to estimate the ultimate strength of a continuous plate, typical in ship bottom plating, subjected to combined transverse thrust and lateral pressure. A series of elastic/elastoplastic large deflection finite element analyses (FEA) were performed. The analysis was focused on the effect of the continuity of plating on its buckling and ultimate strengths. Based on the analysis results from the FEA, a set of formulae was derived for the estimation of the ultimate strength of a continuous plate under combined transverse thrust and lateral pressure.

The analysis was extended to stiffened plates by Fujikubo *et al*. (2005b). The effect of plate/stiffener interaction on the elastic buckling strength of local plate panel was introduced in the formulation as well as the effect of continuity of plating.

Sobey *et al*. (2008) presented a study on the structural optimisation of composite boat hulls. The authors developed a genetic algorithm used to optimise stiffened flat panels and to compare the cost and mass developed from classification society rules with that of a first principles model. Third order shear deformation theory was used to model thickness of the plates while Navier method grillage analysis was used to model the behaviour of the stiffeners. A maximum stress failure criterion was utilised to determine whether the panel meets the minimum required geometry.

Alsos and Amdahl (2007) studied the resistance of tanker bottom structure during stranding. The importance of the shape and size of sea bed topology with respect to grounding damage was studied. The results of the study showed that the traditional pinnacle type indenter gives local damage and results outer skin puncturing easily. However, the study indicated that large “shoals’’ or dish-type indenters may deform large parts of the hull structure crushing the webs and causing grillage deformation of the double bottom web. The method applied considered the changes in bending moments as a result of changing hydrostatic conditions as the ship is displaced out of the water, and these were applied onto the FE models through bending moment functions. It was shown that the coupling between the hogging moments and the contact forces affects both the longitudinal and penetration resistance of the hull.

It is recognized that the ultimate limit state (ULS) approach is more useful for design and safety assessment than the traditional allowable stress approach because it is difficult to determine the real safety margin of any economically designed structure using linear elastic methods alone. Paik and Thayamballi (2006) presented some recent advances in the areas related to the ULS design of ships and ship-shaped offshore structures. The ultimate strength formulae of structural components (e.g., support members, plates, stiffened panels, corrugated panels) and global system structures (e.g., ship hulls) were presented. Paik *et al*. (2006) discussed the effectiveness of the Idealized Structural Unit Method (ISUM) to analyze nonlinear behaviour of large-sized structures under extreme or even accidental actions. The authors presented some techniques of ISUM modelling and surveys available in the literature on the ultimate limit state assessment of ship structures using ISUM. Benchmark studies were made by a comparison with physical test data and ALPS/HULL analyses employing ISUM formulations on a frigate ship hull model under sagging moment and on two double-skin tanker hull models under sagging or hogging moments. It was found that ISUM provides accurate results with short computing time for the progressive hull girder collapse analysis of ships.

A series of three papers by Paik *et al*. (2008a, 2008b and 2008c) were presented on the methods useful for ultimate limit state assessment of marine structures. The papers provided some benchmark studies of the existing methods on ultimate limit state assessment of (unstiffened) plates, stiffened panels, and hull girders of ships and ship-shaped offshore structures, using some candidate methods such as ANSYS nonlinear finite element analysis (FEA), DNV PULS, ALPS/ULSAP, ALPS/HULL, and IACS common structural rules (CSR). In part I, the ultimate limit state assessment of unstiffened plates under combined biaxial compression and lateral pressure loads were considered. Part II of the study focused on methods for the ultimate limit state assessment of stiffened plate structures under combined biaxial compression and lateral pressure loading. The third paper focused on methods for the progressive collapse analysis of hull girders under bending moments.

Jia and Ulfvarson (2005b) presented a systematic approach to analyse the structural behaviour of a lightweight deck–side shell system using high strength steel. An analytical model of the deck–side shell system was first given, which includes the effects of stiffeners for the deck and side shell, the support conditions of the centreline girder (CL-girder), the influence of transverse beams, and the interaction between the side shell and the lightweight deck as parts of problems to the solution. By changing geometric parameters, the sensitivity of both overall and local stress and deflection for the deck–side shell system was investigated. The different geometric parameters analysed comprise of variations in the thickness of the web for transverse beams, longitudinal stiffeners and the CL-girder, the thickness of lower flange for the transverse beam, and the thickness for the panel. Furthermore, the influence of the lightweight deck and loads from the deck above on the side shell, the effects of the side shell and loads from top deck on the deck, the support conditions for the CL-girder, and the influence of deck loads on the eigen modes were analysed. Based on FEA results, the support conditions of the CL-girder, the thickness of the panels, and the lower flange of the transverse beams were identified as the most relevant parameters affecting both the stress and the deflection distribution of the structure.

A great deal of attention has been focused on plates subjected to shear loading over the past decades. One main fact in design of such elements, which fall in the category of thin-walled structures, is their buckling behaviour. Stiffened plates are widely used in ship structures. The role of stiffeners proved to be vital in design of such structures to minimize weight and cost. Alinia (2005) carried out a study using ANSYS finite element method and analysed some 1200 plates to determine the optimum spacing of stiffeners. The results showed that the number of panels produced by intermediate transverse stiffeners should not be less than the value of the plate’s aspect ratio. That is, the transverse stiffeners should divide the length of the plate into portions equal to or less than its width. It was also shown that the optimum geometric properties of the stiffeners correspond to the point when the buckling shape of a plate changes from the overall mode to local mode.

Belenkiy *et al.* (2007) conducted a study to obtain the effective breadth of the flange plating of the primary support members in the double-skin ship structures in the limit state and an elastic-plastic range. Badran *et al.* (2007) investigated buckling behaviour of a Y-stiffener which is considered to be representative of stiffened panel when combined with plate. The local instability (buckling) of Y-stiffeners in stiffened panels under the action of uniaxial compressive loads was analysed. The mathematical derivations were carried out to find the elastic buckling coefficient for the web of the T-part of the Y-stiffener under suitable boundary conditions from which the critical buckling stress was obtained.

The analysis of a stiffened plate, subjected to lateral loading, can be based on one of two different types of models, namely, the orthotropic model and the grillage model. Both models estimate the maximum plate deflection under uniform lateral pressure. Banai and Pedatzur (2006) presented a study where, implementing an orthotropic model, an algorithm/computer program for a fast structural analysis was developed. A mesh-free Galerkin method for the free vibration and stability analysis of stiffened plates via the first-order shear deformable theory (FSDT) was presented by Peng *et al.* (2006).

Chowdhury (2007) presented a probabilistic method based on the first order second moment principles (FOSM) to predict the failure probability of an idealized hull-girder midship section by yielding. The probability was related to the age of the ship when corrosion causes wear of the structural components. Three different corrosion models were discussed.

A paper by Drouin (2006) stipulated that, based on the findings of Canada's Transportation Safety Board (TSB) report on the brittle fracture of the hull of Lake Carling, failure of hull due to brittle fracture can still be a problem for ships constructed with steel of unqualified toughness (grade A steel) and operated at near 0 oC. The paper argued that, due to the uncertainties and variability of fracture arrest toughness for some grade A and B steels, there exists some risk to have unstable brittle fracture in vessels with hulls constructed with these steels, especially when operating in colder climates and, therefore, suggested to have a IACS unified requirement to use steel for qualified toughness in way of a vessel's side shell.

Paik (2007c and 2007e) investigated the ultimate strength characteristics of perforated steel plates under edge shear loading, which is a primary action type arising from cargo weight and water pressure in ships and ship shaped offshore structures. The cut-out was circular and located at the centre of the plate. A series of ANSYS nonlinear finite element analyses (FEA) were undertaken with varying the cut-out size (diameter) as well as plate dimensions (plate aspect ratio and thickness) and a closed form empirical formula for predicting the ultimate shear strength of perforated plates was derived. Paik (2008) extended the study to investigate the ultimate strength characteristics of perforated steel plates under combined biaxial compression and edge shear loads, which is a typical action pattern of steel plates arising from cargo weight and water pressure together with hull girder motions in ships and ship shaped offshore structures.

Suneel Kumar *et al.* (2006) proposed an approximate method based on strut approach to calculate the collapse load of stiffened plates with cut-outs and initial imperfections.

The reduction in strength of the panels due to the presence of square cut-out, rectangular cut-out, and increase in strength due to reinforcement around rectangular cut-out were calculated based on the test results.

Karvinen and Pegg (2006) presented an investigation on whether the application of predetermined failure equations, derived from nonlinear finite element analyses, is effective in determining failure of structural components in a simpler linear finite element analysis. The first step of this method was the nonlinear determination of a component's failure limit. Next, a linear coarse meshed finite element model of the component was analyzed under the failure load determined in the previous step. The resulting linear stress distribution was a 'representative failure stress' for the component because it was in equilibrium with the applied failure load. This 'failure stress' was then used in simpler linear analysis to provide a representative failure limit.

Nakai *et al*. (2006) investigated the effect of pitting corrosion on the local strength of hold frames of a bulk carrier using nonlinear finite-element (FE) analyses with pitted plates subjected to in-plane compressive loads and bending moments. Authors showed that the ultimate compression load or bending moment of pitted plates was smaller than that of uniformly corroded plates in terms of average thickness loss. Teixeria and Guedes Soares (2008) investigated the influence of the number of thickness measurements and the location of each measurement on the accurate estimate of the level of corrosion and indirectly on the correct assessment of the collapse strength of the corroded plates. In the study, the corrosion patterns were represented by random fields, which were then discretized using the Expansion Optimal Linear Estimation method. A comparison was made between the collapse strength of the plates assuming non-uniform corrosion and uniform corrosion, estimated as the average reduction of plate thickness obtained from the different measurement patterns.

2.2 Linearization / Simplification of Nonlinearities

2.2.1 Ice Loads

The increasing demand for ice strengthened tankers and other ice-going vessels along with the need for economic construction and greater structural optimization have been driving regulatory agencies to rationalize ice strengthening design standards. More and more direct calculation approaches have been introduced into design standards, and some guidelines have been developed to guide analyses and evaluations of alternative designs.

In determining ice loads, a number of researchers have carried out numerical and experimental studies. Ice loads arise from the interaction of two (or more) solid bodies, with the ice and sometimes the structure deforming and fracturing. This certainly involves complex and nonlinear phenomena. Gagnon and Daley (2005, 2006) showed from experimental results that highlight the complex nature of ice crushing forces. The interest in ice loads and ice worthy structural design greatly increased in recent years. A large scale field project involving deliberate ship collisions with floating glacial ice was reported in Gagnon *et al.* (2008). That project involved measurement of collision loads with multiple sensor types, including a novel high-resolution ice load panel (see Figure 1). A second project with a new (2nd generation) opto-mechanical ice load panel is being planned (Gagnon, 2008). These field projects are crucial for the development of an understanding of ice loads. There is a significant new focus on the development of large arctic vessels of both low and high ice classes (see, e.g., Daley *et al.* 2007d).

Ice loads, as collision loads, are influenced by the way the contact pressures develop. It is especially interesting to understand if local pressures are influenced by the size of the contact and the total force. If this is the case, available ice load data may not represent the types of pressures that arise on large ships striking large ice features. The question of design for large vessels and large ice forces was discussed in Daley (2007).

Wang *et al.* (2005) studied the high level of uncertainties associated with design ice loads in the Finnish-Swedish Ice Class Rules and the recent Finnish Maritime Administration Guidelines. Extreme ice loads were defined and applied as patch loads on the side shell between supporting members in evaluation of alternative designs using nonlinear FEA. Valkonen *et al.* (2007) conducted ice load measurements in TKK ice tank to study ice load distribution along the ship hull in different operational scenarios. Two different types of models of ice-going vessels were used in the tests. One was a conventional size tanker of 15700 dwt and the other was a larger general cargo carrier of 62000 dwt. In the situation that the vessel is turning in the channel in level ice, the analysis of the measurement results showed that the aft shoulder can experience loading higher than observed in the bow or midship area.

Within the SAFEICE Project a database of forces and local pressures was compiled for icebreakers and commercial ships operating in ice by Frederking and Kubat (2007). The areas of operation included the Arctic Ocean with multi-year ice and first year ice in the Baltic and Bering Seas. This ice type has the greatest effect on ice loading. The maximum local pressure measured in Arctic conditions was 8 MPa on an area of 0.7 m^2 and, in first year sea ice, 1.7 MPa on 0.6 m^2. At a probability of exceedance of 10^{-3} (per impact), local pressures on 0.7 m^2 were 4.5 MPa and 1.25 MPa for multi-year and first year ice, respectively. Comparable line loads were 4.5 MN/m and 1.4 MN/m for multi-year and first year ice, respectively. The study indicated that the average local pressure decreased with the inverse square root of the area.

Kujala *et al.* (2007) investigated the maximum level of ice-induced loads on the shell structures of ships navigating in the Baltic Sea. The authors adopted a semi-empirical approach for estimation of long term ice loads, which relies partly on full-scale measurements and partly on the analysis of ice edge failure process. It was observed that the normal forward navigation of a ship caused a low basic load level at amidships and aftship, but an extensive increase on the load level took place due to the manoeuvring activities of the ship.

A series of ship model tests in level ice were performed by Izumiyama *et al.* (2007). Authors observed that the ice load distribution in the bow region was of a broken-line-like fashion in which short load patches were aligned in a horizontal line. These observations were validated with full-scale measured data on board a Japanese Coast Guard vessel, indicating that the ice load in the bow was also broken-line-like. More importantly, both experimental and full-scale data showed that the higher loads act on shorter load patches.

All available structural design methods for ice class ships treat the ice load as a simple rectangular load patch, assumed to act quasi-statically. The IACS Polar rules (IACS 2006) have come into effect in 2008 and represent a system of ice classes for ship design. The IACS Unified Requirements for Polar Class Ships were developed through a collaborative process involving both IACS member societies and representatives from several countries with ice class ship rules. The effort was lengthy (10 yrs+), and was intended not only to capture the state-of-the-art, but to improve it. The rules were calibrated on earlier rules from Canada, Russia and Finland-Sweden. The world's ice class rules are relatively recent and have evolved during an intense period of full scale testing and research in the 1980s and 1990s, when arctic resource developments were beginning. One key feature of the IACS Polar Rules is the range of ice classes. The higher classes are developed for operations in the most severe ice conditions, while the lower classes are intended only for light ice conditions. It is almost a necessity to introduce various ice classes since possible ice loads range significantly; for example, the loads between the highest and the lowest ice class notations differ at least by an order of magnitude.

Some of the important features of the IACS Polar Rules are

- Scantling formulations are all based on explicitly derived plastic limit states. This provides more transparency for rules and makes it easy to amend rules as new knowledge becomes available.
- The rules consider implicitly both serviceability and safety limit states. As well, the formulations and stability checks tend to ensure that the sections will have significant plastic reserve, this assuring adequate ultimate strength.
- The rules do not present the design situation in probabilistic terms. Rather, the design point is meant to be a capacity specification. While ice loads are highly variable, rather than thinking of ice loads as a random event, the rules consider that loads are mainly the result of operational decisions, thus the vessel's master makes an informed choice to enter increasingly severe ice depending on the vessel's ice class notation. For this reason, it is important for the master to have a clear and specific understanding of the structural capability of the vessel and the designated ice class notation.

As indicated above, IACS Polar rules employ a plastic limit state strength model. However, the ice load is idealised as a simple rectangular patch of uniform pressure. The complex load shape effects are only dealt with by single empirical factor. This is an area where ice research has found a variety of complex phenomena, but few of these are reflected in ice engineering design.

There is still much interest in developing plastic limit state models that reflect the capacity of structures to withstand small patch loads (as ice loads are idealised). Nyseth and Holtsmark (2006) and Hong and Amdahl (2007a) presented analytical methods to calculate the ability of plates to withstand load patches. An experimental study of ice class ship frames subject to small load patches was described in Daley and Hermanski (2008).

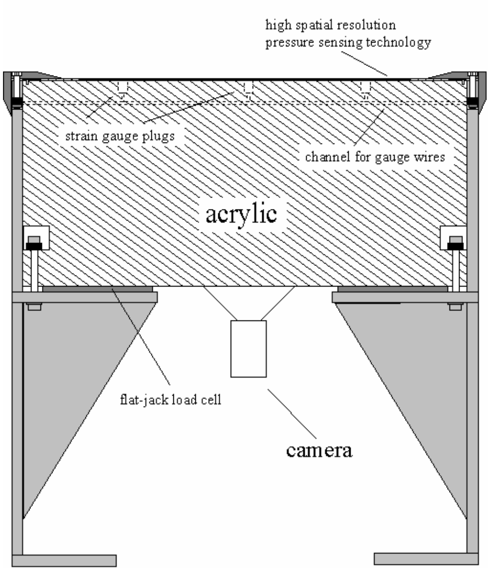

Figure 1: 1m^2 Ice load Panel, with cm resolution. (Gagnon, 2008)

2.2.2 Collision

Accidental loads arising from situations such as collisions and grounding require structural crashworthiness involving crushing, yielding, and fracture of the vessels involved to be assessed. For accidental limit state design and safety assessment associated with collisions and grounding, the progressive structural crashworthiness characteristics of the vessels to be analysed and the energy absorption capability of the structure in the corresponding accidental event should be evaluated.

Early research on the collision analysis studies was focused on analytical and empirical formulations, the majority of which require their coefficients to be determined by experiments. The analysis may be separated into two parts, namely, the external dynamics and internal mechanics. The external dynamics deals with the rigid body motion of the ships under hydrodynamic pressure and the action of collision; the internal mechanics deals with the structural response during the collision, such as deformation, absorbed energy, structural failure, etc. These methods are usually easy to use, efficient and sufficiently accurate for practical assessment. However, they may require some coefficients which can be determined from costly collision experiments.

Yamada and Pedersen (2008) and Yamada *et al*. (2007) reviewed several simplified methods to estimate mean axial crushing forces of plated structures applied to a series of experimental results for axial crushing of large-scale bulbous bow models. Methods based on intersection unit elements, such as L-, T- and X-type elements as well as methods based on plate unit elements were considered in the analyses. The crushing forces and the total absorbed energy obtained by the simplified analyses were compared with those obtained from large-scale bulbous bow experiments.

Paik and Seo (2007) presented a simple and accurate method which is useful for the progressive structural crashworthiness analysis of ships and ship-shaped offshore structures under collisions or grounding. The method was applied to ship-shaped test structures and compared with experimental results. Zhang and Suzuki (2007b) studied the effects of longitudinal and transverse stiffeners on the quasi-static crushing of stiffened square tubes, which have relatively light stiffeners. Based on the experimental data and numerical simulation results, new formulas for equivalent plate thickness and the mean crushing load were developed.

Le Sourne (2007) developed a user friendly rapid prediction tool of damage to struck and striking vessels in a ship collision event. To do this, the so-called super-element method was coupled with the large rotational rigid body dynamic program, MCOL. At each increment of indentation, the crushing force was transmitted to the large rotational rigid body dynamic program, which calculates the global ship motion correction by solving the hydrodynamic force equilibrium equations.

With the advancement and maturity of the finite element methods, it has become possible to simulate the entire collision process. With explicit finite element codes, various collision scenarios and material models can be taken into account in the simulation. For example, structural behaviour of an FPSO subjected to bulbous supply vessel bow collision was evaluated through explicit nonlinear Finite element analysis code LS-DYNA by Hong and Amdahl (2007b). The study evaluated the pressure area relationship of bulb impact developed from the collision force evolution and simple design recommendations for plate thickness, and stiffener scantlings were derived adopting plastic method and appropriate collapse mechanism. However, due to requirement of large computing time and effort, it is not always feasible to run a large number of nonlinear simulations for various situations and, therefore, simplified approaches based on FE analysis results are preferred. Defining relevant FE mesh size, material stress-strain relationship, and critical fracture strain and also to deal with the dynamic effects related to dynamic yield strength, dynamic fracture strain, inertia, and frictions are important parameters for analysing the crushing and rupture behaviour in collisions and grounding (see Paik 2007a and 2007b). Tavakoli *et al*. (2007) studied the crashworthiness of the side structure of one double hull FPSO involved in collision with the stem of a large supply vessel and determined damage and energy dissipation. A simplified analytical method was carried out for external dynamic analysis that calculated the ratio of strain energy to total energy in ship-ship collisions. Internal mechanism was carried out by numerical simulations to assess the strain energy dissipation and damage due to collision with the user defined nonlinear finite element program LS-DYNA. Zheng *et al.* (2007) presented a comparative study on the side structure resistance of double hull (DH) and single hull (SH) tankers in collision scenarios. A DH Aframax tanker and an SH Aframax tanker of similar size were analysed in the study. The two vessels were assumed to be struck by a same bulbous bow, assumed to be rigid, at different locations and angles. Different nonlinear materials and contact models were considered for the struck tankers. The DH tanker was found to be superior to the SH tanker in relation to resistance to side structural damage. Based on the collision analyses, new damage extents were proposed for double hull tankers.

Yamada *et al.* (2007) utilised a newly developed Simplified Ship Collision Analysis Tool (SSCAT) to investigate the effectiveness of buffer bow structures on prevention of oil spills in tanker collisions. A probabilistic approach was adopted where Monte Carlo Simulation (MCS) was carried out using the developed numerical tool for collision scenarios for the striking ship at various velocities, sizes, and bulb shapes colliding perpendicularly with a VLCC. It was estimated that a buffer bulbous bow reduced the probability of rupture by 10 to 12 percent. Yamada and Endo (2008) conducted quasi-static experiments representing a scenario of ship-to-ship collision in oblique angles, using two types of large-scale bulbous bow models –one model is a prototype buffer bow adopting a transverse stiffening system and the other model is a standard bow adopting a longitudinal stiffening system. Collapse mechanism, load-displacement curve, and energy absorption capability of the buffer bow structure were investigated and compared with those of a standard bow structure. Zhu (2007) presented an elasto-plastic impact model based on the quasi-static load-compression relationship of an absorber for the collision protection of structures.

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. When a ship side is strengthened to improve the crashworthiness, it has been argued that a non-negligible part of the energy released for the structural deformation during the collision can be absorbed as elastic energy in global ship hull vibrations. Pedersen and Li (2008) carried out a study to estimate the elastic energy that can be stored in elastic hull vibrations during a ship collision. In a ship–ship collision analysis, usually both the striking and struck ships are considered as rigid bodies –i.e., structural deformation problem is quasi-static. Pedersen and Li (2008) used a simple uniform free–free beam model for estimating the energy transported into the global bending vibrations of the the struck ship hull during ship–ship collisions by considering the striking ship as a rigid body, but struck ship as flexible. Their study showed that for a struck coaster and a large tanker the elastic energy absorbed by the struck ship normally was small and varied from 1 to 6 percent of the energy released for crushing.

Ozguc *et al.* (2005) investigated the collision resistance and residual strength of single side skin (SSS) and double side skin (DSS) bulk carriers subjected to collision damage by employing ANSYS LS-DYNA. In the analysis the struck vessels of Capesize SSS and DSS designs were assumed to be stopped, and the striking vessels (an Aframax size oil tanker with different bulbous bow shapes) were modelled as rigid bodies. Ozguc *et al*. (2006) analysed hull girder ultimate strength of four ISSC benchmark ships by using a proposed simplified formulae. Simple design equations for predicting the ultimate compressive strength of stiffened plates with initial imperfections as a result of welding-induced residual stresses and geometric deflections were derived, based on 60 elastic–plastic buckling analyses of a wide range of typical ship panel geometries using a nonlinear finite element program.

The IACS Polar Rules (IACS 2006) are based on a design scenario involving collision with ice on the bow and shoulder of a ship. The collision is solved analytically using an energy balance approach. The rules give a load and required capacity that can be derived precisely using ship-ice collision mechanics although such calculations are not part of the rules. The rules express the requirements in simple formulae (see Kendrick *et al*. (2007) for summary of the available background material). The approach used in the Polar Rules was extended to a wider variety of ship-ice collision and interaction cases in Daley *et al*. (2007d). As with ship rules in general, there is a strong impetus to clarify the working of ice class rules and to permit the uses to see how the requirements are linked to the performance and safety of the ship structure. This trend will continue and will require continuing improvements in load and structural response models.

3. CALCULATION PROCEDURES

3.1 Load Application Methods

Loads modelling can be conveniently divided into load calculation and load application. Each part may be equally important. Many different approaches exist, and especially the load definition is under continuous development. Since loads acting on ships and offshore structures fall within the scope of Technical Committee I.2, only application of loads to quasi-static response analysis is relevant and discussed here. This is discussed in connection with methods for load calculations. The following methods of load definition are considered:

- Rule formula loads
- Design wave loads (equivalent regular wave amplitudes)
- Physical wave loads (realistic wave amplitudes)

Today, rational dimensioning of complex ship structures is frequently based on refined finite element (FE) analyses of the entire ship. This allows a realistic application of loads and an accurate analysis of stresses, even for complex ship structures. Unlike the traditional rule formula based design, this method realistically accounts for loads experienced by the ship.

In contrast to a physically rigorous load approach, magnitudes of design wave loads based on the equivalent regular wave approach mainly depend on experience-based design load conditions and not on capturing all physical effects by computational fluid dynamics (CFD) simulations. Moreover, increased accuracy of these results is relatively unimportant, because loads finally applied to the FE model are calibrated in accordance with extreme or rule-based loads.

The design wave approach represents a consistent rational procedure that employs a direct analysis for the particular hull structure being considered. It is a practical compromise between the rule load approach and the physical load approach. By defining design wave loads for the FE analysis, it mitigates modelling uncertainties that are introduced when using rule scantling formulas. Development of rule formulas necessarily relied on simplifications to readily account for applied loads and structural response. Thus, the design wave approach provides more reliable structural analysis results as well as improved insight of structural system behaviour.

3.1.1 Rule formula loads

The obvious advantage of rule formula loads is that they are easy to calculate and use. Classification societies developed computer codes that automatically determine rule based loads, and these loads are then applied directly to either a hull structural model or simplified analysis models. Major disadvantages are that the load uncertainty is relatively large with regard to load level, load distribution, and load correlation. Also, these loads are part of the total structural assessment "package," ensuring that the required scantlings are reasonable; however, each component (such as the loading) may not necessarily be the best estimate.

Application of rule based loads is relatively easy. This simplicity, however, does lead to some problems. Correlation or phasing between loads is difficult to account for, and combining different loads acting on the vessel, therefore, may be difficult. Furthermore, it is unfeasible to prepare a set of fully balanced loads for an entire ship. Therefore, global strength analyses based on rule formula loads must be confined to a cargo hold model. By specifying enforced moments and forces at end cross-sections of the model, balanced load sets can be provided. During this process, correct global design moments and shear forces can be obtained for all structural components within a cargo hold model.

The Common Structural Rules (CSR) for double hull oil tankers and bulk carriers require direct strength assessment of primary supporting members. Based on an FE analysis of a cargo hold model, the determination of individual components' buckling and fatigue strength is to be carried out to a level of complexity far exceeding the level previously required for newbuilding approval.

Wong *et al*. (2007) described how Lloyd's Register's developments on the automated load generation procedure to be applied directly to FEM to provide transparency for the assessment process and to build up confidence of potential software users.

3.1.2 Design Wave Load

Reliable computation of loads is crucial for an accurate global FE analysis of a ship structure. Classification society rules require that the ship is to withstand global loads that subject the hull girder to given (rule based) shear forces, bending moments, and torsional loads. Accordingly, major classification societies publish guidelines that are specially suited for structural analysis of ships. Generally, these guidelines are based on the design wave approach to obtain load combinations relevant for dimensioning the ship structure. In contrast to rule formula load approaches documented in the common structural rules for bulk carriers and double hull oil tankers, ship accelerations as well as wave-induced pressures are obtained from first principle hydrodynamic computations of the ship's behaviour in regular waves.

The underlying assumption of the design wave approach is that, if the ship investigated is to resist loadings caused by selected (equivalent) regular waves, it will resist all loads expected during its lifetime. Loads generated from this kind of analysis constitute extreme loads and must be based on a return period of at least 20 years. Instead of long-term load predictions, the rule-based load level is taken into account to determine amplitudes of equivalent regular waves. In assessing dynamic loads, it is necessary to consider a range of sea conditions and headings that cause a critical response of the structure. The resulting loads are then incorporated within a FE analysis of the entire ship to determine the resulting stresses experienced by the hull structure.

Rörup *et al.* (2008) demonstrated for a sample post-panamax containership the load generation for global FE analyses of ship structures with the design wave concept. First, ship and cargo masses were grouped into reusable assembled masses for the ship at hydrostatic equilibrium. Second, regular design wave scenarios were estimated, and hydrodynamic pressures for a large number of regular waves were computed. Third, a reduced number of relevant wave situations were automatically selected, and balanced hydrostatic, hydrodynamic, and inertia loads were applied to the finite element model. Performing most of these tasks is state of the art. Codes based on various numerical methods exist that can obtain wave-induced loads and perform a global FE strength analysis, and pre-processors are commercially available to assist in setting up the required meshes. However, modelling cargo loads efficiently is not addressed by standard tools, because it is specific to the subject ship design. Even if software tools were available for all the above tasks, performing a structural analysis based on computer generated loads remains complex and time consuming. Codes from various vendors need to be interfaced and executed in a coordinated manner, and experts from different departments need to cooperate, which can be an organizational challenge. Software tool GL ShipLoad was developed to address these problems. Cabos *et al.* (2006) and Eisen and Cabos (2007) described how it integrates all algorithms necessary to assess and combine the wave-induced pressures and the ship's structure to generate appropriate external loads for the FE model. In this way it facilitates the application of ship and cargo masses as well as external, wave-induced loads to the FE model.

All major classification societies have developed similar tools that enable to determine design loads and easy application of these to structural strength assessment tools. Shi *et al.* (2005) presented the design philosophy behind the ABS Dynamic Loading Approach that enables comprehensive identification of potential failure mechanisms. Key aspects of the DLA design philosophy, such as nonlinear sea loads, load combinations, various applications derived from full-scale ship finite element analyses were described and several examples were given to highlight some critical failure mechanisms to be considered for ultra large container carriers. Studies carried out by Class NK to develop rational and transparent procedures for the structural strength assessment of container ships were reported by Zhu *et al.* (2006). First, they introduced a comprehensive study on design loads for direct strength assessment of primary structural members of container ships. Second, they discussed a comprehensive study on the method for torsional strength assessment of container ships, based on the results from direct torsional moment analyses using a three-dimensional Rankine source method and FE analyses of the entire ship structure. Last, they documented results of some basic studies, such as three-dimensional numerical simulations of strongly nonlinear ship-wave interactions in extreme waves and full-scale measurements of hull response of a post-Panamax container ship.

3.1.3 Physical Wave Load

The physically most realistic numerical methods to predict wave-induced loads directly solve the Reynolds-Averaged Navier-Stokes (RANS) equations in the time domain. By relying on the interface-capturing technique of the volume-of-fluid (VOF) type, El Moctar *et al.* (2006), for example, showed that this technique accounts for highly nonlinear wave effects in that it computes the two-phase flow of water and air to describe the physics associated with complex free-surface shapes with breaking waves and air trapping. Such simulations need to be carried out for all wave situations that might occur during the operating life of a ship. In addition, results obtained from the FE analysis have to be post-processed. In practice, these are prohibitively time consuming and expensive tasks. Furthermore, such physically realistic loads do not automatically represent reliable loads for design, because they model only physical effects of simulated wave conditions and not loads that subject the ship to experience design bending moments, shear forces, or torsional moments.

Fonseca *et al.* (2006) presented an analysis of the vertical bending moments induced in a container ship by a set of abnormal waves measured at different locations and on different occasions. Probability distributions of ship responses in sea states that included abnormal waves were calculated and compared to responses induced by abnormal waves and to fitted distributions. Finally, structural loads induced by abnormal waves were compared with rule values and long-term predictions.

Design irregular wave is a phase-controlled irregular wave train in which a maximum of a certain ship response can be realized in a given short-term sea state. Fukasawa (2005) and Fukasawa *et al.* (2006) presented a procedure to apply the design irregular wave approach and the direct loading analysis method to estimate the maximum local stresses in ship structural designs. Design irregular wave comprises of intentionally superposed regular waves causing certain maximum ship responses in a given short-term sea state. On the other hand, the direct loading analysis method uses an FE model to obtain the time-varying stresses of the entire ship structure. The application of the method was demonstrated on a 6,200 TEU Post-Panamax size container ship (Fukasawa and Miyazaki, 2007).

Motok and Jovovic (2007) presented a computer program to solve the ship motion equations (combined heave and pitch) and to perform consecutive numerical integration of wave loads resulting in predetermined values of vertical shear force and bending moment. Transfer functions were defined, allowing evaluation of RMS values of amplitudes for different wave spectra. An extensive database was formed by means of systematic analyses of a series of 14 container ships of wide ranging principal dimensions advancing in various sea states at different speeds.

Shibata and Koshizuka (2007) presented a particle method to simulate three-dimensional behaviour of shipping water and to predict the impact pressure on a deck. An experiment carried out in a two-dimensional wave tank with a fixed deck model was numerically analyzed in three dimensions.

Hermundstad and Moan (2007) described a method for calculation of slamming pressures on ship hulls in irregular waves and validated it for a 290 m cruise ship. The method employs a nonlinear strip theory to calculate ship-wave relative motions and the slamming calculation program that uses a two-dimensional boundary element method (BEM) based on the generalized two-dimensional Wagner formulation. Calculated slamming pressures on the bow flare of the cruise ship showed favourable agreement with measured values. Davis and Whelan (2007) presented a computational model for catamaran wet deck slamming. In the case of a wave-piercing catamaran, the bow cross section has a double arch cross section, and slamming occurs when the arches fill. The computational model developed by the authors caters for the introduction of a complicated effect at the top of the arch of entrapped air, bubble formation by turbulent mixing, and their influence on added mass.

Lee *et al.* (2007a) carried out a series of parametric sensitivity studies on unmatched dimensionless scale parameters on the liquefied natural gas (LNG) tank sloshing loads by using a computational fluid dynamics (CFD) program. The study showed that the effects of viscosity and density ratio were insignificant, while the compressibility of ullage space played an appreciable role. The coupling and interactions between ship motions and inner-tank sloshing were investigated by a time-domain simulation scheme (Lee *et al.*, 2007b). The study adopted the following steps. The hydrodynamic coefficients and wave forces were obtained by a potential-theory-based three-dimensional (3D) diffraction/radiation panel program in frequency domain. Then, the corresponding simulations of motions in time domain were carried out using convolution integrals. The liquid sloshing in a tank was simulated in time domain by a Navier–Stokes solver. A finite difference method with SURF scheme was applied for the direct simulation of liquid sloshing. The computed sloshing force and moment were then applied as external excitations to the ship motion. The calculated ship motion was in turn inputted as the excitation for liquid sloshing, which was repeated for the ensuing time steps. A new method to determine sloshing loads on an LNG tank was developed by Graczyk *et al*. (2007).

In Korea, a JIP (Joint Industry Project) named WISH is in progress. Six companies are involved in this collaborative research program, namely Daewoo, Hyundai, Hanjin, Samgsung, STX and Korean Register. The main goal of the phase 1 of this program is to develop a time-domain Rankine panel method called WISH (computer program for Wave-Induced loads and Ship motions). In Kim and Kim (2008), the authors discussed several technical issues and findings in link with WISH development, illustrating the use of their method on several examples. Some differences with other programs such as SWAN were highlighted and explained.

3.2 Model Compatibility and Data Exchange

During the ship design process, finite element analyses (FEA) are performed on global and local models to check the scantlings against rule or rational requirements. These analyses produce a huge amount of data, including the models (geometry, scantlings, and loads) and the results. Several steps of the process imply data exchange: model checks, analysis of the FEA results, post-processing based on the FEA results. These exchanges are mostly non-electronic and time consuming. Industry players are introducing tools to improve the data exchange and analysis through the ship FEA studies (for example, a tailor-made tool called SIN (Ship Information Navigator) has been developed by Principia). Such tools allow navigating through the structure and visualizing the available data (scantlings, loads and results).

Grau *et al*. (2008) discussed application of non-specific standards and approaches for the shipbuilding industry. Particularly the PLM Services specification published under the Object Management Group (OMG) was advocated. This standard combines data and process integration on the basis of STEP and Service Oriented Architecture into one homogeneous approach. Such recent developments will be applicable to the shipbuilding specific CAx tools - such as TRIBON as well as mechanical CAD systems, including NX and CATIA, virtual reality systems and, last but not least, the digital class approval based on 3D-PDF.

Integration between computer aided design (CAD) and computer aided engineering (CAE) was considered and a Data Integration Framework (DIF) that consists of application interface protocols (APIs), and supporting engineering and analysis services was implemented to achieve the integration (Damhaug *et al*. 2007). The DIF enables data exchange between CAD applications and CAE applications. Two main problems associated with this approach, namely, representing the geometry in a practical way and the required simplification of the model when it is transferred to analysis, were addressed. The former, remedied by means of SAT, embedded geometry in the XML data set, and the latter was solved by means of a semi-automated system called the idealization toolbox (IDTB). The IDTB consists of an API (derived from XML) scheme that defines the exchange model, a set of transformations that define adaptations, translations and idealizations, and a part library that provides a set of parameterized structural objects that can be defaults for structural details in the vessel. When the idealization was completed to a user defined level, a numerical model (FEM) was created and the numerical analysis was performed to assess the stresses and strains in the model. The FEM module was integrated in the CAE tool.

Dumez *et al*. (2008) presented a tool (SILEX) for rapid and associated numerical hull models linked to different simulation tools. The tool was developed from the need of having a common product model which “communicates” with different software packages, such as hydrodynamic, structure, stability, class rules, and ship’s signatures. The developed tool is based on object modelling through the implementation of a parametric modeller, generative systems, granularity and propagation. In relation to structural analysis, the tool enables the extraction of a series of ship sections and associated scantlings from the 3-D model, suitable for analysis by MARS software of Bureau Veritas. Inversely, it can construct 2D sections by uploading MARS sections which were developed according to BV rules. These functions enable quick data exchange with associated gains in time and reduced risk of errors. They also significantly accelerate the process of checking the structure for compliance with BV rules. In addition, a special interface was developed for Bureau Veritas for the export of structure models in the HCM format of the Condition Assessment Scheme (CAS) consortium, which enhances the capabilities for better inspection and maintenance of the structure. The tool was successfully applied to an aircraft carrier and a frigate design.

Abt and Harries (2007) described the CAD-CFD integration environment FRIENDSHIP-Framework. This system was developed based on parametric modelling, numerical simulation and formal optimization. More generally, Abt and Harries (2008a) summarized the state-of-the-art in computer aided modelling of functional surfaces and different possibilities in coupling CAD and CFD for simulation driven design. Functional surfaces were considered 2D and 3D curved surfaces, such as compression blades, turbines, pumps, propellers, ship hull and appendages.

In a separate paper (Abt and Harries, 2008b), the authors distinguished more precisely the three methods of coupling, namely, the project based coupling, the tool specific integration, and the coupling via a common interface, and discussed their advantages and draw-backs.

3.3 CFD-FEA

Fluid Structure interaction is a topic of constantly increasing importance in the ship design process. In a weak coupling, the computed pressures from seakeeping analyses are used as input to assess the structural response. In a strong coupling, hydrodynamic and structural problems are solved simultaneously.

Specific problems such as slamming or whipping, have gained some benefit from strong coupling methods (see Oberhagemann *et al*., 2008).

Research in the field of pure CFD has been active during the past three years. As an example, VIRTUE (2005-2009) is an EU initiative of leading marine CFD centres to create a virtual basin by improving available CFD tools and integrating them in a platform for ship behaviour at sea. The five work packages of the project are, respectively, numerical towing tank, numerical seakeeping tank, numerical manoeuvring tank, numerical cavitation tank, and the integration platform.

In the same spirit, CFD remains the most appropriate tool to assess rudder flows and propeller design. The extensive experience gathered in the last five years has resulted in a guideline for rudder design procedure by Germanischer Lloyd (see El Moctar, 2007).

Displacement and pressure transfer between fluid and structure meshes in fluid-structure interaction analysis is complicated substantially when the two meshes on the domain interface are different and, therefore, form two distinct surfaces in three-dimensional space. A new method based on an approximate energy conserving interfacing strategy with two distinct components, mapping and interpolation, was proposed by Huang and Riggs (2005). The mapping between meshes was based on the assumption of a common parametric based description of the wetted surface. The interpolation strategy was based on the smoothing element analysis method developed to recover stresses in finite element analysis, with an additional term to impose an energy conserving constraint. The method was evaluated numerically with several examples.

Yang *et al*. (2006) coupled a VOF technique with an incompressible Euler/Navier Stokes solver operating on adaptive unstructured grids to simulate the interactions of extreme waves and a LNG carrier with fully or partially filled tanks. An Arbitrary Lagrangian-Eulerian (ALE) frame of reference is used. The case of a freely floating LNG carrier in a numerical sea state, where the waves are generated by a sinusoidal excitation, was solved. Highly nonlinear wave-body interactions such as green water and sloshing were modelled successfully.

3.4 Finite Element Modelling and Analysis

Finite element modelling and analysis has become the accepted norm for strength assessment of ship and offshore structures by a dramatic decrease in the computational time in accordance with the advancement of computer technology, but also by improvements in pre- and post-processing in FE analyses. FEA has become a classification society requirement as imposed by the introduction of IACS common structural rules for tankers and bulk carriers.

3.4.1 Finite Element Modelling

Element modelling is an important aspect of finite element modelling and analysis. Considerable research efforts have been devoted to developing simple, robust, generalised and efficient element models. It is common practice to use conventional shell elements such as four noded quad-shell elements or eight noded shell elements with both translational and rotational freedom for quasi-static response of ships. In recent years, the rotation free shell element models have been developed where the curvatures over an element are approximated in terms of deflection of nodes in adjacent patch of elements. This method offers advantages in nonlinear analysis.

In an FE analysis, model generation still accounts for a considerable portion of the total effort. Moreover, accuracy of FE results is influenced by appropriateness of the model. As a means of speeding up the process of model generation, functions such as automatic element division, etc., have been incorporated in analysis tools. Adaptive meshing may play an important role in reducing the effort in mesh generation as well as improving the approximation behaviour of FEM.

Shipbuilding industry increasingly employs 3D CAD systems to integrate all design and production processes by achieving seamless data transfer and data sharing. The availability of 3D geometry increased the recognition of the need for developing automatic FE modelling systems. However, general automatic mesh algorithms developed by the academic research domain have a limitation. The difficulty in satisfying line constraints, and the absence of proper idealization of 3D geometry entities defined in CAD system hinders directly, employing the general mesh algorithms. Jang *et al*. (2008b) developed an automatic FE modelling system for cargo hold FE modelling and whole ship FE modelling. The basic concept of the algorithm is to decompose surfaces using stiffener lines into sub regions and generate mesh using a rule established based on FE modelling practice of ship structure. Since the decomposed sub-regions take a simple polygon, they can be easily transformed into elements by decomposing the polygon according to the rule defined considering the shape of the polygon and the mesh seed on its perimeter.

A specialized data structure to efficiently store and handle ship design information, the analysis model information, and the mesh generation algorithm to generate analysis models for ship structure was proposed by Kim (2006). The data structure can simultaneously and effectively handle analysis model information and the ship design information, comprised of hull form data including structure information and compartment data for ship basic calculation available at the early ship design stage without CAD model. The proposed mesh generation algorithm can fast and robustly generate the quadrilateral mesh satisfying the constraints imposed by the structure information and the connecting relation. Based on the author’s own experience employing the proposed method, modelling time was reduced by 50 percent.

Jang *et al*. (2008a) proposed an approach to construct a simplified FE model using a 3D compartment model and to use this FE model for torsional strength assessment of container ships. Two algorithms were developed for mesh generation of internal structures: one for assembling the broken lines into closed loops and the other for automatically generating mesh from the loops. Another algorithm was proposed to generate mesh for outer hull using outermost nodes of the FE model built for internal members.

Another important aspect is the interconnectivity between coarse global models and detailed local models. Numerical simulation of complex structures containing structural details leads to large finite element models. Local detailed zoom models are needed for detailed stress analysis (for example, fatigue analysis). In some cases, several local zoomings are required for accuracy to determine stresses (hot spot stress). Sophisticated commercial FE packages allow automated detailed local mesh generation and the transfer of boundary conditions obtained from the global model to the local models. Amini *et al*. (2007) presented a domain decomposition method (FETI-DP) to generate course (global) and fine (local) meshes. The efficiency of such decomposition methods depends on its solver. The authors used a conjugate gradient solver, which has to be equipped with pre-conditioners. Defining the preconditioner is difficult for heterogeneous structures consisting of three-dimensional assemblies of plates and beams. A method was developed, taking into account the local interface stiffness of the sub-domain to speed up the convergence. To further reduce on the computational time, the authors proposed a domain decomposition method with different levels of discretisation in sub-domains. The sub-domains in the zones of interest were meshed finely (microscopic), while, the sub-domains in the reminder of the structure were described by a coarse mesh only (macroscopic or homogenized).

3.4.2 New FEA Techniques

The parameters of the line heating process have a significant effect on thermal history and the resulting residual deformation of the heated plate. The thermal transients are dependent on torch speed, torch height, gas pressure, and nozzle size, which in turn controls the residual deformation of the plate. Biswas *et al*. (2007) presented a three-dimensional transient finite element thermo-mechanical analysis of line heating using oxyacetylene gas flame. The analysis was carried out using temperature dependent material properties, Newton's convection, and Gaussian distribution of heat. To reduce computation time, a fine mesh was used along and near the heating line that was coarsened at the edges and away from the heating line. Numerical thermal transients and residual deformation were presented for various torch speeds, heat inputs, and different thicknesses of plate.

Chirica *et al*. (2005) presented a new finite element model quadrilateral finite element, named FEIC to study into design optimisation of walled composite panels. This model was used for linear analysis of thin composite plates with initial deformations. The basis of the FEM model is the Classical Laminate Theory. In each nodal point there are six degrees of freedom: two in-plane displacements, one transverse deflection, two rotations and a generalized twist.

Major research and development programs on the performance of double hull ships and other double wall structures that form the so-called Very Large Floating Structures have been pursued in the last years. Although the finite element stress analysis technique is usually used for design of such very large floating structures, in a preliminary analysis the modelling of such large structures could be more efficient if macro elements were used (Dimache *et al*., 2005). Authors discussed the use of the bending stiffness matrix of a hybrid beam element – which models a deep girder with wide common flanges to be used in a cellular macro element.

Sun and Spencer (2005) carried out buckling analysis of corrugated panels used in living quarters in offshore structures to save construction time and cost. These corrugated panels are different from corrugated bulkheads in ship structures, which are designed in triangular or trapezoidal profile with unequal flanges and with a corrugation angle between 45 deg and 90 deg. The paper discussed the philosophy behind the ABS development of design recommendations for the buckling strength assessment of these corrugated panels. The modelling uncertainty associated with the recommended criteria was established by comparing predictions with laboratory tests and finite element analysis results.

Alshoaibi *et al*. (2007) employed an adaptive finite element method to analyze two-dimensional linear elastic fracture problems. The mesh was generated by the advancing front method, and the norm stress error was taken as a posteriori error estimator for the h-type adaptive refinement. The stress intensity factors were estimated by a displacement extrapolation technique. The near crack tip displacements used were obtained from specific nodes of natural six-noded quarter point elements which are generated around the crack tip defined by the user. The crack growth and its direction were determined by the calculated stress intensity factors. Sui and Bian (2008) developed the topology optimization model for continuum structures based on the ICM (Independent Continuous Mapping) method. It was shown through numerical examples that the method can solve the topology optimization problem of continuum structures with both buckling and displacement constraints efficiently.

3.4.3 FEA Applications

Ok *et al*. (2007) presented a study on the assessment of the effects of localized pitting corrosion, which concentrates at one or several possibly large area on the ultimate strength of unstiffened plates. Over 256 nonlinear finite element analyses (FEA) of panels with various locations and sizes of pitting corrosion have been carried out. The multi-variable regression method was applied to derive new formulae to predict ultimate strength of unstiffened plates with localized corrosion. The results indicated that length, breadth and depth of pit corrosion have weakening effects on the ultimate strength of the plates while plate slenderness has only a marginal effect on strength reduction. Transverse location of pit corrosion was also an important factor determining the amount of strength reduction. The study concluded that when corrosion spreads transversely on both edges, it has the most deteriorating effect on strength.

A collision analysis between a container ship and a very large double hull crude carrier (VLCC) including the effect of fluid structure interaction problem was presented by Zhang and Suzuki (2007a). Three different numerical simulation methods were adopted to model fluid–structure interaction in a liquid filled cargo tank, namely, Arbitrary Lagrangian–Eulerian finite element method (see also Na *et al*. 2007), Lagrangian finite element method and linear sloshing model. The numerical simulation results indicated that the fluid–structure interaction of liquid a cargo-filled tank has a significant effect on the motion and structural response of the struck cargo tank. Compared with calculation results of the ALE FE method, the linear sloshing model underestimates the influence of fluid–structure interaction of liquid cargo tank while the Lagrangian–Eulerian finite element method may be considered as the practical method for engineering applications as it provided more reasonable results with a relatively low CPU time.

Lee *et al*. (2008) considered a probabilistic FE analysis, taking into account that input parameters to a FE analysis are stochastic. Authors investigated the influence and sensitivity of input parameters on the structural robustness. Variability and uncertainty in loads, geometry and lamina stiffness were investigated, employing a stochastic finite element analysis (SFEA) procedure applied to the design of composite yacht hulls.

Ivanov (2007) studied the correlation between maximum still water shear forces and bending moments versus the difference between radii of gyration of gravity and buoyancy forces. It was shown that the difference between the two radii of gyration determines the sign and absolute values of the maximum still water shear forces and bending moments. The author suggested that radii of gyration are to be determined in the early design stages, which then allows the maximum still water shear forces and bending moments even before performing strength calculations.

Jones (2006) presented a review of recent developments on the response of structures subjected to large dynamic loads, which produce large inelastic strains. The strain rate sensitive behaviour of materials, dynamic rupture strains, and the dynamic inelastic failure of structures were commented. Also, dynamic energy absorbing characteristics of structures, scaling, and the response of fibre metal laminates were discussed.

Kabche *et al*. (2007) presented a finite element analysis of a bolted composite/metal hybrid panel assembly subjected to uniform pressure loading. Parametric studies were carried out to quantify the influence of the geometry of the joint constituents on the global response of the hybrid assembly. The model response was found to be the most sensitive to changes in steel component geometries, while the composite laminate geometry had a modest localized effect at the joint region.

Kamenov-Toshkov *et al*. (2006) proposed an approximate method for calculation of the wave-induced design bending moment for any given ship's operational life. Authors assumed that the probabilistic distribution type of the wave-induced bending moment within different time periods does not change, but only the values of the distribution's parameters change.

Lotsberg (2006a and 2007) presented a fatigue assessment method based on FEA, where a link between calculated hot spot stress and fatigue capacity was established. The papers give a review of the fatigue calculations using finite element analysis and provide recommendations to perform fatigue assessment of plated structures based on finite element analysis combined with one hot spot S-N curve.

Welding distortion often results in problems such as dimensional inaccuracies during the assembly and increased fabrication costs. Therefore, prediction and reduction of welding distortion are critical to improve the quality of welded structures. Welding distortions during the assembly process are affected by not only local shrinkage due to rapid heating and cooling, but also root gap and misalignment between parts to be welded. Deng *et al*. (2007) developed an elastic finite element method which is based on inherent strain theory to accurately predict welding distortion. First a thermal elastic-plastic finite element method was employed to estimate inherent deformations for different typical welding joints. Second, the proposed elastic FEM was used to predict welding distortion for large welded structures based on the obtained inherent deformations. Camilleri *et al*. (2005 and 2006) developed and experimentally validated a simulation tool to predict distortion, with particular emphasis on out-of-plane deformation generated in double-sided fillet-welded attachments. Simulation was used to optimise the relative positions of a twin-arc configuration, to give minimum out-of-plane deformation. Jung (2007) reported the development of a new numerical model, Q-Weld, which is a shell element based elastic analysis, for the prediction of distortion induced in ship panels. It was reported that the developed Q-Weld predicted weld induced distortions agreed well with those determined from the three-dimensional thermal-elastic-plastic analysis.

Paik and Shin (2006) developed closed form design formulations for predicting structural damage of ship stiffened panels under impact pressure loads arising from sloshing, slamming or green seas. Existing formulations of permanent panel deflection developed under quasi-static pressure loading condition in the literature were expanded to account for dynamic effects associated with impact pressure actions. The proposed method was validated by a comparison with present DYNA3D numerical simulations for ship stiffened panels and experimental results.

An advanced analytical method (AM) which is design-oriented and coupled with an elastic-plastic method (EPM; which is a combination of elastic large deflection analysis and rigid plastic analysis) was proposed by Qi and Cui (2006) to analyse ultimate buckling strength of stiffened panels. As a special example, analytical formulation of ultimate strength of intact ship hulls under vertical bending was derived. The EPM was improved by including lateral pressure into the energy function and modifying the treatment of initial imperfections.

Vhanmane and Bhattacharya (2007) proposed a simple analytical method to predict the average stress-average strain relationship for plating between stiffeners in ship structures. The method incorporates two different methods the membrane stress method involving large elastic deformation theory and rigid plastic collapse mechanism theory. The plating between stiffeners was analysed under axial load for different aspect ratio values.

Mosaka and Mansour (2008) investigated the behaviour and ultimate compressive strength of stiffened plates with imperfections, using a nonlinear finite element method. The imperfections considered consisted of initial deflection and residual stresses. Several types of initial deflections were investigated, including those that may initiate stiffener column buckling and stiffener tripping. Simple design equations for determining ultimate strength were developed, based on finite element parametric study. It was found that under certain conditions a hybrid type mode of failure was necessary to accurately represent the behaviour of stiffened plates with imperfections, in addition to the usual plate and stiffener failure modes. It was also found that column buckling type initial deflection is the most important form of imperfection.

4. SANDWICH PANELS AND DEFORMATION LIMITS

4.1 Recent Studies on Steel Sandwich Panels

Significant amount of research on steel sandwich panels has been carried out in Europe in SANDWICH project between 2000 and 2003. Several outcomes of this work are reported in the following. After this project EU funded coordinated action project SAND.CORe was established to boost the application of sandwich structures. As a result of this, a three year EU funded project DE-Light Transport was started in 2006 with an aim to investigate different marine applications for sandwich structures.

Metschkow (2006) presented a review on the development of I-core sandwich panels. The topics covered included production and ways to improve the strength performance of these panels. Kujala and Klanac (2005) and Kujala and Noury (2005) summarized recent developments on different steel sandwich topologies, production, application cases and design characteristics. The design algorithms have been developed. From a design point of view, fatigue of joints is an interesting and still open research topic.

Koertenoeven *et al.* (2007) discussed the possible application and benefits of using sandwich panels in construction of dredging ships and dredging equipment to improve the performance of complex and special ship designs and to reduce production costs.

4.1.1 Bending Response of Laser Welded Sandwich Panels

Romanoff and Varsta (2007a and 2007b) presented that the sandwich plate theories based on equivalent stiffness properties and assumption of homogenous core can be used to design periodic steel sandwich structures. The requirement for accurate response prediction is that the periodic structure is taken into account both when determining equivalent stiffness properties and also when calculating stresses. In case of high local loads, such as wheel loads, also a separate analysis is needed for local response of the patch loaded face plate (Romanoff *et al*., 2007a).

4.1.2 Strength of Steel Sandwich Panels

Kozak (2006a) presented a summary of an extensive series of buckling tests for I-core sandwich panels. It was clearly observed that there exists both local and global buckling of the face sheets and the panel, respectively, but also cases where these two types interact. It was also seen that the contact in stake weld area poses problems of numerical modelling of the buckling behaviour of the sandwich panel. Bogdaniuk *et al*. (2006) presented a comparison of simple analytical buckling load estimates and detailed nonlinear FE calculations on buckling strength; it was observed that analytical design formulae are conservative as well as the detailed finite element calculations when compared to experiments.

Kozak (2006b) presented the results of fatigue tests conducted on sandwich panels and based on experiment findings, he made a proposal on what failure models should be taken into account in fatigue assessment. Pyszko (2006) studied by FEA the strength characteristics of the sandwich to steel plate joint under combined bending and in-plane loads.

Elastic buckling and collapse of laser welded sandwich panels with an adhesively bonded core and uni-directional vertical webs was investigated by Kolsters and Zenkert (2006a and 2006b).

4.1.3 Laser Stake Welds in Steel Sandwich Panels

Kozak (2005) showed experimentally that the strain distribution in laser stake welded T-joints is influenced by contacts and laser weld thickness in I-core sandwich panels. The conclusion was that to achieve accurate structural response in, for example, finite element calculations, the laser weld needs to be modelled. Boronski and Szala (2006) carried out experimental full strain field measurements of laser stake welded T-joints in fatigue loading.

Romanoff *et al*. (2007b) carried out extensive tests on laser welded stake joints. Tests revealed that geometric properties show significant deviations and that the contact in the laser weld area is indeed a significant phenomenon when stiffness of the T-joint is of concern. Due to deviations in the geometry of the laser welds and also the complex contact mechanism, the authors proposed an approach where the stiffness of the T-joints iss experimentally derived. These experimentally derived average stiffness values are used together with a plate model based on homogenized stiffness properties. The approach was shown to be fairly accurate compared to tests (Romanoff *et al.*, 2007b). The influence of laser weld flexibility was large when the deflections of the sandwich panels were considered (Romanoff and Varsta, 2007b, 2007c). However, at the range of current T-joint stiffness values, the stress response was found to be unaffected (Romanoff and Varsta, 2007a, 2007b).

4.1.4 Steel Sandwich Panels and Optimization

Kalnins *et al.* (2005) presented an optimization approach for I- and V-core sandwich panels using response surface and finite element method. The method considered 3D shell element model of the actual structure, samples the design space, and calculates the response of the sandwich panel. The proposal for optimum is to find from polynomial approximation of the sampled design space. The method was used in optimization of a stair case landing.

Romanoff and Klanac (2007) used the homogenized plate theory together with optimization based on vectorized genetic algorithm. The benefit of the approach is that the FE mesh is created only once, and only the material definition is changed during optimization. The method can capture the influence of periodic stresses. The study showed that, in case of hoistable car decks, the critical strength criteria is not buckling but yielding of the face and core plates. This is mainly caused by high local loads due to patch loads, but also due to secondary bending stresses induced by shear deformation.

Ehlers *et al.* (2007) presented a comparative study on the side shell performance of a tanker and a RoPax vessels. Based on the investigation of Klanac *et al.* (2005), different X-core sandwich structures were selected to be investigated and to be compared against conventional stiffened plate structures. The structure was optimized using 2D approach and response surface method. In case of a tanker 30 percent better energy absorption capability was obtained by the use of sandwich structure when compared to conventional stiffened plate with only 10 percent increase in weight. For a RoPax, this was 50 percent with the same 10 percent weight increase.

Kolsters and Wennhage (2008) investigated the possibilities for structural optimization 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 were discussed and numerically evaluated to demonstrate the effect of parameter variations on stress and deflection. The closed form expression was coupled with structural optimization method based on the method of moving asymptotes (MMA) and applied in the optimization of a typical accommodation deck configuration. It was concluded that significant weight savings can be obtained using adhesively bonded core inside the steel sandwich panel.

4.2 Steel Sandwich, Elastomer Core

Over the past 12 years a new type of steel sandwich panel, containing an elastomer core, has been widely adopted in the ship industry for applications that require a high resistance to impact damage. The most common application has been the replacement of conventional stiffened steel panels in the inner bottoms of bulk carriers. These sandwich panels also provide excellent protection from blast loads and fire, and have good acoustic and vibration damping properties. Because of their robust and protective properties, these panels need to be designed on the basis of their ultimate strength. A recent Virginia Tech PhD thesis (Zhou, 2007) presented an efficient interaction equation for the ultimate strength of such panels under combined in-plane compressive stress σ and lateral pressure p. The equation is based on nonlinear finite element analysis, verified by experimental results from a University of Alberta Master's thesis (Little, 2006). The FEA results for pure lateral pressure load cases are used to derive an expression for the ultimate pressure, p_{ult} , in terms of a correction factor applied to the pressure pHL corresponding to an idealized "plastic Hinge Line" collapse. The final interactive ultimate strength equation is expressed in terms of two "act alone" strength ratios: $R_\sigma = \sigma / \sigma_Y$ and $R_p = p/p_{\text{ult}}$. The resulting equation was close to both the FEA and the experimental results, with a bias of -0.003 and a standard deviation of 0.029. The interaction equation is

$$R_p^{\ 2} - C\, R_p^{\ 2} R_\sigma^{\ 2} + R_\sigma = 1 \tag{1}$$

in which

$$C = 1 - \frac{3}{1000\ (0.5 + \alpha^2)} \left(\frac{b}{t_c} \right)^2 \tag{2}$$

The "act alone" collapse pressure pult, which is the denominator of Rp, is given by

$$p_{ult} = p_{HL} \times \left[\frac{(0.06\bar{t}_c - 1)\bar{t}_f + \bar{t}_f^{\ 3}\, \dfrac{33.6 + 0.5 \cdot \bar{t}_c}{12 + \bar{t}_c}}{\bar{t}_f^{\ 3}} \right] \times \left[0.23 \tanh(1.5\alpha) + 0.8 \right] \tag{3}$$

The plastic Hinge Line collapse pressure was derived by (Save *et al.* 1997)

$$p_{HL} = \frac{[24(\frac{A}{B} + 1)]}{B^2 (1.5 \cdot \frac{A}{B} - 0.5)} \cdot \sigma_Y \cdot t_f (t_f + t_c) \tag{4}$$

Symbols not already defined are:

a = panel length in the x-direction (direction of σ)
b = panel width in the y-direction

α = aspect ratio of the panel (=a/b)
A = panel long dimension (Hinge Line theory)
B = panel short dimension (Hinge Line theory)
t_f, t_c = thickness of a single face plate and of the core

Equation (3) uses normalised thickness defined as

$$\bar{t}_f = \frac{1000 t_f}{b}$$

$$\bar{t}_c = \frac{1000 t_c}{b}$$

4.3 FRP-GRP Composites

Composite structures are often used when there is a requirement for low weight although Fibre Reinforced Plastic (FRP) / Glass Reinforced Plastic (GRP) composites offer other advantages, such as excellent corrosion and fatigue resistance characteristics, high stiffness to weight ratio, less maintenance cost and non-magnetic properties which may be desirable for naval craft (Shenoi, 2006). For this reason, fibre reinforced polymer composite deck panels are effectively used in the construction of offshore structures, such as pontoons, floating docks, oil drilling platforms, ocean thermal energy conversion (OTEC) systems and harbour structures. A key aspect is to be able to take full advantage of the material and utilise it to its limits. To achieve this, it is important to have a good understanding of the structural behaviour of the product as well as defects and imperfections that are created during the production that can influence the structural performance, so that adequate levels of structural safety and reliability can be achieved without having to apply excessively large factors of safety.

Hayman *et al.* (2007a) reviewed the types of defects relevant to production processes, of their causes and the means that can be used to reduce or eliminate them, and of models that enable the effects of defects and imperfections on structural performance to be predicted. Hayman *et al.* (2007b) investigated improvements of X joints which are used to attach end bulkhead of the superstructure to the deck. The study was focused on the prevention of crushing of the core under compressive load while ensuring adequate damage tolerance for the case of tensile load.

Alagusundaramoorthy and Reddy (2008) carried out an investigation into the load–deflection behaviour of glass fibre reinforced polymer (GFRP) composite deck panels under static loading. Three prototype GFRP composite deck panels were fabricated using hand lay-up process and tested under a factored heavy wheel loads. The deck panels were analyzed using the standard FE software, ANSYS. Maximum deflection and strain at factored load and flexural and shear rigidities were calculated in the FE analysis and compared with the experimental data, and also with the specifications given by the Ohio Department of Transportation (ODOT), USA. It was concluded that the fabricated GFRP deck panels satisfied the performance criteria specified.

Berggreen *et al*. (2007) performed tests on square composite plates under in-plane compression. The plates had a width-to-thickness ratio close to the value for which the elastic critical load and the load for compressive fibre failure over a complete section would be equal. This condition gives the maximum sensitivity to initial geometric imperfections. An advanced digital photogrammetric measurement system was used to monitor deformations of the tested plates. The responses were also calculated by means of geometrically non-linear finite element analysis. It is interesting to note that experimental set-up and numerical modelling considered the assumption of rotationally fixed edges; however examination of test specimens revealed that the loaded edges of the plates rotated significantly during the tests.

Within the EUCLID project, ‘Survivability, Durability and Performance of Naval Composite Structures’, one task is to develop improved fibre composite joints for naval ship super structures. As part of the project, Toftegaard and Lystrup (2005) studied the design and test of a sandwich T-joint with reduced weight but with the same or higher strength than the existing design. The lightweight T-joint was designed for sandwich panels with 60 mm thick PVC foam core and 4 mm thick glass fibre/vinyl ester skin laminates. The panels were joined by use of filler and two triangular PVC foam fillets (core triangles). A method for a finite element (FE) parameter study was developed and used for selection of a promising (strong) configuration of the T-joint. The improved lightweight T-joint offered 20 percent higher strength than the existing design, and the weight was only about 40 percent of that of the existing design.

Canyurt and Zhang (2006) provided a validation study of a simple but effective design to improve the strength of thick adhesive composite strap joints using experiment and finite element method. The strap joint under investigation, with a particular application to naval ship structures, consists of two thick woven E-glass/vinyl ester laminates joined together with two steel doublers. The authors suggested that the proposed simple, yet effective design / technique can considerable improve composite joints’ strength for composites with low transverse interlaminar strength and susceptible to delamination.

Pre-formed composite components have the potential to provide an economical alternative to traditional construction techniques for the manufacture of ship structures in the same way as the use of aluminium extrusions in the construction of decks and superstructures of high speed craft that could be replaced with pultruded glass-reinforced plastic (GRP) profiles. The length of the pultruded section is limited and therefore, efficient and economic jointing techniques must be developed that can withstand the loads applied to ship structures. Boyd *et al*. (2006) investigated finger joints in GRP components manufactured from material that models pultruded construction. Various joint geometries were examined, load displacement behaviour was established.

Chen and Soares (2007a) presented an approach to estimate the longitudinal strength of ship hulls in composite materials. Typical ship configurations have as dominant failure mode the failure of the deck under compression associated with sagging moments. Ship hulls were modelled as assemblies of stiffened composite panels. Buckling, material failure and ultimate collapse of the stiffened panels were predicted by nonlinear finite element analysis, which is based on a degenerated three-dimensional laminated composite shell element with updated Lagrangian formulation and first-order shear deformable kinematics. Chen and Soares (2007b) calculated the ultimate longitudinal strength of a ship hull by a progressive collapse analysis based on load–average strain curves of stiffened composite panels that are developed by a progressive failure nonlinear finite element analysis. The reliability analysis was carried out using an improved first-order reliability algorithm and considering an appropriate stochastic modelling of the basic design variables, such as the modelling uncertainties, the materials properties, the lamina thickness, the lamination angle, and bending moments. An all-composite ship was analysed for demonstration.

Cao *et al*. (2006) and Maroon *et al*. (2007) investigated a hybrid ship hull made of a steel truss and composite sandwich skins experimentally and numerically. The steel truss was designed to carry the bending loads, whereas the composite skins were designed to carry shear and water pressure loads. A model was tested under hogging loads, after having previously been subjected to sagging loads. All loads were introduced as shear through brackets welded to bulkheads. At the design load condition, it was observed that plastic yielding of the steel truss took place, whereas there was no indication of failure in any of the composite sandwich panels, nor in the adhesive bonds between the panels and the steel truss. Nonlinear elastic-plastic finite element analyses were performed on the complete hull. Results from the numerical analyses were compared with data from both sagging and hogging tests and good correlation was found. The study was extended to include a design optimisation for a 142 m ship hull representing a destroyer structure employing a FEA with loads determined from the American Bureau of Shipping (ABS), (Cao *et al*., 2007).

In a study presented by Caccese *et al*. (2007), structural response of a full scale composite structure and a hybrid strut/ship connection was analysed.

Chirica *et al*. (2005) presented a research study to introduce an optimum design method for walled composite panels using a new finite element model: quadrilateral finite element. This model was used for linear analysis of thin composite plates with initial deformations. The FEM model was based on the Classical Laminate theory. In each nodal point there are six degrees of freedom: two in-plane displacements, one transverse deflection, two rotations, and a generalized twist. Bending and in-plane analysis may be studied with this element model.

Ojeda *et al*. (2007) presented a new approach for the large deflection analysis of isotropic and composite arbitrary orientated stiffened plates. Nonlinear equilibrium equations are derived, using the principle of virtual work applied to a continuum with a total Lagrangian description of motion. Eight node isoparametric plate elements are combined with three node beam elements, using the concept of equal displacements at the plate-stiffener interface to represent the stiffened plate. The stiffness of the beam element was computed first, irrespective of its position within the plate element, and then transferred to the plate nodes depending on its orientation and position within the plate element. The Newton-Raphson incremental-iterative solution technique was used to obtain the nonlinear response path. Shear carrying capability was found to be a major requirement for ship bottom panels. Kampner and Grenestedt (2008) adopted a simplified approach to study the potential of using a corrugated skin in a sandwich to carry shear loads. The authors' approach requires a major simplification in the sense that the corrugated skin is modelled as a conventional material with a homogenous stiffness. Chakrabarti and Sheikh (2007) studied the buckling of laminated sandwich plates using an efficient finite element plate model, developed by the authors, which is based on a refined higher order shear deformation theory.

5. SHIP STRUCTURES

5.1 Design Development, Trends and Challenges

The common structural rules for tankers and bulk carriers were implemented in April 2006 and the shipbuilding industry had to cope with two completely new design standards. Whilst the rule development over the last ten to fifteen years can be characterized more as a slow evolution, the introduction of common structural rules represented a step change in assessing the structural adequacy of designs. Tougher strength and fatigue requirements were introduced, and more extensive design calculations to fulfil both the prescriptive scantling requirements and direct strength assessment using finite element analysis were made mandatory. All existing designs that had been developed for years had to be reassessed, redesigned and documented for compliance with the new rules.

In parallel with the introduction of the common structural rules, the newbuilding market has been booming, and the yards' order books are filled up for the next few years. Existing yards improve their production lines, and new yards are established to cover the market demand for newbuildings. The high activity combined with completely new design standards for tank and bulk vessels resulted in a gap between available structural design competence and the shipping industry's needs.

The new rule requirements, high newbuilding activity, and establishment of new shipyards resulted in design and engineering competence challenges and increased demand for support and training from classification societies and other resource hubs. Combined with shorter building schedules, the pressure on structural engineers involved in the design and approval process is high.

Although revolutionary design concepts are presented from time to time, there are rarely new concepts put into production. Ships for carrying compressed natural gas

(CNG) have been a hot topic, and many different concepts have been presented at various conferences, but so far none of these have materialized in a sailing ship. A significant amount of work to qualify both technology and designs are, however, carried out, and with the technology in place and the worlds' demand for cleaner energy it is likely that the CNG marine industry will grow in the years to come.

Record breaking ships with respect to size have been launched frequently the during last few years. From the early nineties until today, the largest containerships increased in size from about 4,500 TEU to 8,500 TEU in 2004 and around 14,000 TEU in 2006. Also, LNG carriers increased in size from the conventional size around 135,000m^3 to the recently delivered Qflex and Qmax vessels of 210,000 m^3 and 260,000 m^3, respectively. With this development it is pertinent to question if class rule calculation models are stretched beyond its premised and intended area of application. In 2014 the Panama Canal expansion will be completed, increasing maximum breadth from 32m to 49m and maximum ship length from 294m to 366m. New limits will open up for novel designs and the number of mega ships will further increase.

Another aspect that has high attention is design for arctic operation and ice strengthening. Retreat of the summer ice in the arctic basin will open The Northern Sea Route for more commercial traffic.

In the area of inspection and maintenance of ships' structures, current R&D included development of computer based condition monitoring and recording for real time structural maintenance decisions (CAS project, Cabos *et al*. (2008)). In CAS project, a standard exchange format called Hull Condition Model (HCM) and a suite of tools which uses HCM was developed to provide a permanent easy and transparent access to all ship structural data. This is particularly important, considering inspection and thickness measurements are conducted by various NDT companies to all class societies, and ships sometimes change their classification societies. For maintenance of tanker structures, Hu and Prusty (2007) presented a new structural condition monitoring method utilising existing and new systems. The authors elaborated on the scheme of this system, position of sensors, data acquisition, and signal analysis. As part of a pro-active fatigue management system, a compact fatigue damage sensor that is attached to the structural member and inspected after a certain period has been applied to the hull of an LNG carrier (see, Yamamoto *et al*., 2007). The sensor's long-term durability under severe environment was investigated.

Kawamura and Sumi (2005) proposed a new concept of an information system for structural integrity of ships to improve safety and to assess the condition of structural strength in service. In this system, all information of damages in a certain ship obtained from hull surveys is managed in an information database, allowing assessments to be made at any time in the ship's life of the present structural integrity status or provisions to be made for the future. A prototype system for the evaluation of corrosion damages was developed, using the STEP (standard for the exchange of product model data) technologies with the proposal of a data model of the information system.

5.2 Types of Analysis for Various Ship Types

5.2.1 Passenger Ships

In recent years passenger ships have seen dramatic changes with respect to their size and design features. The superstructure volume in relation to that of a hull increased significantly due to a growing need for open spaces such as restaurants, theatres and atriums. Also, the size of ships has increased, based on the advantage offered by scale of economy with larger ships. A modern passenger ship is a complicated structure, which has a high and long superstructure with several decks supported by pillars, longitudinal and transverse bulkheads on the hull as well as large openings. For such a vessel with a large superstructure consisting of numerous decks, ultimate strength of the structure becomes increasingly important since the structure may collapse at the load level close to the design load.

Naar (2006) carried out a PhD study on the ultimate strength of large passenger ships with multiple decks. The study was based on the linear coupled beam theory meant for the estimation of hull girder response of ships with large superstructures. The theory was extended to cover ultimate strength of the hull girder composed of stiffened panels, which allows for a better explanation of the effects of various parameters on ultimate strength of the hull girder in passenger ships.

The influence of extensive superstructure and upper decks in the primary strength must be considered in the early concept design phase, where important, but not always optimal, decisions are made. Zanic *et al.* (2005) presented characteristic aspects of structural interactions between lower hull and superstructure for generic ship types (based on full-ship FEM models of a car carrier, cruise ship, a tank car carrier, and a livestock carrier) and algorithm for their synthesis in the concept design phase that combines fast generation of FE models (using macro elements) and decision support through fast optimization method (SLP and FFD).

The IMO Maritime Safety Committee (MSC) at its 82nd session in November-December 2006 adopted a package of amendments to SOLAS for large passenger ships currently being built. The amendments include new concepts, such as incorporation of criteria for the casualty threshold (amount of damage a ship is able to withstand, according to its design basis, and still safely return to port) into SOLAS chapters II-1 and II-2. The amendments also provide regulatory flexibility, so that ship designers can meet any safety challenges the future may bring. The amendments are expected to enter into force on 1 July 2010 (IMO, 2008).

Development of a new innovative concept of RoPax ships at the IT environment of Uljanik Shipyard was discussed by Dundara *et al.* (2008). In the structural related part of the study, the design methodology necessary to perform extensive multi-objective structural optimization of RoPax structures using the extended OCTOPUS-MAESTRO software was discussed. The multi-objective optimization (minimum cost/minimum weight/maximum safety measures/etc.) satisfies structural constraints: yielding, buckling, displacements, and ultimate strength of hull girder and ship panels.

5.2.2 Ice Going Vessels

Demand for ice strengthened tankers and other ice-going vessels have increased significantly in recent years. As a result and needs for economic construction and greater structural optimization have been driving regulatory agencies to rationalize ice strengthening design standards. More and more direct calculation approaches are introduced into design standards, and some guidelines have been developed to guide analyses and evaluations of alternative designs. Wang *et al*. (2005) studied results of a recent project aimed at rationalizing the design of side shell. High level of uncertainties associated with design ice loads in Finnish-Swedish Ice Class Rules and the recent Finnish Maritime Administration Guidelines were addressed. Wang *et al*. (2007b) presented structural reliability levels from studies performed on the implied reliability level of Baltic Ice class rules. The influence on reliability levels of different ship sizes and different ice classes were considered focusing on hull scantling design. The sensitivity of target reliability level was presented to demonstrate various options for optimisation of ship structural design without compromising structural safety.

The "Machinery Requirements for Polar Class Ships" IACS URI3 has been released and is to be uniformly applied by IACS Societies on ships contracted for construction on and after 1 March 2008. Unlike the pervious ice class rule, URI3 relies more on direct calculations for propeller strength assessment. Some concerns on general practice on finite element analysis according to the URI3 Rule was discussed by Lee (2007) based on current experiences.

Han *et al*. (2007) presented results of a structural risk analysis for a 170K m3 with Ice Class 1A for operation from the Baltic Sea to Quebec, Canada. The target vessel was characterized by GTT NO 96 containment system for LNG cargo. Capacity of the double hull structure was assessed considering inner hull deflection as the critical factor of safety of the containment system. This capacity was compared with accidental ice load, as 'demand' to the LNG carrier, from ice hazards that can take place in the Baltic Sea operation in winter or in the East Canadian Coast. Risk analysis was performed to evaluate risks of considered ice features in the operation route based on the study of capacity and demand.

5.2.3 Container Vessels

The steady increase of global container traffic boosted demand for ever larger containerships. Until the late 80's, dimensions of the Panama Canal limited the maximum size of ships up to 4,400 TEU. However, this limit was broken as early as 1988, with the first post-Panamax ships carrying more than 5,000 TEU. It is estimated that by 2011, nearly 40 percent of the world's container ship fleet will be too large for the current size of the Panama Canal locks. The decision of the Panama Canal Authority to build a third set of locks, which is scheduled for completion in 2014, heralded in a new era: vessels of up to 366 m length, 49 m width, and 15 m maximum draft will be able to navigate the canal. They will have a nominal cargo capacity of up to 12,500 TEU. But even these dimensions have been surpassed today: ships of the Emma Maersk series, currently the biggest container ships in the world, carry up to 13,000 TEU. In December 2008, South Korean shipyards started to deliver a significant number of 12,000 TEU and larger ships. Most of these container ships opted in favour of a concept originally developed by Hyundai Heavy Industries and Germanischer Lloyd in 2005. Commonly referred to as “twin-island design,” this design places the superstructure and the engine room in different parts of the ship. Arranging the deckhouse in the forward part of the ship permits an even greater container capacity, thanks to the improved bridge visibility according to SOLAS requirements. The design also meets international regulations governing protection of fuel tanks.

Probst (2007) predicted an ongoing trend for larger container ships. The author predicted that the breakeven point will be governed by economics and not by technical considerations. The enlarged principal dimensions are also linked to the container itself and to the maximum number of tiers. The container strength is the real bottleneck and cannot be resolved in the next years due to the large number of existing containers. However, new designs are often beyond the direct experience of present vessels and, therefore, Probst (2006) demonstrated that aspects such as structural integrity, manoeuvrability, propulsion, and especially operational management must be carefully considered at an early design stage. The structural feasibility of 13,400 TEU container ships has been proven, and this investigation verified that a further enlargement of Post-Panamax container ships is possible.

Optimization of initial design of container ships is an important issue, and Okada *et al.* (2007) developed a design optimization system using a genetic algorithm. Todays large container ships require new constraints to be fully accounted for, such as torsional deflection and hatch opening deflection. Under these circumstances, the authors incorporated torsional strength and hatch opening deflection calculation in the optimization system. To rationally take account these parameters, it is important to account for the correlation of various modes of deflection in actual seas and also to calculate torsional strength and hatch opening deflection correctly in a simple manner suitable for the initial optimization process.

One of the most important points in structural design of container ships is the strength of hatch corners. Okada *et al.* (2006) reported that, formerly, hatch corners used to be assessed by combining the component induced by hull girder vertical bending and the component induced by hull girder torsion. In the design of new generation container ships without deck girders, the effect of cross deck fore-aft deflection also became prominent. Another point was the impact of structural displacement on deck fittings. Regarding new generation ships, large fore-aft deflection of cross decks gave rise to the new problem of interference of hatch covers, lashing bridges, and other deck fittings.

Some fatigue damages were reported by Ryu *et al*. (2004) at hatch corners in way of the fore hold of a container carrier, supposedly as a result of the combination of pitching and high torsional moment at the fore hold part. The conventional method of wave load analysis, however, was unable to generate the high torsional moment at the fore hold part. An advanced wave load analysis was proposed in this paper (i.e., by analysing the ship's torsional moment, assuming the ship to be in a stationary heeled condition). The result of the structural analysis by this advanced method produced the high torsional moment at the fore hold part and generally confirmed the fatigue damages at hatch corners in way of the fore hold.

Strong demand of efficient container trading accelerated the development of large container ships. The increased size, which has never been experienced, raises many challenges for designers, such as initial design optimization, hatch opening deflection, and strength. To achieve these challenges, Toyoda *et al*. (2006) developed and conducted an initial design optimization system, an extensive structural analysis system named SPB-HULL, and an onboard measurement campaign of ships in service. In this paper, results of these activities and actual examples were described, and it was shown that overall safety and economy can be achieved simultaneously, even for ultra large container ships, by an effective combination of initial design optimization, extensive structural analysis through SPB-HULL, and feedback from onboard measurements. These achievements were adapted to actual designs.

Shi *et al*. (2006) demonstrated that extra design efforts are imperative for enhancing structural integrity and safe operations of large container carriers that possess significant bow flare and low torsional rigidities due to the open deck structural configuration. Proper and rational classification assessment requires that first principles based engineering calculation methods be used to augment the standard classification review. The scope of the essential engineering assessment should encompass full-ship finite element analysis under nonlinear sea loads, spectral fatigue analysis, transient and impact load analysis, finite element lashing analysis, parametric roll prevention, and vibration analysis. The authors stipulated that design and operation of large container carriers are beginning to benefit from technological advances in hydrodynamics and structural analysis.

As modern container carriers become larger, certain parts of the existing prescriptive rules may pose increased uncertainty due to a lack of service experience. Yu *et al*. (2006) were concerned about the envelope of wave-induced sag-hog moments; specifically, whether the nonlinear effects due to hull form and forward speed are properly reflected. Direct calculation methods are often used by ship designers to apply the ship motions and sea loads calculated from nonlinear seakeeping theory, and then the FE structural analysis is carried out to assess the structural integrity of the vessel.

The 4400 TEU container vessel MSC Napoli encountered heavy seas and suffered structural failure while on passage through the English Channel on 18 January 2007. The crew abandoned the vessel safely. MSC Napoli was subsequently taken under tow towards UK but, because of a severe risk of the ship breaking up or sinking, it was intentionally beached. An investigation that was carried out by the MAIB (Marine Accidents Investigation Board), UK (MAIB, 2008) identified a number of factors which contributed to the failure of the hull structure.

The committee members decided to discuss this accident specifically in the report since a number of lessons can be learnt from this accident. Some of the findings of the MAIB report were

- The vessel's hull did not have sufficient buckling strength in way of the engine room.
- The classification rules applicable at the time of the vessel's construction did not require buckling strength calculations to be undertaken beyond the vessel's amidships area.
- There was no, or insufficient, safety margin between the hull's design loading and its ultimate strength.
- The load on the hull was likely to have been increased by whipping effect.
- The ship's speed was not reduced sufficiently in the heavy seas.

In view of the potential vulnerability of other container ships of a similar design, the MAIB (2008) requested the major classification societies to conduct urgent checks on the buckling strength of a number of ship designs. Over 1500 container vessels were checked, of which 12 vessels were identified as requiring remedial action; a further 10 vessels were identified as being borderline and require more detailed investigation; and the screening of 8 container ships was still in progress at the time of publication of MAIB (2008) report.

MAIB report (2008) draws some conclusions in relation to safety issues contributing to the accident:

- There were discrepancies between the declared weights and actual weights of containers onboard. Although, it is believed, that these weight discrepancies could not have caused alone the catastrophic failure of the vessel, but it would have contributed to the reduction of the safety margin between the total bending moment experienced and the strength of the hull. The stresses acting upon a container ship's hull cannot be accurately controlled unless weight of containers is determined before embarkation.
- Although it is likely that the wave loading experienced by MSC Napoli was increased by whipping effects, the quantification of these vibration effects are uncertain with the hydrodynamic analysis tools available today. MAIB recommended further research in this area so that sufficient allowance is made for the effect when determining a design margin.
- As the area of the hull which failed was outside of the 0.4L amidships area, the applicable classification society rules did not require the buckling strength of the hull in this area to be checked. Therefore, the buckling strength of the

hull in way of the engine room was not calculated by either the ship builder or BV (class society when the vessel was built).
- MSC Napoli design incorporated transverse framing in the engine room, which was an inherently weak structure when under compressive loading.
- It is apparent that UR S11 lagged behind the development of container ship design and operation and requires immediate revision. Buckling checks must be based on global hull stresses along the entire length of the hull and not left to the discretion of individual societies. The use of common method in this respect would provide greater assurance that the strength of all new build container ships is being adequately addressed.
- The vessel had left port with bending moments in excess of the permissible seagoing maximum value at the location of failure. This was as a result of a draught with enough under clearance so that the vessel could leave the port at any tide condition. MAIB report highlighted that the practice of arriving and departing from berths, in a loaded condition that was in excess of permissible seagoing maxima, was potentially detrimental to safety but is commonplace within the container ship industry.

The International Association of Classification Societies is recommended to review the contents of UR S11 (Longitudinal Strength Standard) to ensure that hull girder strength and buckling checks are carried out on all critical sections along the entire length of the hull and to evaluate the suitability of current UR S11 design wave bending moment criteria for vessels with a low block coefficient.

Steen (2008) reassessed the strength of the container NAPOLI vessel with focus on the hull girder wave loads and hull capacities as relevant for the sea states during the incident. Results from a set of hydrodynamic wave load analyses and from nonlinear structural FE analyses of the hull girder sections in way of the engine room bulkhead are documented. It was shown that for a severe hogging state, the vessel may collapse into a failure mode similar to the one observed on the vessel. DNV's conclusion as a result of its extensive investigation into the MSC Napoli accident in January 2007 is: The accident's cause is not a general problem for the container shipping industry at large. However, minor structural modifications have to be made to a restricted number of the existing container ship fleet.

5.2.4 LNG Vessels

The consumption of natural gas is predicted to increase by nearly 70 percent from 2002 to 2025, and the market for seaborne gas transport is increasing accordingly. The world's gas carrier fleet is rapidly growing in both number and size of vessels, and new trading routes are established. The operational and technical challenges following this development were considered by Valsgård *et al.* (2006), describing the work carried out by Det Norske Veritas to meet new challenges facing the gas carrier industry. Increased cargo tank sizes, possibilities for spot trading and offshore discharge, sloshing loads, and tank system strength have to be carefully studied to ensure safe operation. Another important operational aspect is increased cross Atlantic trading with significantly higher loads than for traditional Asian trading routes. Larger sizes of carriers and new operational profiles make relying on past experience for structural performance of vessel hulls and containment systems uncertain, and use of state-of-the-art methods for ultimate strength and fatigue is essential for safe and trouble-free operation.

The number of papers on sloshing loads and structural strength of the tank containment systems being presented at various conferences and journals confirms that uncertainties in calculation of loads and assessing strength of the containment system are acknowledged and processed by the industry. Dynamic calculation models are used to determine response, and details are outside the mandate of the committee for quasi static response.

Yaakob (2006) discussed the ship owners' and operators' perspective on the design and construction of large LNG carriers. The design of the 145,000 m^3 ship was developed from a standard 138,000 m^3 ship, and strength analyses were carried out according to standard requirements of classification societies. According to ship owners' experience, typical structural failures occur at upper and lower hopper connections and longitudinal girder connections at cofferdam bulkheads. Without going into details of calculation procedures, it was concluded that modifications and reinforcements of structural details investigated are needed to achieve sufficient fatigue strength.

Toderan *et al*. (2008) presented a paper on the multi objective structural optimisation of a 220,000 m^3 LNG carrier design. The study made references to issues related to loading cases identified in LBR5 tool and suggested several new load cases and a different structural optimisation analysis based on VERISTAR (BV software) and LBR5.

Lindemark *et al*. (2006) presented the analysis work carried out on a 216000 m3 gas carrier with membrane tanks. The paper focused on direct calculation procedures, including determination of design loads, global and local strength analysis, and fatigue demands. A detailed description of the calculation procedure was presented and advantages of applying direct load and strength calculations were discussed. By global finite element analysis and direct application of pressures and inertia forces derived by hydrodynamic software tools, the model was in full balance, and uncertainties related to boundary conditions and simplifications in the load application method we reduced to a minimum. Critical areas and structural details were identified by analysis of selected design cases and a spectral screening procedure. The paper identified the inner hull knuckles and dome openings as critical for fatigue strength and also recommended bending of the double deck at transverse bulkheads to be considered in structural design.

5.3 Common Rules Development

The IACS common structural rules (CSR) entered into force on 1st April 2006, and apply to all bulk carriers with length above 90 meters and all double hull oil tankers with length above 150 meters. The background and basis for common structural rules development has been discussed by Løvstad *et al*. (2007), and Horn and Baumans (2007) outlined challenges in rule development regarding modelling techniques, structural response and acceptance criteria.

Since April 2006, few amendments to the CSR were made in an effort to harmonise the CSR for tankers and bulk carriers, and the latest versions of the rules were published on July 2008. IACS also published common interpretations for the rules to assist its member societies and industry in implementing the CSR in a uniform and consistent manner. There is also a long-term plan put in place to further increase harmonisation between the tanker and bulk carrier common structural rules.

CSRs for tankers and bulk carriers initially considered different approaches for corrosion additions, and this was identified as an issue that required harmonization between common structural rules for tankers and bulk carriers in the short term. The common corrosion additions will be applied to both CSR for tankers and bulk carriers. Summary of corrosion harmonization is as follows:

- A corrosion propagation model based on probabilistic theory for each structural member was developed, and corrosion diminution was estimated at the cumulative probability of 95 percent for 20 years using the corrosion propagation model;
- Corrosion additions were determined for each structural member and corrosion environment.

Figure 2 shows how net scantling thickness and corrosion addition is to be adopted during design and in service conditions. While the corrosion addition approach in CSR rules appears more rational than prescriptive corrosion allowance requirements for pre-CSR rules, it does not necessarily justify the use of corrosion additions as structural design requirements. If net thickness is accepted as representing the minimum acceptable value, it should be owners' choice to adopt a variety of techniques to determine corrosion additions or adopting to have zero corrosion addition by maintaining the structure with the use of advanced coatings, aggressive inspection and repair regimes, etc.

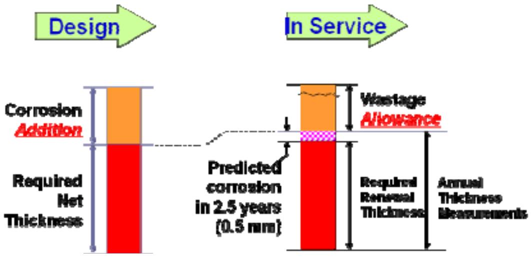

Figure 2 : IACS CSR net scantling approach to be adopted during design and in-service conditions.

Rizzo and Rizzuto (2007) compared scantling criteria of rules individually issued in the last years by classification societies with the common structural rules and assessed common structural rules in context of IMO goal based standard and IACS unified requirements. Differences between common structural rules for bulk carriers and tankers were identified and discussed on all levels from basic rule principles through loads and strength criteria.

A study by Cho *et al*. (2007) presented a comparison between IACS common structural rules and previous Class Rules for VLCC designed, based on CSR (common structural rules) by DSME (Daewoo Shipbuilding and Marine Engineering Co., LTD) showing significant differences. The paper elaborated on the main causes and results of scantling increase, structural modifications, and final change in hull weight of the VLCC design based on CSR requirements. Based on CSR for tankers, Chunyan (2007) investigated optimisation of a 76000 DWT tanker design. The study showed that the weight of the tanker amidships section structure optimally designed using CSR increased 5.6 percent of the same optimal algorithm based on pre-CSR rules.

Chen and Zhan (2007) carried out a study on differences between IACS CSR on bulk carriers and traditional design rules for bulk carriers. The findings were based on the first bulk carrier designed and built with CSR Notation in China.

Hovem *et al*. (2007) discussed requirements for the assessment of the scantling's ultimate and serviceability limit states; each load scenario was represented by two combinations of static and dynamic loads to achieve a consistent rule set with respect to safety level along with the methodology behind the development of CSR. It was argued that a risk based approach can be beneficial for structural rule development and that such methodology can be useful for future rule development projects and for assessment of novel designs.

Paik (2007) presented a study on the evaluation of the ultimate limit state (ULS) performance of an Aframax class hypothetical double hull tanker designed by IACS common structural rules (IACS CSR), compared with the tanker structure designed by IACS pre-CSR method. The study considered limit state design approach, which is considered a more rational basis for design and strength assessment than the traditional working stress approaches since the true safety margin of any economically designed structures can be determined more accurately by the limit state design approach. For the hypothetical Aframax class double hull tanker, the structural weight of approximately 1000 tonnes was additionally needed by the application of IACS CSR requirements. The ultimate strength of deck stiffened plate structures designed by the CSR method was increased by 0.7 to 2.3 percent (depending on the methods applied) compared to the deck structures designed by the pre-CSR rules. Similarly, the ultimate strength of bottom stiffened plate structures was increased by 7 to 12 percent compared to the bottom structures designed by the pre-CSR rules. Overall, the ultimate bending capacity of the hull structure designed by the CSR method was increased by 8.3 percent for sagging and 10.6 percent for hogging compared to the hull structure designed by the pre-CSR rules.

Parunov *et al*. (2007) investigated comparative hull-girder reliability for a new generation oil tanker, which is characterized by shallow draught and low length-to-beam ratio, using vertical wave bending moments obtained by direct hydrodynamic and statistical analysis and CSR for tankers. The reliability assessment was performed for the ship in ‘‘as built’’ and ‘‘corroded’’ conditions, assuming 20 year corrosion. Results of the analysis of ‘‘as built’’ ships showed that the structural reliability of the new generation oil tanker was higher than the reliability of the ‘‘rule’’ oil tanker. The authors carried out a sensitivity analysis which showed while for the new generation tanker, the calculated reliability index was sensitive to the still-water bending moment in ballast, the reliability of the ‘‘rule’’ tanker was almost completely insensitive to this variable. The sensitivity analysis showed that the uncertainty of the ultimate bending moment capacity is generally the most important variable in reliability assessment.

Parunov and Soares (2008) investigated changes in notional reliability levels that result from redesigning an existing Aframax tanker to comply with CSR for double-hull oil tankers. It was shown that the hull-girder failure probability of an Aframax tanker was reduced several times due to reinforcements according to CSR. The results of the performed reliability analysis indicated that the probability of structural failure in sagging is reduced about five times based on CSR requirement. From the reliability analysis, it was further shown that the safety index in sagging is much lower than in hogging. This is expected since the sagging failure mode is more important for these ships.

It was reported in the ISSC 2006 Technical Committee II.1 report that fatigue assessment methodologies differ from each other in Joint Tanker Project (JTP) and Joint Bulker Project (JBP) which are now referred to as IACS common structural rules for tankers and for bulk carriers, respectively. Lotsberg (2006b) reviewed the two procedures with respect to fatigue capacity.

Summary of the JBP and the JTP procedures with respect to fatigue capacity are

Item	JBP procedure	JTP procedure
Stress to be used in fatigue assessment	Hot spot stress with a notch factor before entering the S-N curve	Nominal stress or hot spot stress
Residual stress and shake down	Included	Not included
Mean stress effect	Included	Included
S–N curve	B-curve	Nominal and hot spot stress S–N curves can be used

From the results, the author concluded that both procedures were considered to be non-conservative for cyclic stresses into compression and suggested changes in the coefficients’ values to satisfy an acceptable level of safety.

5.3.1 Case study on scantling requirements by common structural rules for oil tankers and bulk carriers

A case study has been carried out for direct comparison of prescriptive scantlings and fatigue requirements according to CSR tanker and CSR bulk carrier rules. The calculations were carried out using DNV software program Nauticus Hull.

The case study was carried out based on a typical bulk carrier design with main particulars given in

Table 1. The vessel is a BC-A carrier with eight cargo holds, and calculations were carried out in the middle of the forward, mid, and aft holds to include possible variations along the cargo area. In the study focus is put on plate and stiffener of the outer hull, which are subjected to similar loading regardless of vessel type; external sea pressure loads, internal pressure loads from the ballast water, and hull girder loads. Internal structures subjected to loads from bulk or oil cargo were, therefore, ignored.

Table 1
Main Particulars of Vessel Used in Case Study

Length between perpendiculars	222	[m]
Rule length	218	[m]
Breadth moulded	32.24	[m]
Depth moulded	20.1	[m]
Draught moulded	14.5	[m]
Block coefficient	0.88	[-]
Maximum service speed	15	[knots]
Minimum design draught	5.5	[m]
Heavy ballast draught	7.0	[m]

The cross section used in the calculations is shown in Figure 3. The stiffener and plates investigated are indicated by circles. The top wing tank and double bottom tank are connected, and the ballast tank arrangement is thus comparable with a typical oil tanker.

The cross section properties are given in Table 2. High tensile steel with specified minimum yield stress of 315 N/mm^2 is applied to the bottom and bilge plating and stiffeners. In the deck area high tensile steel with specified minimum yield stress of 355 N/mm^2 is applied.

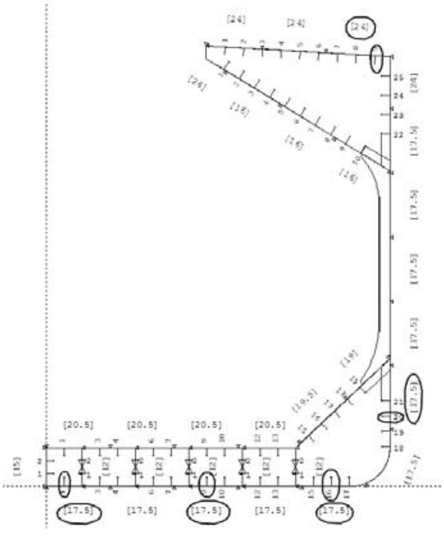

Figure 3: Midship section of bulk carrier used in case study

Table 2
Cross Section Data (As Built)

Moment of inertia about horizontal neutral axis	263.740	[m^4]
Moment of inertia about vertical neutral axis	529.706	[m^4]
Height of neutral axis	8684	[mm]
Section modulus, bottom	30.370	[m^3]
Section modulus, deck line	23.103	[m^3]
Section modulus, at side	32.862	[m^3]

The design bending moments, and draughts and motion parameters are given in Table and Table , respectively. These were based on rule default data, but since there are some differences in the number of loading conditions and bending moment in the rules, the following assumptions were made to obtain a sound comparison basis:

- The CSR bulk carrier rule stillwater bending moments were used also for the CSR tanker calculations
- The fatigue calculations were based on the homogeneous full load condition and normal ballast condition, assuming 50 percent of life time in each condition as proposed by CSR tanker rules.

Table 3
Design Bending Moments

Stillwater bending moment, sagging	3173659	[kNm]
Stillwater bending moment, hogging	3214138	[kNm]
Wave bending moment, sagging	2664904	[kNm]
Wave bending moment, hogging	2563705	[kNm]

Table 4
Draught and Motion Parameters

	Full load	Ballast	
Draught	14.5	5.5	[m]
Roll radius of gyration, kr	11.284	14.508	[m]
Metacentric height, GM	3.869	10.639	[m]

The required scantlings and fatigue life as calculated by common structural rules for tankers and bulk carriers are given in Table . It is observed that the resulting scantling requirements are significantly different in the two rule sets, with up to 3 mm difference in plate thickness in some areas.

The deviation in calculated fatigue life is remarkable; for the stiffener located in the bottom at bilge in the mid hold the calculated fatigue life is 18 years according to the bulk carrier rules and 126 years according to the tanker rules. Further on, the calculated fatigue life of the stiffener located at the deck is 74 years based on the bulk carrier rules, but only 19 years based on the tanker rules. Since this stiffener is only subjected to hull girder loads which are the same for both rules, the difference is related to the fatigue capacity model. Both rules refer to 25 years operation in North Atlantic environment for fatigue calculations, but the value referring to a common design basis may be questioned when the results differ to this extent.

Table 5
Required Scantlings and Calculated Fatigue Life

Position		Plate thickness [mm]		Stiffener section modulus [cm^3]		Calculated fatigue life [years]	
		CRS Bulk	CSR Tank	CRS Bulk	CSR Tank	CRS Bulk	CSR Tank
Fore hold	Bottom CL	17	15	675	649	499	777
	Bottom at B/4	15.5	15	673	649	860	1876
	Bottom at bilge	16.5	17.5	744	749	398	1440
	Side below WL	15.5	15	582	611	207	129
	Deck at side	13	15	251	384	2967	450000
Mid hold	Bottom CL	17.5	15.5	983	983	29	164
	Bottom at B/4	18	15	1021	955	24	196
	Bottom at bilge	18	17	1143	1024	18	126
	Side below WL	17	15	686	656	24	49
	Deck at side	16	15.5	284	252	74	19
Aft hold	Bottom CL	17	15	660	742	249	1701
	Bottom at B/4	16	15	648	718	292	4056
	Bottom at bilge	16	17	700	767	196	3164
	Side below WL	15.5	15	582	612	148	287
	Deck at side	13	15	244	219	1044	1162

5.4 Review of Classification Societies Rules

Ship Structures Committee recently published the report SSC 446 (Kendrick and Daley, 2007 and Daley *et al.*, 2007a and 2007c). The report was aimed at reviewing and identifying best practice in ship regulations. The study considered the hull girder and bottom structure of a vessel in an attempt to identify implicit and explicit factors of safety in rule based formulations. However, the report surprisingly identified no such factors of safety against yielding. Figure 4 illustrates the estimated 'design' stresses in ships, showing them to be above yield. Although this raises the question of why, then, ships do not fail, the best explanation may be given that ships, especially new ships, rely on small levels of plastic deformation to create a significant reserve strength.

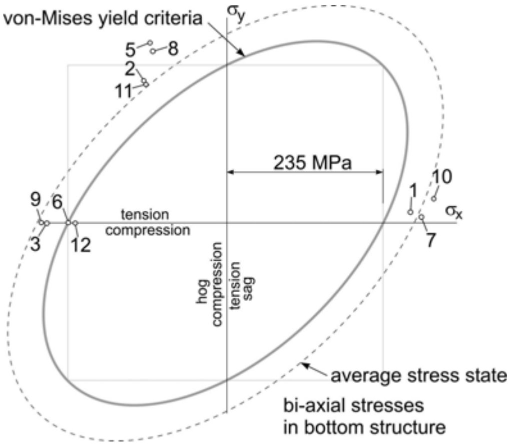

Figure 4 : Estimated von-Mises Stresses for Vessels in 'Design' Condition (see Daley *et al*., 2007c).

There has been a trend towards the inclusion of a partial safety factor method in some new ship structural standards. Amongst the IACS member of classification societies, BV has introduced scantling formulations using partial safety factors. However, SSC report 446 (Kendrick and Daley, 2007) argued that in cases examined by the report these have been implemented in a way that did not accomplish any improvements in safety levels of the design and, in fact, it is argued that it may create a false impression of safety levels, potentially undermining the safety of vessels.

Despite the abovementioned comments, there is a trend that classification societies are moving from prescriptive rules towards rationally based strength assessment methods. Currently, there are provisions for a first principles based design approach, to be reviewed and accepted by the majority of class societies. In line with this development, classification societies have been improving capabilities of their numerical tool sets. Such tool sets are able to perform scantlings checks, define loads for various analyses, and directly apply these loads to, say, finite element models, etc.

5.5 IMO Goal Based Standards - New Approach to Regulations for Ship Construction

The notion of "goal-based ship construction standards" was introduced in IMO in 2002 through a proposal by the Bahamas and Greece, suggesting that IMO play a larger role in determining standards to which new ships are built, traditionally the responsibility of classification societies and shipyards. The Organization agreed to develop ship construction standards that permit innovation in design but, at the same time, ensure that ships are constructed in such a manner that, if properly maintained, they would remain safe throughout their economic life.

Since then, IMO's Maritime Safety Committee (MSC) diligently worked on the subject, developing GBS for hull construction of bulk carriers and oil tankers, based on the vast practical experience gained with these ship types over the years, and, at the same time, advocating the application of a holistic approach, which define a procedure for risk-based evaluation of the current safety level of existing mandatory regulations related to ship safety and consider ways forward to establish future risk acceptance criteria using Formal Safety Assessment (FSA). It is expected that over time GBS will also be developed for other ship types.

The MSC agreed on the basic principles of IMO goal-based standards, applicable to all goal-based standards to be developed by IMO. For the GBS for oil tankers and bulk carriers, a five-tier system was agreed, comprising goals (Tier I), functional requirements (Tier II), verification of compliance (Tier III), rules for ships, e.g., IMO requirements, classification rules, relevant national requirements (Tier IV), and industry standards and practices (Tier V). The first three tiers constitute the IMO GBS, whereas Tiers IV and V contain detailed prescriptive provisions developed/to be developed by IMO, national administrations, recognized organizations and industry organizations.

MSC also agreed that GBS establish rules for rules, as opposed to rules for ships. The verification of compliance of ship construction rules with the GBS will be carried out by an international Group of Experts established by IMO's Secretary General in accordance with Guidelines for the verification of compliance with GBS, which are currently under consideration by the Committee. These Guidelines foresee that national Administrations submit requests for verification of their ship construction rules, or those developed by an organization recognized by it (in most cases classification societies), to the Secretary General of IMO, who will forward these requests to the Group of Experts for a verification of the submitted information through an independent review. The final report of the group with relevant recommendations will then be forwarded to the MSC for consideration and approval and circulation to the IMO membership by appropriate means, e.g., MSC circulars.

MSC 85, which met in November/December 2008, considered and reviewed relevant draft amendments to the SOLAS Convention. Although the WG on GBS recommended that amendments to SOLAS should be approved and that the GBS Standards be considered for approval, neither of these actions was agreed in plenary. It appears that there are still many issues which need resolution before that step can be taken. It is, therefore, expected that further deliberations will be made at future MSC meetings. The GBS verification process is not yet agreed upon, and alternative methods are being considered.

6. OFFSHORE STRUCTURES

As the offshore oil and gas technology is moving to deep and ultra deep water, demand for FPSOs has been increasing. For FPSO conversions rather than a new build which offers significant economic benefits for operations in benign environments, determining the remaining fatigue life of the structure is an important consideration. Similarly, 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 which we will review. We will also provide a brief review of the development of very large floating structures. Finally, recent studies in the area of uncertainty in risk and reliability assessment of offshore structures are reviewed.

6.1 Types of Analysis for Various Offshore Structures

Henriksen *et al*. (2007) discussed unique structural requirements for successful conversion of tankers for FPSO or FSO service. The study detailed steps undertaken during two different conversions of a highly optimized 1980's VLCC to FPSO service and a typical robust 1970's ULCC to FSO service. The analysis included the procedure for a detailed structural finite element analysis of the two vessels, considering past tanker service and future FPSO or FSO service. Paik (2007f) discussed the limit state design approaches in association with serviceability limit states, ultimate limit states, fatigue limit states, and accidental limit states for design of ship-shaped offshore units.

For fixed offshore structures, Biennen and Cassidy (2006) introduced the numerical program SOS_3D, which incorporates appropriate models for the three components of the structure, the soil, and environmental loading. Quasi-static push-over analyses were used to illustrate aspects of jack-up behaviour in three dimensions and jack-up response to storm loading conditions was predicted in dynamic wave loading analyses. A study on the stress concentration factor analysis for notched welded tubular T-joints was presented by N'Diaye *et al*. (2007) (see also Shao (2008) for the estimation of fatigue life of tubular joints in offshore structures where an interpolation method based on Lagrange shape function was presented to predict the stress distribution along the weld toe for tubular T-joints).

The detailed design of a very large floating structure (VLFS) requires integrated and well-balanced hydroelastic simulations that use realistic structural and hydrodynamic models that correspond to actual environmental conditions. There has been substantial development in computer codes for linear hydroelasticity in recent years, driven in part by the motivation to investigate wave-induced response of very large floating structures (VLFSs) initiated in Japan. Various methods have been proposed to predict the hydroelastic behaviour of VLFSs (Ohmatsu, 2005; Suzuki, 2005). Seto *et al*. (2005) developed a versatile modal approach for fluid-structure interactions, which incorporates the use of NASTRAN and a hybrid, finite/infinite element method of domain decomposition type. Moreover, ISSC 2006 Specialist Committee VI.2 (ISSC, 2006) was dedicated on VLFS. The committee report (see also Riggs *et al*. 2008; Suzuki *et al*. 2007) included a comparative study of simulation results from different computer codes for a pontoon (mat-like) VLFS. The codes covered a mix of both fluid models (potential and linear Green–Naghdi) and structural models (3-D grillage, 2-D plate, 3-D shell).

Fujikubo (2005) presented a review of linear and nonlinear structural analyses for the design of very large floating structures (VLFS), with particular focus on the pontoon-type VLFS. Structural modelling techniques for hydroelastic global response analysis and a two-step approach for stress analysis of detailed structures, based on the results of global response analysis, were outlined. To reduce structural deflections on the VLFS, a reverse T-shape freely floating breakwater with a built-in oscillating water column (OWC) chamber placed behind VLFS was investigated (see Hong *et al.*, 2006; Hong and Hong, 2007).

The characteristics of bending moments, shear forces and stresses at unit connections of very large floating structures (VLFS) under wave loads were investigated by Kim *et al.* (2007). The responses of VLFS were calculated by solving multi-body motion equations considering hydroelasticity and connection stiffness. Hydroelastic responses were calculated by the direct method. A higher-order boundary element method (HOBEM) was used for fluid analysis, and a finite element method (FEM) was introduced for structural analysis. Two types of VLFS units such as tandem arranged units and side-by-side arranged units were investigated.

Second application of very large floating structure is the Mobile Offshore Base (MOB) for military application initiated by USA. Palo (2005) provided a comprehensive review of a research program that examined the full spectrum of SeaBase design and analysis issues and significant hydrodynamic and structural assessment advancements.

Theotokoglou (2006) presented a study which deals with plane finite element analysis of thick composite tubes that are commonly used in deep-water offshore applications. Two kinds of interlaminar delamination defects in a thick walled cylinder subjected to external pressure were confronted; an annular or ring like delamination and a strip delamination. The effects of these defects in relation to buckling, the annular and the strip delamination buckling, and the subsequent loss of load carrying capacity of the delaminated region were investigated.

Solutions for the steady-state buckle propagation modes and pressures in a corroded pipeline subjected to external hydrostatic pressure are presented by Xue and Hoo Fatt (2005). The buckle propagation pressure of a corroded pipeline was obtained analytically with a rigid-plastic analysis and numerically from finite element analysis.

Naess *et al.* (2008) conducted a study on the development of efficient and accurate methods for estimating extreme response statistics of combined load effect processes.

6.2 Uncertainty, Risk and Reliability in Offshore Structural Analysis

Reliability based methods have been applied to assess the structural soundness of offshore structures for many years. The application of such probabilistic methods to assess new designs and existing offshore structures continues (see, for example, Bellendir *et al*., 2006 and 2007; Wang *et al*., 2007a). Wang *et al*. (2007a) presented a structural reliability assessment method to quantify the probability of platform failure for Trinidad offshore platforms subjected to hurricane events. Platforms were modelled as a series system composed of topsides and jacket, including foundation. The platform capacity was evaluated by nonlinear pushover analysis. The first-order reliability method (FORM) was used to estimate the annual failure probability, and the relationship between the probability of platform failure and the reserve strength ratio (RSR) of platforms was investigated. Traditionally, deterministic pushover analyses are performed for steel-jacket offshore platforms in order to calculate RSR (Reserve Strength Ratio) values as the representative reliability measure for the total collapse of the structure. Sørensen *et al*. (2008) demonstrated that it is possible to perform probabilistic reliability analyse for collapse of a jacket platform using the so-called Model Correction Factor Method (MCFM).

Wave conditions in extra-tropical regions have seasonal variations. The wave condition in a period of one or more years exhibits variation, as displayed by samples of data for such a period. It is important to have a measure of the variability in the wave-induced extreme response and fatigue damage for marine structures due to this statistical uncertainty for sea states in various service periods. Moan *et al*. (2005) considered 1-, 2-, 4- and 29-year wave statistics to analyse the effect of variability in the wave induced response on the fatigue induced damage. It was found that, compared with the 29-year distribution, the variation in annual distributions was considerable as measured either by distribution parameters, predicted extreme value of significant wave height, or long-term response for extreme and fatigue loading. This variability is important when assessing the safety of a structure until the next inspection or repair after damage. Grim and Langley (2008) presented a frequency domain response model that is coupled with a pseudo-asymptotic integration scheme to provide a rapid estimate of lifetime reliability and hence the extreme response at a design target level. Reliability bounds and associated convergence criteria were defined, and the method was tested on a representative FPSO in a wave-dominated environment. Moan (2007) discussed development of reliability-based management of inspection, monitoring, maintenance and repair (IMMR) of various types of offshore structures.

Offshore structures are exposed to random wave loading in the ocean environment, and hence the probability distribution of their response to wave loading is a minimum requirement for efficient probabilistic analysis of these structures. Due to nonlinearity of Morison wave loading and also due to intermittency of wave loading on members in the splash zone, the response is often non-Gaussian. For this reason, existing probability models may not accurately predict the response distribution. A new probability model was proposed by Najafian (2007a and 2007b) which is aimed at overcoming this deficiency. When performing fatigue analysis on fixed offshore structures, instead of incorporating nonlinear and non-Gaussian modelling in the analysis, Gaidai and Naess (2008) presented a study where for drag dominated offshore structures, it was shown that it is sufficient to perform linearization to obtain accurate estimates of fatigue damage. Moarefzadeh and Melchers (2006) investigated the reliability analysis of offshore structures under wave and wind actions using second order random wave theory. To represent non-Gaussian properties of the resulting wave kinematics, the Hermite moment transformation was used. The so-called sample-specific linearization method developed already was extended to take into account both non-Gaussian properties of wave/wind load due to nonlinear load processes and wave kinematics due to nonlinear wave theory.

Improving the accuracy and efficiency of predicting ultimate strength of structural components, such as unstiffened panels and stiffened panels, has a significant impact on structural design. Empirical formulations which are usually developed using regression analysis have been widely used to predict ultimate strength, but model uncertainties of good empirical formulations are around 10 to 15 percent in terms of coefficients of variation. Pu and Mesbahi (2006) presented an artificial neural network (ANN) method that is applied to predict ultimate strength of unstiffened plates under uniaxial compression. The proposed ANN models were trained and cross-validated using existing experimental data. Mesbahi and Pu (2008) extended their work to an artificial neural network based response surface method (ANN-RSM) to derive a formula to predict ultimate strength of stiffened plates under uniaxial compression using existing experimental data.

IMO recommends formal safety assessment (FSA) for future development of rules and regulations. Ruud and Mikkelsen (2008) reported on the FSA study in a pilot research project for development of risk based rules and functional requirements for offshore crane systems. A method for estimating target reliability for the risk-control options (safety functions) using the cost/benefit decision criterion was developed and presented.

De Leon and Ang (2008) performed second-order estimates to measure platform reliability so that safety margins appropriate to the owner's perception or for risk averse managers can be established. The aleatory and epistemic uncertainties in the parameters of an offshore platform were explicitly considered in the reliability analysis. A procedure was proposed to generate the frequency diagram of platform reliability with the use of confidence bounds to support reliability and cost decisions based on percentiles instead of mean values. The concepts were illustrated on a typical offshore platform in Mexico.

Li *et al.* (2006) presented a study on the fatigue of the tubular joints of offshore platforms operating in the ice-zone and the time-dependent fatigue reliability of MSW platforms of JZ20-2 in Bohai bay was evaluated. Li *et al.* (2008a and 2008b) studied the statistical properties of global resistance and extreme responses of jacket platforms in Bohai Bay, considering randomness of ice load, dead load, steel elastic modulus, yield strength and structural member dimensions. Based on results of the statistical analysis, the authors proposed an approximate method for global reliability analysis which converts the implicit nonlinear performance function in the conventional reliability analysis to linear explicit ones.

Marshall (2007) presented a study on the risk assessment philosophy behind the old and revised API standards. Specifically, the paper discussed changes in API RP2A.

Kumar *et al.* (2008) developed an inspection frequency optimization model which can be used to estimate the number of inspections/optimum preventive maintenance time required for a degrading component at any age or interval in its lifecycle at a minimum total maintenance cost. A case study on the reliability of flow lines installed on the top side of an offshore oil and gas platform in the North Sea was presented. Such an analysis may be useful for life extension of ageing platforms and systems in the North Sea.

Karadeniz (2006a) discussed uncertainties in spectral fatigue damages of offshore structures and then presented a procedure for a fast and efficient computation of fatigue reliability estimates. Using an advanced FORM reliability method, the reliability index was calculated, and important uncertainty parameters were identified for an example jacket structure. The time independent and time dependent system reliability methods for parallel and series systems in a conceptual form with essential formulations and boundary conditions of failure probabilities and the transformation of time dependent failure modes into a corresponding time independent mode to facilitate the calculation procedure using load combination models were discussed by Karadeniz (2006b). Karadeniz (2008) presented a method for modelling offshore structures' member deterioration, using a spring system as an efficient, practical technique to determine progressive failure mechanism of structures. The procedure employs updates of member stiffness and mass matrices as well as the random load vector in incremental forms. The technique can be efficiently used in the reliability calculation as well.

The Inverse First Order Reliability Method (I-FORM) was employed to determine response maxima using environmental contours and response surfaces for moored FPSOs in West Africa (François *et al*., 2007; Orsero *et al*., 2007). Islam and Ahmad (2007) investigated the reliability of an articulated tower connected to the sea-bed through a universal joint under fatigue loading.

Xue *et al.* (2006) presented the concept of non-probabilistic reliability to measure the reliability in terms of the amount of uncertainty consistent with the condition of no failure to establish a new model for fatigue reliability analysis. It was argued that the new approach overcomes shortcoming of traditional probabilistic methods, which need large number of statistical data and a large computational efforts.

Madhavan and Veena (2006) described a method for computation of reliability of members of fixed offshore platform structures with respect to fatigue. Failure criteria were formulated using fracture mechanics approach and failure was defined as a first passage problem. The method was illustrated by through application to a typical plane frame structure.

Structural response of a fixed offshore platform was simulated based on sampling ones by means of the Kriging model, and its reliability index was calculated by using an optimization method (Zhang and Li, 2006). As a semi-parameter interpolation technique, the Kriging model can avoid the restriction and the influence of different limit state functions and evaluate the structural response with high accuracy by combining advantages of Monte-Carlo and response surface techniques. A Synthesis Searching Method (SSM) and corresponding software tool for system fatigue reliability analysis of structure systems was proposed by Wang *et al*. (2006). The method can identify the dominant fatigue failure paths of structures efficiently and faster.

7. CONCLUSIONS AND RECOMMENDATIONS

The committee reviewed recent works concerning topics identified by the committee mandate. 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 linearization/simplification approaches to determine the corresponding responses.

The interest in ice loads and ice worthy structural design greatly increased in recent years. Ice loads and the corresponding responses certainly involve complex and nonlinear phenomena. Experimental results that highlight the complex nature of ice crushing forces are discussed. The report highlighted that there is a significant new focus on development of large arctic vessels of low and high ice classes.

The compatibility amongst structural analysis tools, other naval architecture software packages and CAD/CAM tools improves and accelerates design and construction process. This can be achieved through a large-scale introduction of the 3-D ship product model. Such a product model enables the required information, such as general arrangement, ship systems, specifications, materials, planning and scheduling, to be stored within and made available to other programs such as FEM, stability, seakeeping and CFD. Recent works in the development of 3-D product models suggests that a two-way interconnectivity between a 3-D model and structural tools is not yet fully achieved.

Today, rational dimensioning of complex ship structures is frequently based on refined finite element analyses of the entire ship. This allows a CFD based load application and an accurate analysis of stresses. Particularly for complex ship structures, a proper and rational classification assessment requires that first principles based direct calculation methods be used to augment the standard classification review. Therefore, major classification societies developed tools to determine design wave loads and to easily apply these loads for the structural strength assessment with the Finite Element Method.

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. Fatigue strength and ultimate strength assessment of deteriorated (corroded) structures are also discussed.

Steel sandwich panels containing an elastomer core have been widely adopted in the ship industry for applications that require high resistance to impact damage. These sandwich panels also provide excellent protection from blast loads and fire and have good acoustic and vibration damping properties. Recent works on steel sandwich panels covering aspects such as bending response of laser-welded sandwich panels, laser stake welds, and ultimate strength have been reviewed. An efficient interaction equation for ultimate strength of steel sandwich panels under combined in-plane compressive stress and lateral pressure is presented.

A comprehensive review of passenger vessels, ice-going vessels, LNG 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, gas carriers and passenger vessels increased dramatically and the committee focused on and reviewed recent works concerning strength and analysis methods.

The container vessel MSC Napoli suffered global structural failure while on passage through the English Channel on 18 January 2007, and the committee discussed the report from MAIB and related papers.

Common structural rules for bulk carriers and oil tankers entered into force in April 2006, and the committee reviewed works concerning both the development and impact of the common structural rules on practical design. The new design rules led to increased steel weight and ultimate strength is increased compared to pre-CSR designs, and the probability of hull girder failure is reduced.

The previous committee reported differences in load and modelling and acceptance criteria between the two common rules and recommended harmonization in view of assessment methods and criteria. To assess the effect of these differences, the committee carried out a case study calculating the required plate thickness, stiffener section modulus and fatigue life. The case study using CSR for tankers and bulk carriers revealed serious inconsistencies in calculated fatigue life between these two rules. For a stiffener located in the bottom at bilge in the mid hold the calculated fatigue life is 18 years according to the bulk carrier rules and 126 years according to tanker rules. Further on, the calculated fatigue life of a stiffener located at the deck is 74 years based on bulk carrier rules but only 19 years based on tanker rules. Since this stiffener is only subjected to hull girder loads which are the same for both rules, the difference is related to the fatigue capacity model. Both rules refer to 25 years operation in the North Atlantic environment for fatigue calculations, but the value by referring to a common design basis may be questioned when the results differ to this extent.

The review of FPSOs revealed that an extensive recent research has been concentrated on the determination of fatigue characteristics of welded joints. Similarly, fatigue of tubular joints typically used in fixed offshore structures is still amongst the most researched areas.

For VLFS platforms, the quasi-static and hydroelastic responses are considered together. Structural evaluation is often carried out based on advanced direct methods and reliability principles owing to the lack of service experience and novelty of designs. It was apparent from the review that there is less research published in the literature during the current review period than during of the previous ISSC reporting period, indicating, perhaps, maturity of some analysis concepts for VLFSs.

The recent works on reliability analysis of offshore structures have been reviewed. It was evident that significant research effort has been expended on the development of new reliability models that are able to take into account non-Gaussian distributions of environmental loads and responses for fixed offshore structures. For fatigue assessment of FPSO structures, the review identified the importance of statistical uncertainty in wave loading for various service periods.

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
- Further progress on the harmonisation process of IACS common structural rules and impact of common structural rules on design
- Development of IMO Goal Based Standards on ship structural design
- Structural aspects of specialised ships
- Structural aspects of offshore structures

REFERENCES

Abt, C. and Harries, S. (2007). A New Approach to Integration of CAD and CFD for Naval Architects, *6th International Conference on Computer Applications and Information Technology in the Maritime Industries* (COMPIT2007), Cortona, April 2007.

Abt, C. and Harries, S. (2008a). Direct Coupling of CAD and CFD for the Design of Functional Surfaces, *NAFEMS Seminar: 'Simulation Driven Design – Potential and Challenges'*, Wiesbaden, March 2008.

Abt, C. and Harries, S. (2008b). Tight and Loose Coupling CAD and CFD - Methods, Practical Aspects, Advantages, *RINA Marine CFD 2008*, Southampton, March 2008.

Aksu, S. (Chairman), Buannic, N., Hinrichsen, B., Kamsvag, F., Tanaka, Y., Tonelli, A., Vink, J.H., Yang, J.M. and Yang, P. (2006). TCII.1 - Quasi-static Response. *Proceedings of the 13th International Ship and Offshore Structures Congress*, vol. 1;

171-256, 20-25 August 2006, Southampton, UK.

Aksu, S., Buannic, N., Hinrichsen, B., Kamsvag, F., Tanaka, Y., Tonelli, A., Vink, J.H., Yang, J.M. and Yang, P. (2007). Recent Advances on Quasi-static Response of Ship and Offshore Structures, *Proceedings of the 26th International Offshore Mechanics and Arctic Engineering Conference, OMAE2007*, 10-15 June 2007, San Diego, USA.

Alagusundaramoorthy, P. and Reddy, R.V.S. (2008). Testing and evaluation of GFRP composite deck panels, *Ocean Engineering*, 35: 5-6, 287-293.

Alinia, M. M. (2005). A study into optimization of stiffeners in plates subjected to shear loading. *Thin-Walled Structures*, 43:5, 845-860.

Alshoaibi, A.M., Hadi, M.S.A. and Ariffin, A.K. (2007). Two-dimensional numerical estimation of stress intensity factors and crack propagation in linear elastic analysis, *SDHM Structural Durability and Health Monitoring*, 3:1, 15-27.

Alsos, H.S. and Amdahl, J. (2007). On the resistance of tanker bottom structures during stranding, *Marine Structures*, 20:4, 218–237.

Amini, A.M., Dureisseix, D., Cartraud, P. and Buannic, N. (2007). Multi-scale domain decomposition method for structural analysis of a passenger ship, *Proceedings of International Conference on Computational Methods in Marine Engineering , MARINE 2007 5-7 Juan 2007, Barcelona, Spain*

Badran, S. F., Nassef, A. O. and Metwalli, S. M. (2007). Stability of Y stiffeners in ship plating under uniaxial compressive loads, *Ships and Offshore Structures*, 2:1, 87-94.

Banai, L. and Pedatzur, O. (2006). Computer implementation of an orthotropic plate model for quick estimation of the maximum deflection of stiffened plates, *Ships and Offshore Structures*, 1:4, 323-333.

Belenkiy, L. M., Raskin, Y. N. and Vuillemin, J. (2007). (Review) Effective plating in elastic–plastic range of primary support members in double-skin ship structures, *Marine Structures*, 20:3, 115-123.

Bellendir, E.N., Glagovsky, V.B. and Finagenov, O.M. (2006). Conceptual risk assessment of offshore structures, *Proceedings of the International Offshore and Polar Engineering Conference*, 411-417.

Bellendir, E.N., Finagenov, O.M. and Glagovsky, V.B. (2007). Hazard analysis of failures on the substructure of stationary offshore platform, *Proceedings of the International Offshore and Polar Engineering Conference*, 3713-3717.

Berggreen, C. Jensen, C. and Hayman, B. (2007). Buckling strength of square composite plates with geometrical imperfections – preliminary results, Marstruct Glasgow 2007.

Bienen, B. and Cassidy, M.J. (2006). Advances in the three-dimensional fluid-structure-soil interaction analysis of offshore jack-up structures, *Marine Structures*, 19:2-3, 110-140.

Biswas, P., Mandal, N. R. and Sha, O.P. (2007). Three-dimensional finite element prediction of transient thermal history and residual deformation due to line heating, *Proceedings of the Institution of Mechanical Engineers, Part M: Journal of Engineering for the Maritime Environment,* 221:1, 17-30.

Błachut, J. and Smith, P. (2008). Buckling of multi-segment underwater pressure hull, *Ocean Engineering*, 35:2, 247-260.

Bogdaniuk, M, Górecki, Z. and Brzóska, M. (2006). FEM Analysis of Ultimate Strength of Steel Sandwich Panels, *Polish Maritime Research, Special Issue on All Steel Sandwich Panels – An Alternative for Classical Ship Hull Structure*, S1, 2006, 21-23.

Boronski D. and Szala, J. (2006). Tests of Local Strains in Steel Laser-Welded Sandwich Structures, *Polish Maritime Research, Special Issue on All Steel Sandwich Panels – An Alternative for Classical Ship Hull Structure*, S1, 2006, 27-30.

Boyd, S. W., Dulieu-Barton, J.M and Rumsey, L. (2006). Stress analysis of finger joints in pultruded GRP materials. International Journal of Adhesion & Adhesives, 26:7, 498-510.

Cabos, C., Eisen, H. and Kroemer, M. (2006). GL ShipLoad: An Integrated Load Generation Tool for FE-Analysis, *Proceedings of 5th Int. Conf. on Computer Application and Information Technology, COMPIT'06*, TU Delft, 199-210.

Cabos, C., Jaramillo, D., Stadie-Frohbös, G., Renard, P., Ventura, M., Dumas, B. (2008). Condition Assessment Scheme for Ship Hull Maintenance *Proceedings of 7th International conference on Computer and IT Applications in the Maritime Industries, COMPIT 08, 21-23 April 2008, Liege, Belgium, pp 222-243.*

Caccese, V., Kabche, J.-P., Berube, K. E. and Boone, M. J. (2007). Structural response of a hybrid composite/aluminum strut assembly. *Composite Structures*, 80:2, 159-171.

Cambos, P. (2008). Structural Design of Large LPG Carriers, *Proceedings of RINA Int. Conf. on Design and Operation of LPG Ships*, London.

Camilleri, D., Comlekci, T. and Gray, T.G.F. (2005). Design support tool for prediction of welding distortion in multiply stiffened plate structures: Experimental and computational investigation, *Journal of Ship Production*, 21:4, 219-234.

Camilleri, D., Comlekci, T. and Gray, T.G.F. (2006). Thermal distortion of stiffened plate due to fillet welds computational and experimental investigation, *Journal of Thermal Stresses*, 29:2, 111-137.

Canyurt, O. E. and Zhang, J. (2006). Pre-stressed adhesive strap joints for thick composite sandwich structures. *International Journal of Mechanical Sciences*, 48:4, 389-399.

Cao, J., Grenestedt, J. L. and Maroun, W. J. (2007). Steel truss/composite skin hybrid ship hull. Part I: Design and analysis. *Composites: Part A*, 38:7, 1755-1762.

Cao, J., Grenestedt, J.L. and Maroun, W.J (2006). Testing and analysis of a 6-m steel truss/composite skin hybrid ship hull model, *Marine Structures*, 19:1, 23–32.

Chakrabarti, A. and Sheikh A.H. (2007). Buckling of laminated sandwich plates using an efficient plate model, *International Shipbuilding Progress*, 54:1, 63-81.

Chen, N.-Z. and Soares, C.G. (2007a). Reliability assessment for ultimate longitudinal strength of ship hulls in composite materials. *Probabilistic Engineering Mechanics*, 22:4, 330-342.

Chen, N.-Z. and Soares, C.G. (2007b). Longitudinal strength analysis of ship hulls of composite materials under sagging moments. *Composite Structures,* 77:1, 36-44.

Chen, Y. and Zhan, Z. (2007). The Application of CSR for Design of Bulk Carriers with CSR Notation, *The Proceedings of the 10th International Symposium on Practical Design of Ships and Other Floating Structures*, Houston, Texas, October 1st - 5th, 2007, pp. 776-783.

Chirica, I. Gavrilescu, I., Boazu, D. and Beznea, E.F. (2005). Optimum design of composite ship panels, *Maritime Transportation and Exploitation of Ocean and Coastal Resources* – Guedes Soares, Garbatov & Fonseca (eds) © 2005 Taylor & Francis Group, London, ISBN 0 415 39036 2, pp. 365-372.

Cho, M., Kim, S., Kim, M. and Han, S. (2007). A Study on Design Modification of a VLCC Based on CSR Requirements, *The Proceedings of the 10th International Symposium on Practical Design of Ships and Other Floating Structures*, Houston, Texas, October 1st - 5th, 2007, pp. 674-676.

Chowdhury, M. (2007). On the probability of failure by yielding of hull girder midship section, *Ships and Offshore Structures*, 2:3, 241-260.

Chunyan, J. (2007). Optimal Design of Longitudinal Scantlings Amidships for Oil Tanker Based on JTP Rule, *The Proceedings of the 10th International Symposium on Practical Design of Ships and Other Floating Structures*, Houston, Texas, October 1st - 5th, 2007, pp. 784-789.

Crupi, V., Guglielmino, E., Risitano, A. and Taylor, D. (2007). Different methods for fatigue assessment of T welded joints used in ship structures, *Journal of Ship Research*, 51:2, 150-159.

Daley, C. and Hermanski, G. (2008). Ship Frame Research Program- an Experimental

Study of Ship Frames and Grillages Subjected to Patch Loads, *Ship Structures Committee Project SR* 1442 – Final report.

Daley, C. and Kendrick, A. (2008). Direct Design Of Large Ice Class Ships With Emphasis On The Midbody Ice Belt, *Proceedings of Int. Conf. on Offshore Mechanics and Arctic Engineering OMAE 2008*, Estoril, Portugal.

Daley, C., Kendrick, A. and Pavic, M. (2007a). New Directions in Ship Structural Regulations, *Proceedings of 10th International Symposium on Practical Design of Ships and Other Floating Structures*, Houston, Texas, October 1st – 5th 2007, pp 1016-1024.

Daley, C., Hermanski, G., Pavic, M. and Hussein, A. (2007b). Ultimate Strength of Frames and Grillages Subject to Lateral Loads– an Experimental Study, *Proceedings of 10th International Symposium on Practical Design of Ships and Other Floating Structures*, Houston, Texas, October 1st – 5th 2007, paper 20224.

Daley, C., Kendrick, A., Pavic, M., (2007c). Comparative Study of Ship Structural Regulations, *Proceedings of RINA Int. Conf. on Developments in Classification and International Regulations*, London, UK.

Daley, C., Kendrick, A., Yu, H. and Noh, B-J. (2007d). Structural Design of High Ice Class LNG Tankers, *Proceedings of RINA Int. Conf. on Design and Construction Of Vessels Operating In Low Temperature Environments*, London, UK.

Daley, C.G. (2007). Re-Analysis of Ice Pressure-Area Relationships, *SNAME Marine Technology*, 44:4, October 2007, 234-244.

Damhaug, A.C., Stang, J. and Schult, M. (2007). From Design to Analysis – Integrated Design and Strength Assessment of Det Norske Veritas Software, *Proceedings of International Conference on Computer Application to Shipbuilding, ICCAS 2007.*

Davis, M.R. and Whelan, J.R. (2007). Computation of wet deck bow slam loads for catamaran arched cross sections, *Ocean Engineering*, 34: 17-18, 2265-2276.

De Leon, D. and Ang, A. H.-S. (2008) Confidence bounds on structural reliability estimations for offshore platforms, *Journal of Marine Science and Technology*, 13:3, 308-315.

Deng, D., Murakawa, H. and Liang, W. (2007). Numerical simulation of welding distortion in large structures, *Computer Methods in Applied Mechanics and Engineering*, 196:45-48, 4613-4627.

Dimache, A., Olaru, D., Modiga M. and Stoicescu, L. (2005). Some considerations on the structural modelling technique of double wall structures, *Maritime Transportation and Exploitation of Ocean and Coastal Resources* – Guedes Soares, Garbatov & Fonseca (eds) © 2005 Taylor & Francis Group, London, ISBN 0 415 39036 2, pp. 379-385.

Drouin, P. (2006). Brittle fracture in ships - a lingering problem, *Ships and Offshore Structures*, 1:3, 229-233.

Dumez, F.-X., Cheylan, C., Boiteau, S., Kammerer, C., Mogicato, E., Dupau, T. and Bertram, V. (2008). A Tool for Rapid Ship Hull Modelling and Mesh Generation, *Proceedings of 7th International conference on Computer and IT Applications in the Maritime Industries, COMPIT 08, 21-23 April 2008, Liege, Belgium, pp 6-18.*

Dundara, D., Bocchetti, D., Kuzmanovic, O., Zanic, V., Andric, J. and Prebeg, P. (2008). Development of a New Innovative Concept of Ropax Ship, *Proceedings of 7th International conference on Computer and IT Applications in the Maritime Industries, COMPIT 08, 21-23 April 2008, Liege, Belgium, pp 435-449.*

Ehlers, S., Klanac, A. and Tabri, K. (2007). Increased Safety of a Tanker and Ropax Vessel by Implementing a Novel Sandwich Structure, *Proceedings of 4th International Conference on Collision and Grounding of Ships*, Hamburg University of Technology, September 9th – 12th 2007, 109-115.

Eisen, H. and Cabos, C. (2007). Efficient application of CFD-based loads for the FEM-analysis of ship structures by means of GL ShipLoad, *Proceedings of International Conference Computer Applications in Shipbuilding*, *ICCAS 2007*, Portsmouth, UK, volume II, 91-98.

El Moctar, O., Schellin, T.E., and Priebe, T. (2006). CFD and FE Methods to Predict Wave Loads and Ship Structural Response. *Proc. 26th Symposium on Naval Hydrodynamics*, Rome, Italy.

El Moctar, O.M. (2007). How to avoid or minimize rudder cavitation, *10th Nuerical. Towing Tank Symposium, Hamburg.*

Fonseca, N., Guedes Soares, C. and Pascoal, R. (2006). Structural loads induced in a containership by abnormal wave conditions, *Journal of Marine Science and Technology*, 11: 4, 245-259. JMST

François, M., Camps, C., Alvarez, J. and Quiniou, V. (2007). Multi-variate I-FORM contours for the design of offshore structures (practical method and application to a West Africa FPSO), *Proceedings of the International Offshore and Polar Engineering Conference*, 59-68.

Frederking, R. and Kubat, I. (2007). A Comparison of Local Ice Pressure and Line Load Distributions from Ships Studied in the SAFEICE Project, *The Proceedings of the 10th International Symposium on Practical Design of Ships and Other Floating Structures*, Houston, Texas, October 1st - 5th , 2007, 1221-1229.

Fujikubo, M. (2005). Structural analysis for the design of VLFS, *Marine Structures*, 18:2, 201-226.

Fujikubo, M., Yao, T., Khedmati, M.R., Harada, M. and Yanagihara, D. (2005a). Estimation of ultimate strength of continuous stiffened panel under combined transverse thrust and lateral pressure Part 1: Continuous plate, *Marine Structures*, 18:5-6, 383-410.

Fujikubo, M., Harada, M., Yao, T., Khedmati, M.R. and Yanagihara, D. (2005b). Estimation of ultimate strength of continuous stiffened panel under combined transverse thrust and lateral pressure Part 2: Continuous stiffened panel, *Marine Structures*, 18:5-6, 411-427.

Fukasawa, T. (2005). Maximum Response Estimation by means of Design Irregular Wave, *Journal of The Japan Society of Naval Architects and Ocean Engineers*, 2, 123-129 (in Japanese). JJASNAOE.

Fukasawa, T. and Miyazaki, S. (2007). Estimation of Maximum Stress of a Container Ship by Means of Design Irregular Wave and Direct Loading Analysis Method, *The Proceedings of the 10th International Symposium on Practical Design of Ships and Other Floating Structures*, Houston, Texas, October 1st - 5th, 2007, pp. 716-723.

Fukasawa, T., Kanehira, Y. and Miyazaki, S. (2006). Maximum Response Estimation by means of Design Irregular Wave - 2nd Report : Estimation of local Stress of a Container Ship -, *Journal of the Japan Society of Naval Architects and Ocean Engineers*, 4, 221-227 (in Japanese). JJASNAOE.

Gagnon, R. (2008). A New Impact Panel To Study Bergy Bit / Ship Collisions, *Proceedings of 19th IAHR International Symposium on Ice*, Vancouver, Canada, July 6 to 11.

Gagnon, R. and Daley, C. (2005). Dual-Axis Video Observations of Ice Crushing Utilizing High Speed Video For One Perspective, *POAC'05*, Potsdam, USA.

Gagnon, R. and Daley, C. (2006). Apparatus Design Evolution and Supporting Experiment for a Novel Technique to Study Ice Crushing, *18th Intl. Symposium on Ice*, Sapporo, Japan, Sept. 2006.

Gagnon, R., Cumming, D., Ritch, R., Browne, R., Johnston, M., Frederking, R., McKenna, R. and Ralph, F. (2008). Overview accompaniment for papers on the bergy bit impact trials, *Cold Regions Science & Technology*, 52:1, 1-6.

Gaidai, O. and Naess, A. (2008). Nonlinear Effects on Fatigue Analysis for Fixed Offshore

Structures, *Journal of Offshore Mechanics and Arctic Engineering*, 130:3, art. no. 031009.

Germanischer Lloyd (2007). Rules for Classification and Construction, V − Analysis Techniques, Part − 1 Strength and Stability, Chapter 1 − Guidelines for Strength Analyses for Ship Structures with the Finite Element Method, Section 2 − Global Strength Analysis for Containership Structures. Hamburg.

Graczyk, M. and Moan, T. (2008). A probabilistic assessment of design sloshing pressure time histories in LNG tanks, *Ocean Engineering*, 35: 8-9, 834-855.

Graczyk, M., Moan, T. and Wu, M.K. (2007). Extreme sloshing and whipping-induced pressures and structural response in membrane LNG tanks, *Ships and Offshore Structures*, 2:3, 201-216.

Grau, M., Zerbst, C. and Sachers, M. (2008). Building the Business Process View into Shipbuilding Data Exchange, COMPIT 2008.

Grime, A.J. and Langley, R.S. (2008). Lifetime reliability based design of an offshore vessel mooring, *Applied Ocean Research*, Article in Press.

Han, S., Lee, J.Y., Park, Y.I. and Che, J. (2007). Structural Risk Analysis of a NO96 Membrane Type LNG Carrier in the Baltic Ice Operation, *The Proceedings of the 10th International Symposium on Practical Design of Ships and Other Floating Structures*, Houston, Texas, October 1st - 5th , 2007, pp. 1346-1357.

Hayman, B., Berggreen, C. and Tsouvalis, N.G. (2007a). A review of the causes of production defects in marine composite structures and their influence on performance, *Marstruct Workshop*, Glasgow 2007.

Hayman, B., Berggreen, C., Lundsgaard-Larsen, C., Karlsen, K. and Jenstrup, C. (2007b). Design of X-joints in Sandwich Structures for Naval Vessels, *The Proceedings of the 10th International Symposium on Practical Design of Ships and Other Floating Structures*, Houston, Texas, October 1st - 5th , 2007, pp. 1086-1095.

Henriksen, L., Kamishohara,A. and Hosokawa, H. (2007). Structural Analysis and Modifications - Two Tankers for Offshore FPSO and FSO Service, *The Proceedings of the 10th International Symposium on Practical Design of Ships and Other Floating Structures*, Houston, Texas, October 1st - 5th , 2007, pp. 1303-1310.

Hermundstad, O.A. and Moan, T. (2007). Efficient calculation of slamming pressures on ships in irregular seas, *Journal of Marine Science and Technology*, 12:3, 160-182. JMST

Hong, D.C, Hong, S.Y. and Hong, S.W. (2006). Reduction of hydroelastic responses of a very-long floating structure by a floating oscillating-water-column breakwater system, *Ocean Engineering*, 33:5-6, 610-634

Hong, D.C. and Hong, S.Y. (2007). Hydroelastic responses and drift forces of a very-long floating structure equipped with a pin-connected oscillating-water-column breakwater system, *Ocean Engineering*, 34: 5-6, 696-708.

Hong, L. and Amdahl, J. (2007a). Plastic design of laterally patch loaded plates for ships, *Marine Structures*, 20:3, 124-142.

Hong, L. and Amdahl, J. (2007b). Strength Design of FPSOs against Supply Vessel Bow Collision, *Proceedings of International Conference on Computer Application to Shipbuilding, ICCGS 2007,* 1-10.

Horn, G. and Baumans, P. (2007). The Development, Implementation and Maintenance of CSR for Bulk Carriers and Oil Tankers, *Proceedings of RINA Int. Conf. on Developments in Classification and International Regulations*, London, 25-36.

Hovem, L., Thunes, R., Horte, T. and Boe, Å. (2007). Common Structural Rules for Tankers: From Design Situations to Rule Requirements, *The Proceedings of the 10th International Symposium on Practical Design of Ships and Other Floating Structures*, Houston, Texas, October 1st - 5th, 2007, pp. 677-686.

Hu, Y. and Prusty, B.G. (2007). A new method for oil tanker structure condition, *Ships and*

Offshore Structures, 2:4, 371-377.

Huang, L.L. and Riggs, H.R. (2005). Development of a New Interfacing Strategy for Fluid-Structure Interaction, *Proceedings of the Institution of Mechanical Engineers, Part M: Journal of Engineering for the Maritime Environment*, 219:3, 131-148.

IACS (2006) Unified Requirement URI -Structural Requirements for Polar Class Ships, *IACS Publications*, London.

Islam, N. and Ahmad, S. (2007). Reliability of articulated tower joint against random base shear, *Structural Engineering and Mechanics*, 27:1, 33-48.

Ivanov, L.D. (2007). On the relationship between maximum still water shear forces, bending moments, and radii of gyration of the total ship's weight and buoyancy forces, *Ships and Offshore Structures*, 2:1, 39-47.

Izumiyama, K., Takimoto, T. and Uto, S. (2007). Length of Ice Load Patch on a Ship Bow in Level Ice, *The Proceedings of the 10th International Symposium on Practical Design of Ships and Other Floating Structures*, Houston, Texas, October 1st - 5th , 2007, 1287-1294.

Jang, B.-S., Jung, J.-H. and Suh, Y.-S. (2008a). Use of 3D compartment model for simplified full ship FE model. Part I: Construction of FE model, *Journal of Marine Science and Technology*, 13:2, 154-163.

Jang, B.-S., Suh, Y.-S., Kim, E.-K. and Lee, T.-H. (2008b). Automatic FE modeler using stiffener-based mesh generation algorithm for ship structural analysis, *Marine Structures*, 21:2-3, 294-325.

Jia J. and Ulfvarson A. (2005a). Structural behaviour of a high tensile steel deck using trapezoidal stiffeners and dynamics of vehicle-deck interactions, *Marine Structures*, 18:1, 1-24.

Jia, J. and Ulfvarson, A. (2005b). A systematic approach towards the structural behaviour of a lightweight deck–side shell system, *Thin-Walled Structures*, 43:1, 83-105.

Jones, N. (2006). Some recent developments in the dynamic inelastic behaviour of structures, *Ships and Offshore Structures*, 1:1, 37-44.

Jung, G. (2007). A shell-element-based elastic analysis predicting welding-induced distortions for ship panels, *Journal of Ship Research*, 51:2, 128-136.

Kabche, J.-P., Caccese, V. And Berube, K. A. and Thompson, L. (2007). Analysis of a hybrid composite/metal ship hull structural system with removable panels, *Ships and Offshore Structures*, 2:3, 227-240.

Kalnins, K., Skukis, E. and Auzins, J. (20050. Metamodels for I-core and V-core Sandwich Panel Optimization, *Proceedings of 8th International Conference on Shell Structures: Theory and Applications*, SSTA-05, Jurata, October 12th – 14th 2005, 569-572.

Kamenov-Toshkov, L., Ivanov, L. D. and Garbatov, Y. (2006). Wave-induced design bending moment assessment for any given ship's operational life, *Ships and Offshore Structures*, 1:3, 221-227.

Kampner, M. and Grenestedt, J.L. (2008). On using corrugated skins to carry shear in sandwich beams, *Composite Structures*, 85:2, 139-148.

Karadeniz, H. (2006a). Uncertainties in spectral fatigue damages and an efficient simple-reliability calculation of offshore structures, ASME, *Safety Engineering and Risk Analysis Division*, 9p.

Karadeniz, H. (2006b). Review of structural reliability methods with applicability in practice, *Proceedings of the International Offshore and Polar Engineering Conference*, 393-402.

Karadeniz, H. (2008). Spectral analysis of deteriorated offshore structures, *ASME International Mechanical Engineering Congress and Exposition, Proceedings*, 14, 71-78.

Karvinen, K.G. and Pegg, N.G. (2006). A simplified method for nonlinear failure analysis of stiffened plates, *Marine Structures*, 19:2-3, 97-109.

Kawamura, Y. and Sumi, Y. (2005). Information System for Structural Integrity of Ships, *Proceedings of the Institution of Mechanical Engineers, Part M: Journal of Engineering for the Maritime Environment*, 219:2, 93-106.

Kendrick, A., Daley, C., Santos-Pedro, V. and Hayward, R. (2007) "Classification of Polar Class Ships" *Proceedings of RINA Int. Conf. on Design & Construction Of Vessels Operating In Low Temperature Environments*, London, UK.

Kim, B.W., Hong, S.Y., Kyoung, J.H. and Cho, S.K. (2007). Evaluation of bending moments and shear forces at unit connections of very large floating structures using hydroelastic and rigid body analyses, *Ocean Engineering*, 34: 11-12, 1668-1679.

Kim, I.I. (2006). A development of data structure and mesh generation algorithm for whole ship analysis modeling system, *Advances in Engineering Software*, 37:2, 85-96.

Kim, K-H. and Kim, Y. (2008). On Technical Issues in the Analysis of Nonlinear Ship Motion and Structural Loads in Waves by a Time-Domain Rankine Panel Method, *23rd International Workshop on Water Waves & Floating Bodies*, Jeju, Korea.

Klanac, A., Ehlers, S., Tabri, K., Rudan, S. and Broekhuijsen, J. (2005). Qualitative design assessment of crashworthy structures, *Proceedings of International Maritime Association of Mediterranean - IMAM*, Lisboa 2005, 461-469.

Koertenoeven, J., Boon, B. and de Bruijn, A. (2007). Application of Sandwich Panels in Design and Building of Dredging Ships, *The Proceedings of the 10th International Symposium on Practical Design of Ships and Other Floating Structures*, Houston, Texas, October 1st - 5th , 2007, pp. 855-864.

Kolsters, H. and Zenkert, D. (2006a). Buckling of laser-welded sandwich panels. Part 1: elastic buckling parallel to the webs, *Proceedings of the Institution of Mechanical Engineers, Part M: Journal of Engineering for the Maritime Environment*, 220:2, 67-79.

Kolsters, H. and Zenkert, D. (2006b). Buckling of laser-welded sandwich panels. Part 2: elastic buckling normal to the webs, *Proceedings of the Institution of Mechanical Engineers, Part M: Journal of Engineering for the Maritime Environment*, 220:2, 81-94.

Kolsters, H. and Wennhage, P. (2008). Optimisation of laser-welded sandwich panels with multiple design constraints, *Marine Structures*, Accepted for Publication, 2008.

Kozak, J. (2005). Strength Tests of Steel Sandwich Panel, *Proceedings of International Maritime Association of Mediterranean - IMAM*, Lisboa 2005, pp. 471-476.

Kozak, J. (2006a). Problems of the Modelling of Steel Sandwich Panels under In-Plane Load, *Polish Maritime Research, Special Issue on All Steel Sandwich Panels – An Alternative for Classical Ship Hull Structure*, S1, 2006, 9-12.

Kozak, J. (2006b). Fatigue Life of Steel Laser-Welded Panels, *Polish Maritime Research, Special Issue on All Steel Sandwich Panels – An Alternative for Classical Ship Hull Structure*, S1, 2006, 13-16.

Kujala, P. and Klanac, A. (2005). Steel sandwich panels in marine applications, *Journal of Naval Architecture and shipbuilding industry (Brodogradnja)*, 56:4, 305-314.

Kujala, P. and Noury, P. (2005). Design of ship structures from metallic sandwich topology, *WEGEMT course lecture published in: Theory and Applications of Sandwich Structures,* Edited by Shenoi, Groves and Rajapakse, University of Southampton, 2005, 515-569.

Kujala, P., Valkonen, J. and Suominen, M. (2007). Maximum Ice-Induced Loads on Ships in the Baltic Sea, *The Proceedings of the 10th International Symposium on Practical Design of Ships and Other Floating Structures*, Houston, Texas, October 1st - 5th , 2007, 1278-1286.

Kumar, S., Dandotiya, R., Kumar, R. and Kumar, U. (2008). Inspection frequency optimization model for degrading flowlines on an offshore platform, *International*

Journal of Reliability, Quality and Safety Engineering, 15:2, 167-180.

Le Sourne, H. (2007). A ship collision analysis program based on super-element method coupled with large rotational ship movement analysis tool, *Proceedings of International Conference on Computer Application to Shipbuilding, ICCGS 2007*, 131-138.

Lee, D.H., Kim, M.H., Kwon, S.H., Kim, J.W. and Lee, Y.B. (2007a). A parametric sensitivity study on LNG tank sloshing loads by numerical simulations, *Ocean Engineering*, 34: 1, 3-9.

Lee, S.J., Kim, M.H., Lee, D.H., Kim, J.W. and Kim, Y.H. (2007b). The effects of LNG-tank sloshing on the global motions of LNG carriers, *Ocean Engineering*, 34: 1, 10-20.

Lee, M.C.W., Payne, R.M., Kelly, D.W. and Thomson, R.S. (2008). Determination of robustness for a stiffened composite structure using stochastic analysis, *Composite Structures*, 86:1-3, 78-84.

Lee, W.H. and Bøe, A. (2008) A Study on Support Arrangements of a Cargo Tank for Tank Type-A LPG Ships *Proceedings of RINA Int. Conf. on Design and Operation of LPG Ships*, London.

Lee. S.K. (2007). Engineering Practice on Ice Propeller Strength Assessment Based on IACS Polar Ice Rule - URI3, *The Proceedings of the 10th International Symposium on Practical Design of Ships and Other Floating Structures*, Houston, Texas, October 1st - 5th , 2007, pp. 1337-1345.

Li, G., Zhang, D.-Y. and Yue, Q.-J. (2006). Time-dependent fatigue reliability analysis of offshore platforms in ice zone, *Jisuan Lixue Xuebao/Chinese Journal of Computational Mechanics*, 23:5, 513-517.

Li, G., Zhang, D.-Y., Yue, Q.-J. and Spurgeon, E.C. (2008a). Efficient approximate method of global reliability analysis for offshore platforms in the ice zone, *China Ocean Engineering*, 22:2, 303-311.

Li, G., Zhang, D.-Y., Yue, Q.-J. and Spurgeon, E.C. (2008b). Efficient approximate method of global reliability analysis for offshore platforms in ice zone, *Dalian Ligong Daxue Xuebao/Journal of Dalian University of Technology*, 48:2, 157-161.

Lindemark, T., Austefjord, H. N., Sele, H. O., Urm, H. S., Lee, K. J. and Ha, T. M. (2006) CSA-2 Analysis of a 216k LNG Membrane Carrier, *Proceedings of RINA ICSOT 2006: Design, construction and operation of natural gas carriers and offshore systems*, Busan, Korea

Little, J. Sandwich Plate System Panels under In-plane and Uniform Lateral Pressure, Master's Thesis, University of Alberta, Department of Civil and Environmental Engineering, Edmonton, Alberta, Canada, 2007

Lotsberg, I. (2006a). Fatigue design of plated structures using finite element analysis, *Ships and Offshore Structures*, 1:1, 45-54.

Lotsberg, I. (2007). Recent advances on fatigue limit state design for FPSOs, *Ships and Offshore Structures*, 2:1, 49-68.

Lotsberg, I. (2006b). Assessment of fatigue capacity in the new bulk carrier and tanker rules, *Marine Structures*, 20:1-2, 83-96.

Lovstad, M. and Guttormsen, V. (2007). Impact of Common Structural Rules on Software for Ship Design and Strength Assessment, *Proceedings of RINA Int. Conf. on Developments in Classification and International Regulations*, London, 119-132.

Madhavan, P.T.M. and Veena, G. (2006). Fatigue reliability analysis of fixed offshore structures: A first passage problem approach, *Journal of Zhejiang University: Science*, 7:11, 1839-1845.

MAIB (2008). Report on the investigation of the structural failure of MSC Napoli English Channel on 18 January 2007, *Marine Accident Investigation Branch, Southampton,* *UK, Report No 9/2008*, *April 2008.*

Maroun, W. J., Cao, J. and Grenestedt, J. L. (2007). Steel truss/composite skin hybrid ship hull. Part II: Design and analysis. *Composites: Part A*, 38:7, 1763-1772.

Marshall, P.W. (2007). How risky were my old platforms? *Proceedings of the International Conference on Offshore Mechanics and Arctic Engineering - OMAE*, vol 2, 511-520.

Masaoka, K. and Mansour, A. (2008). Compressive strength of stiffened plates with imperfections: Simple design equations, *Journal of Ship Research*, 52:3, 227-237.

Mesbahi, E. and Pu, Y. (2008). Application of ANN-based response surface method to prediction of ultimate strength of stiffened panels, *Journal of Structural Engineering*, 134:10, 1649-1656.

Metschkow, B. (2006). Sandwich Panels in Shipbuilding, *Polish Maritime Research, Special Issue on All Steel Sandwich Panels – An Alternative for Classical Ship Hull Structure*, S1, 2006, 5-8.

Moan T., Gao Z. and Ayala-Uraga E. (2005). Uncertainty of wave-induced response of marine structures due to long-term variation of extratropical wave conditions, *Marine Structures*, 18:4, 359-382.

Moan, T. (2007). Fatigue reliability of marine structures, from the Alexander Kielland accident to life cycle assessment, *International Journal of Offshore and Polar Engineering*, 17:1, 1-21.

Moarefzadeh, M.R. and Melchers, R.E. (2006). Nonlinear wave theory in reliability analysis of offshore structures, *Probabilistic Engineering Mechanics*, 21:2, 99-111.

Motok, M.D. and Jovovic, J. (2007). Wave induced Shear force and Bending Moment for Series of Ships - Comparison & Some Interpolation Procedures, *Proceedings of RINA Int. Conf. on Developments in Classification and International Regulations*, London, 111-118.

N'Diaye, A., Hariri, S., Pluvinage, G. and Azari, Z. (2007). Stress concentration factor analysis for notched welded tubular T-joints. International Journal of Fatigue, 29:8, 1554-1570.

Na, R.-S., Ren, H.-L., Gao, Z.-L. and Jin, X.-D. (2007). Simulation of sloshing and structural response in VLCC tanks, *Chuan Bo Li Xue/Journal of Ship Mechanics*, 11:6, 879-887.

Naar, H. (2006). Ultimate Strength of Hull Girder for Passenger Ships, PhD Thesis, Helsinki University of Technology, March 2006.

Naess, A., Gaidai, O. and Batsevych, O. (2008). Extreme value statistics of combined load effect processes, *Structural Safety*, Article in Press.

Najafian, G. (2007a). Probability models for offshore structural response due to Morison wave loading Part I: Drag-only response, *Ocean Engineering*, 34: 17-18, 2277-2288.

Najafian, G. (2007b). Probability models for offshore structural response due to Morison wave loading: Part II: Inertia-only and total responses, *Ocean Engineering*, 34: 17-18, 2289-2299.

Nakai, T., Matsushita, H. and Yamamoto, N. (2006). Effect of pitting corrosion on the ultimate strength of steel plates subjected to in-plane compression and bending, *Journal of Marine Science and Technology*, 11:1, 52-64.

Nyseth, H. and Holtsmark, G. (2006). Analytical Plastic Capacity Formulation For Plates Subject To Ice Loads And Similar Types Of Patch Loadings, *Proc. OMAE2006*, Hamburg, Germany.

Oberhagemann, J., El Moctar, O., Holtmann, M., Schellin, T., Bertram, V. and Kim, D.W. (2008). Numerical simulation of stern slamming and whipping, *11th Numerical Towing Tank Symposium*, Brest.

Ohmatsu, S. (2005). Overview: Research on wave loading and responses of VLFS, *Marine Structures*, 18:2, 149-168.

Ojeda, R., Gangadhara, P.B., Lawrence, N. and Thomas, G. (2007). A new approach for the large deflection finite element analysis of isotropic and composite plates with arbitrary orientated stiffeners, *Finite Elements in Analysis and Design*, 43:13, 989-1002.

Ok, D., Pu, Y. and Incecik, A. (2007). Computation of ultimate strength of locally corroded unstiffened plates under uniaxial compression, *Marine Structures*, 20:1-2, 100-114.

Okada, T., Takeda, Y. and Maeda, T. (2006). On board measurement of stresses and deflections of a Post-Panamax containership and its feedback to rational design, *Marine Structures*, 19:2-3, 141-172.

Okada, T., Toyoda, M. and Kobayashi, E. (2007). Practical Initial Design Optimization of Large Container Ships, *Proceedings of 10th Int. Symp. on Practical Design of Ships and other Floating Structures PRADS 2007*, volume 1, 574-579.

Orsero, P., Fontaine, E. and Quiniou, V. (2007). Reliability and response based design of a moored FPSO in West Africa using multivariate environmental contours and response surfaces, *Proceedings of the International Offshore and Polar Engineering Conference,* 51-58.

Ozguc, O., Das, P.K. and Barltrop, N. (2005). A comparative study on the structural integrity of single and double side skin bulk carriers under collision damage, *Marine Structures*, 18:7-8, 511-547.

Ozguc, O., Das, P.K. and Barltrop, N. (2006). A proposed method to evaluate hull girder ultimate strength, *Ships and Offshore Structures*, 1:4, 335-345.

Ozguc, O., Das, P.K. and Barltrop, N. (2007). The new simple design equations for the ultimate compressive strength of imperfect stiffened plates, *Ocean Engineering*, 34: 7, 970-986.

Paik, J.K. (2007a). Practical techniques for finite element modeling to simulate structural crashworthiness in ship collisions and grounding (Part I: Theory), *Ships and Offshore Structures*, 2:1, 69-80.

Paik, J.K. (2007b). Practical techniques for finite element modelling to simulate structural crashworthiness in ship collisions and grounding (Part II: Verification), *Ships and Offshore Structures*, 2:1, 81-85.

Paik, J.K. (2007c). Ultimate strength of perforated steel plates under edge shear loading, *Thin-Walled Structures*, 45:3, 301-306.

Paik, J.K. (2007d). Ultimate limit state performance of oil tanker structures designed by IACS common structural rules, *Thin-Walled Structures*, 45:12, 1022-1034.

Paik, J.K. (2007e). Ultimate strength of steel plates with a single circular hole under axial compressive loading along short edges, *Ships and Offshore Structures*, 2:4, 355-360.

Paik, J.K. (2007f). Recent Design Advances in Ship-shaped Offshore Installations, *The Proceedings of the 10th International Symposium on Practical Design of Ships and Other Floating Structures*, Houston, Texas, October 1st - 5th , 2007, pp. 1230-1246.

Paik, J.K. (2008). Ultimate strength of perforated steel plates under combined biaxial compression and edge shear loads, *Thin-Walled Structures*, 46:2, 207–213.

Paik, J.K. and Seo, J.K. (2007). Method for Progressive Structural Crashworthiness Analysis under Collisions and Grounding, Marstruct Glasgow 2007.

Paik, J.K. and Shin, Y.S. (2006). Structural damage and strength criteria for ship stiffened panels under impact pressure actions arising from sloshing, slamming and green water loading, *Ships and Offshore Structures*, 1:3, 249-256.

Paik, J.K. and Thayamballi, A.K. (2006). Some recent developments on ultimate limit state design technology for ships and offshore structures, *Ships and Offshore Structures*, 1:2, 99-116.

Paik, J.K., Kim, B.J. and Seo, J.K. (2008a). Methods for ultimate limit state assessment of ships and ship-shaped offshore structures: Part I—Unstiffened plates, *Ocean Engineering*, 35: 2, 261-270.

Paik, J.K., Kim, B.J. and Seo, J.K. (2008b). Methods for ultimate limit state assessment of ships and ship-shaped offshore structures: Part II stiffened panels, *Ocean Engineering*, 35: 2, 271-280.

Paik, J.K., Kim, B.J. and Seo, J.K. (2008c). Methods for ultimate limit state assessment of ships and ship-shaped offshore structures: Part III hull girders, *Ocean Engineering*, 35: 2, 281-286.

Paik, J.K., Seo, J.K. and Kim, D.M. (2006). Idealized structural unit method and its application to progressive hull girder collapse analysis of ships, *Ships and Offshore Structures*, 1:3, 235-247.

Palo, P. (2005). Mobile offshore base: Hydrodynamic advancements and remaining challenges *Marine Structures*, 18:2, 133-147.

Parunov, J. and Guedes Soares, C. (2008). Effects of common structural rules on hull-girder reliability of an Aframax oil tanker, *Reliability Engineering and System Safety,* 93, 1317-1327.

Parunov, J., Senjanovic, I. and Guedes Soares C. (2007). Hull-girder reliability of new generation oil tankers, *Marine Structures*, 20:1-2, 49-70.

Pedersen, P.T. and Li, Y. (2008). On the global ship hull bending energy in ship collisions, *Marine Structures*, 21, (article in press).

Peng, L.X., Liew, K.M. and Kitipornchai, S. (2006). Buckling and free vibration analyses of stiffened plates using the FSDT mesh-free method, *Journal of Sound and Vibration*, 289:3, 421-449.

Probst, J.-O. (2006) The 13,400 TEU Container Ship, *Proceedings of RINA Int. Conf. on Design and Operation of Container Ships*, London, 11-20.

Probst, J.-O. (2007) Shiphull Design and Limitations for Containerships, *Proceedings of Sea Asia Conference,* Singapore

Pu, Y. and Mesbahi, E. (2006). Application of artificial neural networks to evaluation of ultimate strength of steel panels, *Engineering Structures*, 28:8, 1190-1196.

Pyszko, R. (2006). Strength Assessment of a Version of Joint of Steel Sandwich Panels, *Polish Maritime Research, Special Issue on All Steel Sandwich Panels – An Alternative for Classical Ship Hull Structure*, S1, 2006, 17-20.

Qi, E. and Cui, W. (2006). Analytical method for ultimate strength calculations of intact and damaged ship hulls, *Ships and Offshore Structures*, 1:2, 153-163.

Riggs, H.R., Suzuki, H., Ertekin, R.C., Kim, J.W. and Iijima, K. (2008). Comparison of hydroelastic computer codes based on the ISSC VLFS benchmark, *Ocean Engineering*, 35: 7, 589-597.

Rizzo, C.M. and Rizzuto, E. (2007). Comparison of common structural rules with Previous Class Rules *Proceedings of RINA Int. Conf. on Developments in Classification and International Regulations*, London, 41-50.

Romanoff, J. and Klanac, A. (2007). Design Optimization of Steel Sandwich Hoistable Car-Decks Apply-ing Homogenized Plate Theory, *Proceedings of 10th International Symposium on Practical Design of Ships and Other Floating Structures*, Houston, Texas, October 1st – 5th 2007.

Romanoff, J. and Varsta, P. (2007a). Bending Response of Laser-Welded Web-Core Sandwich Plates, *1st International Conference on Advancements in Marine Structures*, Editors Guedes Soares and Das, Taylor & Francis Group, 2007, 263-271.

Romanoff, J. and Varsta, P. (2007b). Bending response of web-core sandwich plates, *Composite Structures*, 81:2, 292-302.

Romanoff, J., Remes, H., Socha, G., Jutila, M. and Varsta, P. (2007a). The Stiffness of Laser Stake Welded T-joints in Web-core Sandwich Structures, *Thin- Walled Structures*, 45:4, 453–462.

Romanoff, J., Varsta, P. and Remes, H. (2007b). Laser-welded web-core sandwich plates under patch loading, *Marine Structures*, 20:1-2, 25-48.

Rörup, J., Schellin, T. and Rathje, H. (2008). Load Generation for Structural Strength

Analysis of Large Containerships, *Proceedings of Int. Conf. on Offshore Mechanics and Arctic Engineering OMAE 2008*, Estoril, Portugal.

Ruud, S. and Mikkelsen, A. (2008). Risk-based rules for crane safety systems, *Reliability Engineering and System Safety*, 93:9, 1369-1376.

Ryu, H.R., Priebe, T., Probst, J-O., Rörup, J. (2004). Advanced Structural Analysis for 8000 TEU Class Container Carrier by Wave Load Analysis Method Combined with Roll Motion, *Proceedings of 9th Int. Symp. on Practical Design of Ships and other Floating Structures, PRADS 2004*, vol 1, 87-92.

Save, M.A., Massonnet, C.E. and Saxce, G.D. (1997). Plastic Limit Analysis of Plates, Shells and Disks, Elsevier, Amsterdam.

Seto, H., Ohta, M., Ochi, M. and Kawakado, S. (2005). Integrated hydrodynamic-structural analysis of very large floating structures (VLFS), *Marine Structures*, 18:2, 181-200.

Shao, Y.B. (2008). Prediction of the hot spot stress distribution of tubular T-joints under axial load based on shape function interpolation method, *Chuan Bo Li Xue/Journal of Ship Mechanics*, 12:5, 757-764.

Shenoi, A. (2006). Composite Lightweight Structures and their Application in Shipbuilding, *Schiffbauforschung 45 (2006) 1,* Rostock, Germany, 46-58.

Shi, B., Liu, D. and Wiernicki, C. (2005). Dynamic Loading Approach for Structural Evaluation of Ultra Large Container Carriers. *Trans SNAME*, 113, 402 415.

Shi, B., Lui, D., Weirnicki, C., Tang-Jensen, P. (2006) Technology advances in Design and Operation of Large Container Ships, *Proceedings of RINA Int. Conf. on Design and Operation of Container Ships*, London, 1-11.

Shibata, K. and Koshizuka, S. (2007).Numerical analysis of shipping water impact on a deck using a particle method, *Ocean Engineering*, 34: 3-4, 585-593.

Ship Structures Committee (2007). Comaparative study of ship structure design standards, Ship Structures Committee Report: SSC-446, SR-1444, March 2007.

Sobey, A., Blake, J. and Shenoi, A. (2008). Optimization of Composite Boat Hull Structures, *Proceedings of 7th International conference on Computer and IT Applications in the Maritime Industries,* COMPIT 08, 21-23 April 2008, Liege, Belgium, 502-515.

Sørensen, J.D., Friss-Hansen, P. and Nielsen, J.S. (2008). Reliability analysis of offshore jacket structures with wave load on deck using the model correction factor method, *Structure and Infrastructure Engineering*, 4:5, 393-398.

Steen, S., Storhaug, G., Kippenes, J., Sadó, O., Austefjord, H. and Dugstad, G. (2008). Ultimate Strength Assessment of the Engine Room Area of the Container Vessel MSC Napoli - January 2007 Incident, *Proceedings of RINA Int. Conf. on Design and Operation of Container Ships*, London, 23-37.

Sui, Y.-K. and Bian, B.-C. (2008). Topology optimization of continuum structures under buckling and stress constraints, *Gongcheng Lixue/Engineering Mechanics*, 25:8, 6-12.

Sun, H.-H. and Spencer, J. (2005). Buckling strength assessment of corrugated panels in offshore structures, *Marine Structures*, 18:7-8, 548-565.

Suneel Kumar, M., Alagusundaramoorthy, P. and Sundaravadivelu, R. (2006). Ultimate strength of ship plating under axial compression, *Ocean Engineering*, 33:8-9, 1249-1259.

Suzuki, H. (2005). Overview of Megafloat: Concept, design criteria, analysis, and design, *Marine Structures*, 18:2, 111-132.

Suzuki, H., Shugar, T.A., Bhattacharya, B., Riggs, H.R., Seto, H., Hudson, D.A., Fujikubo, M., Yasuzawa, Y. and Shin H. (2007). Very large floating structures, *Proceedings of the International Conference on Offshore Mechanics and Arctic Engineering - OMAE*, vol 2, 597-608.

Tavakoli, M.T., Amdahl, J., Alsos, H.S. and Klaebo, F. (2007). Analysis of supply vessel stern impacts with an FPSO. *Proceedings of International Conference on Computer Application to Shipbuilding, ICCGS 2007,* 19-28.

Teixeira, A.P. and Guedes Soares, C. (2008). Simulation of inspections on ship plates with random corrosion patterns, *Journal of Ship Production*, 24:3, 168-175.

Theotokoglou, E.E. (2006). Behaviour of thick composite tubes considering of delamination. *Theoretical and Applied Fracture Mechanics*, 46:3, 276-285.

Toderan, C., Guillaume-Combecave, J.-L., Boukaert, M., Hage, A., Cartier, O., Caprace, J.-D., Amrane, A., Constantinescu, A., Pircalabu, E. and Rigo, P. (2008) Structural Optimization of a 220 000 m³ LNG Carrier. *Proceedings of 7th International conference on Computer and IT Applications in the Maritime Industries, COMPIT 08, 21-23 April 2008, Liege, Belgium, pp 107-120.*

Toftegaard, H. and Lystrup, A. (2005). Design and test of lightweight sandwich T-joint for naval ships, *Composites: Part A*, 36:8, 1055-1065.

Toyoda, M., Kusumoto, T., Okada, T. and Kobayashi, E. (2006). Advanced structural design of containerships to achieve overall safety and economy, *Proceedings of RINA Int. Conf. on Design and Operation of Container Ships*, London, 31-42.

Valkonen, J., Izumiyama, K. and Kujala, P. (2007). Measuring of Ice Induced Pressures and Loads on Ships in Model Scale, *The Proceedings of the 10th International Symposium on Practical Design of Ships and Other Floating Structures*, Houston, Texas, October 1st - 5th, 2007, 1206-1213.

Valsgård, S., Østvold, T. K., Rognebakke, O., Byklum, E. and Sele, H.O. (2006). Gas carrier development for an expanding market, *Proceedings of RINA ICSOT 2006: Design, construction and operation of natural gas carriers and offshore systems*, Busan, Korea

Vhanmane, S. and Bhattacharya, B. (2007). On improved analytical method for stress-strain relationship for plate elements under axial compressive load, *Ships and Offshore Structures*, 2:4, 347-353.

VIRTUE: The VIRtual Tank Utility in Europe, EU 6th Framework Programme in Sustainable Development, global change and ecosystems, Jan 2005 to Dec 2009, http://www.virtual-basin.org/

Wang, G., Basu, R., Chavda, D. and Liu, S. (2005). Rationalizing the design of ice strengthened side structures, *Maritime Transportation and Exploitation of Ocean and Coastal Resources* – Guedes Soares, Garbatov & Fonseca (eds) © 2005 Taylor & Francis Group, London, ISBN 0 415 39036 2, pp. 549-557.

Wang, L., Chen, K. and Bucknell, J. (2007a). Structural reliability assessment of offshore platforms under hurricane events, *Proceedings of the International Conference on Offshore Mechanics and Arctic Engineering - OMAE*, vol 2, 213-218.

Wang, X., Sun, H. and Basu, R. (2007b). Structural reliability levels in ice class rules, *The Proceedings of the 1st International Conference on Advancements in Marine Structures,* Editors Guedes Soares and Das, Taylor & Francis Group, 2007, pp. 557-563.

Wang, Y., Shi, Y., Wang, C. and Li, S. (2006). A new method for system fatigue reliability analysis of offshore steel jacket, *Advances in Structural Engineering*, 9:2, 185-193.

Wong, S., Yu, L., Le Callet, M. and Gong, N. (2007). ShipRight SDA - An Integrated Finite Element Solution for CSR, *Proceedings of Int. Conf. on Computer Applications in Shipbuilding ICCAS 2007*, Portsmouth, UK, Vol III, 275-281.

Xue, J. and Hoo Fatt, M.S. (2005). Symmetric and anti-symmetric buckle propagation modes in subsea corroded pipelines, *Marine Structures*, 18:1, 43-61.

Xue, H.X., Tang, W.Y., Zhang, S.K. and Yuan, M. (2006). Interval analysis method of fatigue and fracture reliability for offshore structures based on probabilistic and non-probabilistic hybrid model, *Proceedings of the International Offshore and Polar Engineering Conference*, 370-375.

Yaakob, M.F. (2006). Ship structural design and construction of large LNG Carriers (LNGCs) at Samsung Heavy Industries (SHI) – Malaysia International Shipping Corporation (MISC) representative perspectives, *Proceedings of RINA ICSOT 2006: Design, construction and operation of natural gas carriers and offshore systems*, Busan, Korea

Yamada, Y. and Endo, H. (2008). Experimental and numerical study on the collapse strength of the bulbous bow structure in oblique collision, *Marine Technology*, 45:1, 42-53.

Yamada, Y. and Pedersen, P.T. (2008). A benchmark study of procedures for analysis of axial crushing of bulbous bows, *Marine Structures*, 21:2-3, 257-293.

Yamada, Y., Pedersen, P.T. and Hansen, P.F. (2007). The effect of Buffer bow Structures on Probabilistic Collision Damages of Oil Tankers, *Proceedings of International Conference on Computer Application to Shipbuilding, ICCGS 2007,* 235-242.

Yamamoto, N., Koiwa, T., Dobashi, H., Muragishi, O. and Takaoka, Y. (2007). A study of a fatigue management system for long LNG carriers using a new fatigue damage sensor, *Ships and Offshore Structures*, 2:4, 361-370.

Yan, H.-S., Yu, J.-X., Hu, Y.-C. and Liu, C.-L. (2007). System reliability analysis of large-scale offshore platform based on neural network response surface and ductile limit theory, *Chuan Bo Li Xue/Journal of Ship Mechanics*, 11:3, 444-452.

Yang, C., Löhner, R. and Lu, H. (2006). An unstructured-grid based volume-of-fluid method for extreme wave and freely-floating structure interactions, *Journal of Hydrodynamics*, 18:3-1, 415-422.

Yu, H., Ha, M.-K., Choi, J.-W. and Tai, J.S.-C. (2006). Design and Implementation of a Comprehensive Full-Scale Measurement System for a Large Container Carrier, *Proceedings of RINA Int. Conf. on Design and Operation of Container Ships*, London, 51-60.

Yuen, D.Z., Ivanov, L.D., Wang, G. and Choo, Y.S. (2008). Structural reliability assessment of aging ships using the concept of level of certainty, *Marine Technology*, 45:3, 132-146.

Zanic, V., Andric, J. and Prebeg, P. (2005).Superstructure deck effectiveness of the generic ship types – a concept design method, *Maritime Transportation and Exploitation of Ocean and Coastal Resources* – Guedes Soares, Garbatov & Fonseca (eds) © 2005 Taylor & Francis Group, London, ISBN 0 415 39036 2, pp. 579-588.

Zhang, A. and Suzuki, K. (2007a). A comparative study of numerical simulations for fluid–structure interaction of liquid-filled tank during ship collision, *Ocean Engineering*, 34: 5-6, 645-652.

Zhang, A. and Suzuki, K. (2007b). A study on the effect of stiffeners on quasi-static crushing of stiffened square tube with nonlinear finite element method, *International Journal of Impact Engineering*, 34:3, 544-555.

Zhang, Q. and Li, X.-S. (2006). Sampling and simulation method for reliability analysis of offshore jacket platform, *Dalian Ligong Daxue Xuebao/Journal of Dalian University of Technology*, 46:2, 166-169.

Zheng, Y., Aksu, S., Vassalos, D. and Tuzcu, C. (2007). Study on side structure resistance to ship-ship collisions, *Ships and Offshore Structures*, 2:3, 273-293.

Zhou, F. (2007). Ultimate Strength of Clamped Steel-Elastomer Sandwich Panels under Combined In-plane Compression and Lateral Pressure", PhD thesis, Virginia Tech, Dept. of Aerospace and Ocean Engineering, 2007.

Zhu, B. (2007). Elasto-plastic impact model and experimental study of new absorber for structural collision protection, *Tumu Gongcheng Xuebao/China Civil Engineering Journal*, 40:2, 13-24.

Zhu, T., Shigemi, T., Miyake, R., Kumano, A. and Abdul Rahim, M. (2006). Comprehensive studies on the wave load analysis and structural strength assessment of container ships, *Proceedings of RINA Int. Conf. on Design and Operation of Container Ships*, London, 75-94.