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OFFSHORE STRUCTURES CONGRESS

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COMMITTEE II.1 QUASI-STATIC RESPONSE

COMMITTEE MANDATE

Concern for the quasi-static response of ships 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.

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B.R. van der Sluijs, *Netherlands*
M. Taczala, *Poland*
Z. Wan, *China*
A. Zamarin, *Croatia*
O. Økland, *Norway*

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Container ships, corrosion, direct calculations, experiments and testing, extreme load, fatigue assessment, finite element analysis, IACS Common Structural Rules, IMO Goal-Based Standards, impact loads, loads modelling, offshore structures, optimisation, probabilistic approach, quasi-static response, reliability analysis, ship structures, strength assessment, stress response calculation, structural integrity, uncertainty analysis.

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1. INTRODUCTION

Ships and floating offshore installations are large-scale, complex structures that are designed and built to operate for long periods in an ever changing environment. For safe and sustainable structural design, the design process should follow the limit-state-based design philosophy which encompasses serviceability, ultimate strength, fatigue and accidental limit states. For engineering economy in the early design stage it is common to employ quasi-static approaches for the evaluation of loads. It is then important to have good understanding of the difference between quasi-static and dynamic response analyses as well as the available engineering techniques (e.g. empirical approaches, direct analysis methods, reliability analysis, etc.) and associated modelling procedures that can be applied for design assessment.

A convenient and useful computational tool for structural response analysis is the finite element (FE) method which, if used properly, can model efficiently the complexity and interaction between components and parts of large structures and the maritime environment. Knowledge and treatment of uncertainties that may relate with the modelling of loads and the constitutive materials modelling, may have great impact on the accuracy and reliability of results. Past reports by the ISSC Technical Committee II.1 have presented comprehensive reviews of various strength assessment approaches (for example, see ISSC 2012). The present committee report is organised as follows.

Chapter 2 is a general introduction to strength assessment approaches for quasi-static response of ships and offshore structures. Its objective is to give a brief overview on modelling of quasi-static loads and subsequently elaborate the procedures and available technologies for the evaluation of associated responses within the context of reliability assessment.

Chapter 3 is the major part of the report and presents a comprehensive review of existing calculation procedures. At first instance, different levels of analysis that relate to different design stages are discussed. Then, a review of direct assessment procedures for ships and offshore structures also including composite applications is presented. Finally, recent studies and recommendations emerging from the application of Fluid Structure Interaction (FSI) methods for buckling, ultimate and fatigue strength assessment are discussed. Special emphasis is attributed to the importance of validation of numerical prediction methods against model-scale experiments and full-scale monitoring.

Awareness of the risks that relate to uncertainties in modelling, analysis and assessment is crucial for safe design. For this reason, Chapter 4 discusses the importance of uncertainties associated with reliability based quasi-static response assessment. Methods and criteria for reliability and risk-based structural assessment are presented in the context of structural capacity methods. Finally, a review of recent work and methods that consider existing and aged vessels with regard to risk-based inspection, maintenance and repair is presented.

Chapter 5 focuses on ship structures and discusses developments in international rules and regulations, followed by some specific ship types such as service vessels for wind mills and offshore platforms, container ships, and LNG/LPG tankers.

In Chapter 6, various types of floating and fixed offshore structures are reviewed. The chapter ends with a more specific discussion and review of methods for uncertainty, risk and reliability analysis of offshore structural analyses which are not covered by Chapter 4.

The committee has carried out a benchmark study where design against impact loads (slamming) was studied for a free fall lifeboat case. The results from the study are presented in Chapter 7, followed by a presentation of the conclusions and recommendations for future work and progress of the committee's work in Chapter 8.

2. STRENGTH ASSESSMENT APPROACHES

A wide variety of strength assessment approaches that may be used for the design assessment and structural optimisation of ships and offshore structures are available. Simplified solutions although conservative are usually applied at preliminary stage. More detailed, yet time-consuming and precise methods are usually applied for detailed design. Irrespective to their degree of fidelity available methods reflect three main aspects namely: (1) modelling idealisations/assumptions, (2) the process of load derivation and application onto the model, and (3) uncertainty modelling and quantification. Each of these aspects is introduced in separate sections of this report.

2.1 *Modelling of loads by quasi-static analysis*

Within the reporting period the development of suitable methods for the simulation and evaluation of quasi-static responses incorporating the influence of nonlinearities by multi-physics methods has proved challenging, particularly within the context of industrial applications. This is primarily due to the lack of unified validation studies or verification schemes that can limit the number of uncertainties related with the computation of wave-induced dynamic loads (Hirdaris et al. 2014a and Hirdaris 2014b). From a mari-

time classification perspective, the main advances within the committee's reporting relate to the implementation of mature (e.g. 3D linear seakeeping methods) or semi-mature (e.g. weakly nonlinear hydrodynamic) computational methods for the generation of the quasi-hydrodynamic pressures and their influence on dynamic response. In the short-term understanding the modelling assumptions and the influence of "weak nonlinearities" on quasi-dynamic response is considered as the obvious next step for design development. Medium to long-term use of multi-physics methods and their implementation on computational robust solvers may assist with the following:

- The idealisation of wave free-surface effects because of the nature of the free-surface boundary conditions and the nonlinear characteristics of the incident waves. Within this context it is now understood that the time-dependent change of position and wetted surface of the ship in waves often cause nonlinear hydrostatic restoring forces and nonlinear force contributions in way of the free-surface intersection.
- The idealisation of viscous force contributions that depends on the water velocity and introduces velocity-squared terms in the pressure equation.
- The need to design for optimum sagging/hogging ratios of loads especially for the case of the latest generation of ships that are long and slender (e.g. container ships).

Emerging multi-physics methods can be classified into three categories: (1) Rankine source/panel method, (2) frequency domain Green function method, and (3) time domain transient Green function method. In view of the importance of the subject and its impact on ship design, members of IACS Common Structural Rules for Bulk Carriers and Oil Tankers (CSR- BC&OT) recently compared 3D linear seakeeping method programs (IACS 2013c). In this study it was shown that wave-induced ship motions and loads obtained in way of different cross-sections and in different wave conditions are effective for conventional ships. In a more recent paper, Hirdaris et al. (2014a) reviewed a large number of different nonlinear methods for the forward speed problem. The methods reviewed are classified using six different levels (see Figure 1):

- level 1: linear,
- level 2: Froude-Krylov nonlinear,
- level 3: body nonlinear,
- level 4: body exact - weak scattered,
- level 5: fully nonlinear - smooth waves, and
- level 6: fully nonlinear.



Figure 1. Level of idealisation for forward speed hydrodynamic solutions. Numbers 1 to 6 refer to levels 1 to 6 of idealisation according to Hirdaris et al. (2014a).

In this range of methods one may distinguish between methods based on potential theory and those solving the Reynolds-Averaged-Navier-Stokes (RANS) equations (e.g. Stern et al. 2013). Within this group there is also a large variety of methods ranging from linear theories to fully nonlinear methods. Between these two extremes there are many partially nonlinear, or blended, methods, in which one aims at including the most important nonlinear effects. As techniques become more sophisticated assumptions become more complex and uncertainties may vary. Equally, validation, computation time and complexity may be an issue when we try to understand, simplify or validate the modelling assumptions (for example, see Eça & Hoekstra 2013). It appears that within the context of quasi-static/dynamic response the use of weakly nonlinear or fully nonlinear methods is feasible over the medium to long-term provided that validation efforts are extended and modelling assumptions are well understood. Another example of this is illus-

trated in the work presented by Southall et al. (2014), where a prediction of impact pressures on a dropping wedge using Computational Fluid Dynamics (CFD) has been compared against experimental results.

2.2 *Response calculation*

The approaches where the uncertainty in loads and structural resistance are covered by one or more safety factors are often referred to as the deterministic (or working stress design) approach, and as load and resistance factor design (or partial safety factor) approach. These methods are nowadays widely used for the design of ships and offshore structures. Within these classes of calculations one could further distinguish between more simplified, analytical or semi-analytical analysis and direct calculation methods, referring either to the way the quasi-static loads are derived or to the complexity of the structural model used. More and more, classification rules provide guidance on modelling and acceptance criteria based on either beam theory or direct calculations using the FE method.

For example, traditionally the design of Ultra Large Container Ships includes mandatory items such as quasi-static analyses of mid-hold, full-ship, and detailed fine mesh of local structures (LR 2013). In recent years with the advances in technology and design innovation it is required to also perform additional analyses of the influence of hull flexibility on dynamic response (LR 2014). Such methods specifically address the impact of springing and whipping for the evaluation of the ultimate strength and fatigue life of the hull structure. Plunging, bow and stern slamming analysis methods also emerge as the obvious mean of confirming hull scantlings (Hirdaris et al. 2014a).

Within the reporting period literature review presents a trend in the development of procedures for the idealisation and analysis of accidental limit states. For example, Nguyen et al. (2011) presented some of the key idealisation parameters for dynamic grounding scenarios (e.g. seabed shape, the initial height over the keel of the obstruction, the forces emerging from the penetration of the obstruction into the bottom of the ship) and associated estimates of the damage to a ship's bottom and seabed topology. In a similar type of study Hong & Amdahl (2012) developed a simplified analytical method for the predictions from numerical simulations of structural performance of double bottom ship groundings over shoal seabed obstacles with large contact surfaces of trapezoidal cross-section. The method was verified against FE results by Zhiqiang et al. (2011) and the verification was completed by comparing horizontal, vertical resistances and the distortion energy between seven numerical simulation cases by their simplified analytical method. Following a study by Khedmati et al. (2009) on the post-buckling behaviour and ultimate strength analysis of stiffened aluminium plates under combined axial compressive and lateral pressure loads, a set of empirical formulations or equations was derived by Khedmati et al. (2010). The purpose of this work has been to estimate the ultimate strength of stiffened plates under load combinations. The formulations were verified against numerical results and they may be useful for the ultimate strength reliability analyses of high speed aluminium made ship structures.

Yu et al. (2013c) introduced a theoretical model for the assessment of the structural performance of stiffeners in way of the double bottom floor plating under a shoal grounding accidental scenario. Their study introduced a set of numerical simulations that may be able to describe the progressive deformation of a ship's stiffened bottom structure because of the nonlinear effects of plasticity. They showed that the preferred method for modelling such accidental scenario is to smear the stiffeners into the plating thickness. A comparison of the results from FE simulations indicated that the proposed analytical model accounts satisfactorily for the dominant deformation pattern.

Within the reporting period, FE analysis remains the principal approach for investigating structural response under accidental loading scenarios that may be associated with grounding, collision, ice structure interaction or design for crashworthiness. For example, a few authors presented approaches where results from detailed FE analysis were parametrically combined to produce simplified structural response methods (for example, see Ehlers 2009, Ehlers 2010, Ehlers & Tabri 2012, Tabri 2010). In these papers the term engineering simplification reflects the derivation of combined numerical and semi-analytical techniques that could be used primarily for collision damage assessment procedures. Based on these developments it may be concluded that by using existing technology it is possible to apply an engineering procedure that considers the energy available for structural deformations as well as the damage extent for various collision locations, striking angles and collision velocities. Such engineering approach that allows for different accidental scenarios and load combinations may be significantly faster in comparison to a fully coupled numerical simulation.

Liu et al. (2011a) proposed an ice material model that can be used in FE analysis of ship-iceberg collisions. This model was used further by Liu et al. (2011b) to perform large deformation, elasto-plastic FE analysis of ship-iceberg collisions based on continuum mechanics. The authors concluded that the dissipated energy from an iceberg and foreship structure collision may be mainly determined by their masses and the relative velocity between them. Hogström & Ringsberg (2012, 2013) compared the so-called strength and ductile design approaches that may be used to improve the crashworthiness of ship struc-

tures. In their work the structure has been assessed against five criteria namely: (a) the intrusion depth, (b) the energy dissipation, (c) the damage opening area after the collision, (d) the weight, and (e) the manufacturing cost. They concluded that there is potential for mitigating the consequences of a collision between ships by replacing conventional side-shell structures. The authors recommend that the global parameters of the collision case should be based on statistical analysis to establish the most likely values. On the other hand, Koukounas & Samuelides (2013) addressed modelling aspects for the strength capacity of intact and damaged ship girders considering the criteria set by the IACS CSR-BC&OT. Zilakos et al. (2013) proposed a methodology that combines CSR fatigue loadings with the FE method for the study of cracks on actual marine structure subjected to high-cycle fatigue. The ultimate purpose of this work is to establish a common base for evaluating different crack arrest technologies by developing a three-compartment model of a tanker. Accordingly, stress intensity factors were calculated for different geometries and loading conditions, and growth rate of cracks was calculated using the Paris-Erdogan law. It was concluded that it is necessary to analyse fatigue cracks on a case by case basis due the variability in wave loads, structural configurations and boundary conditions.

2.3 Reliability

Reliability can be defined as the ability of a structure to comply with given requirements under the operational conditions it may experience through its service life. Probabilistic analysis methods because of their inherent variability are, in principle, capable to idealise the influence of such effects. In this sense reliability analysis may be used to measure the probability of structural failure by considering both the loads acting on a vessel and the resistance (strength) of the structure.

This section of the report classifies strength assessment approaches as follows: (0) deterministic approach, (I) partial safety factor approach, (II) approximate reliability analysis, and (III) fully probabilistic approach. Within the reporting period the first two approaches (0 and I) have been well used and implemented in design standards (see Chapters 3 to 6). Based on the allowable stresses design method (deterministic approach) the maximum acting stresses on a structure should not exceed the critical value of material strength divided by a safety factor. The disadvantage of this method is that it relies on the evaluation of a suitable safety factor that at the moment may not necessarily consider load combinations or the use of different materials. A more up-to-date method is the partial safety factor method (also known as the limit-state method) that allows for design optimisation, load combinations and different materials (for example, see BV (2014) and DNV (2011a)).

Class II and III approaches have the potential to provide a better indication of the structural reliability at the expense of more information and computational effort. Examples justifying this statement can be found e.g. in Zayed et al. (2013a) and Sobey et al. (2013). Taflanidis et al. (2013) addressed a simulation-based probabilistic framework for detailed estimation of the risk for tension leg platforms. Liu et al. (2014) established the probability density equation based on a crack propagation rate model, and then obtained the crack size probability density function that varies throughout the loading cycle.

In reliability-based design, the design value of the target reliability index can be derived by analytical probabilistic processes. For example, Gaspar & Guedes Soares (2013) assessed hull girder reliability using a Monte Carlo-based simulation method. Silva et al. (2014) used FORM techniques to analyse the ultimate strength reliability of a steel plate subjected to distributed and localized corrosion wastage allowance during the service life of a ship. Luís et al. (2009) studied the reliability of an accidentally grounded Suezmax tanker with the objective to determine the influence of the damage on the ultimate moment of the ship. In Deco et al. (2012) an efficient approach for the evaluation of ship reliability and redundancy including the effects of corrosion for aging vessels was presented.

The concept of probabilistic analysis can be used to calibrate the values of the partial factors in the Load and Resistance Factor Design (LRFD) methods. Faber et al. (2012) and Heredia-Zavoni et al. (2012) introduced a generic framework for consequence assessment and risk analysis of Floating Production Storage and Offloading (FPSO) units for the purpose of establishing structural design criteria including the scenarios considered for the risk-based calibration of design codes. Another example of reliability analysis to assess the implicit safety levels of the buckling strength requirements in IACS-CSR can be found in Gaspar et al. (2011). In this study they considered three modes of collapse because of: (a) uniaxial buckling of the plating between stiffeners, (b) column buckling of stiffeners with attached plating, and (c) lateral-torsional buckling or tripping of stiffeners. Using five oil tankers' designs that represent the range of application of the IACS-CSR design rules, they estimated the implicit safety level and variability of each buckling strength requirement. It was concluded that probabilistic design methods are very important for the design of special cases or novel structures where previous experience does not exist.

3. CALCULATION PROCEDURES

The degree of engineering complexity associated with different stages of the design process should be aligned with the degree of fidelity in methods of analysis that are used throughout the design assessment. For example, rapid assessment methods are needed in the early stages to assess global behaviour. More detailed modelling and analysis techniques are required for detailed design. This chapter presents a range of quasi-static engineering techniques that within the reporting period have been applied for design assessment. Special emphasis is attributed to the significance of qualifying the use of different technologies.

3.1 *Taxonomy of engineering assessment methods*

Analysis approaches range from first principles methods that can ensure that the structure is adequate at preliminary stage, to ultimate strength methods used at the detailed design stage, reliability analysis methods for lifetime prediction of loads, and optimisation analysis of the design for production loads modelling.

3.1.1 *Simplified analysis (rule-based design) / first principles*

Simplified methods are preferable for the assessment of ship structures during the early stages of the design process. Laakso et al. (2013) presented an analytical method for calculating the fundamental frequency of cabin deck structures in passenger ships. The method considers the structure as a combination of several structural members. Assumed mode shapes were created by using static bending equations. Corresponding frequencies were then calculated by Rayleigh's method. The method was validated against fine mesh FE analysis for a variety of typical design space boundaries.

Paik et al. (2013) modified the Paik-Mansour method for the case of pure vertical bending moment. The method is based on a "credible" bending stress distribution over the hull cross-section presumed at the ultimate limit state. The accuracy of this method is demonstrated through comparison with computations obtained using more refined methods, such as the nonlinear FE method, the intelligent supersize FE method (ALPS/HULL 2006), and idealised structural unit method used in the IACS-CSR. The comparisons showed that the modified Paik-Mansour formula was in very good agreement with both the nonlinear and intelligent supersize method and was shown to have good potential for the prediction of hull ultimate strength.

3.1.2 *Direct calculations*

Wilken et al. (2011) presented an efficient calculation method of Fluid Structure Interaction (FSI) in ship vibration. Their approach is based on reduction methods for the hydrodynamic mass matrix and uses fast solution methods for the exterior fluid problem when the velocity distributions of the shell are prescribed. By projecting the vibration equation into a set of semi wet modes they combine a typical Lewis method (Lewis 1929) with an advanced fast boundary element. The later yields accurate frequencies under forced vibration conditions. The FE software package ABAQUS was utilised by Van den Abeele & Verleysen (2013), who simulated the transient response of a subsea pipeline subjected to an underwater explosion. In their approach an explicit dynamic solver was used to tackle acoustic pressure and structural response, and to predict the behaviour of subsea pipelines exposed to an underwater explosion.

3.1.3 *Reliability analyses*

Hussein & Guedes Soares (2011) studied the ultimate strength and reliability of two single hull bulk carriers subjected to side collision and bottom grounding. The reliability calculations were carried out using the COMREL software (Gollwitzer et al. 1988), considering the distribution of the extreme values of the loads effects under different loading conditions. A sensitivity analysis was done to identify the importance of variables included in the used limit state function. Results showed that sagging is more critical than hogging. Reliability assessment of the damaged ships showed that the homogenous loading conditions represent the safest condition, while the ballast loading condition and the alternative loading condition provided low reliability.

Material reliability was investigated by Yu & Karr (2011). In this study the statistical data for ship steel strength suggested that best-fit probability density functions vary depending upon the type of steel and the type of failure mode. The authors made use of several distributions such as the lognormal, Weibull, or Gumbel to describe the yield stress, the ultimate stress and the failure strain. They selected several distribution functions for yield limit states of steels and studied the resulting reliability of a steel beam subjected to compressive loading conditions. In their approach the loading resultants were treated as random variables. It was concluded that the probability of failure can vary by orders of magnitude for similar nominal safety factors depending upon the type of steel or the yield function employed.

Kawamura & Miyazaki (2011) presented a method for structural optimisation with the main objective function defined as construction costs. The method was tested on the hold frame of a bulk carrier. One of the constraint conditions in the optimisation was the probability of failure in way of the hold frame. Life cycle cost analysis considered both the risk of failure and the frequency of re-coating (as part of the maintenance plan). It was concluded that by considering risks associated with life cycle costs and life cycle revenues CAPEX expenditure, safety and reliability are well balanced.

3.1.4 *Optimisation-based analyses*

Polic et al. (2011) identified the optimum shape for joint structures in terms of possible equivalent stress levels by using FE analysis-based procedures and a genetic algorithm for fatigue life prediction. A similar type of structural idealisation was considered by Yoon et al. (2011), who developed an optimisation method considering the basic functions generated from Non-Uniform Rational B-Spline (NURBS). Numerical examples for design-dependent design problems were demonstrated to verify the effectiveness of the proposed method.

Mao et al. (2014) focused on the dimensional optimisation study of the round-bilge craft taking the resistance as target. By multiple regression of the residual resistance, a fast method based on Froude theory was set up to predict the resistance. They demonstrated that after optimisation of the principal dimensions, not only the resistance may be greatly reduced but the seakeeping indexes are also greatly improved.

Hu et al. (2013) presented a study where the magnitude of wind loads acting on a jack-up unit according to ABS rules (ABS 2010) for Mobile Offshore Drilling Units (MODU) was questioned in the context of structure optimization. Following wind tunnel tests for a case study jack-up unit it was found that, in comparison with the wind loads calculated according to the MODU rules, the measured wind loads were lower. This discrepancy was explained by the aerodynamic interference between platform components, such as wind shielding effects and acceleration flow effects that are not considered by the MODU rules.

3.2 *Design for production loads modelling*

3.2.1 *Rules versus rational based ship design*

For years, classification rules considered only still water and seaway loads. To this end, the use of empirical formulae for the determination of the scantlings of structural members and the suitable arrangement of the ship's principal structure has been fundamental. *Quasi-static* load assessment has been defined in way of the so-called ultra-low frequency (still water) ship bending regime. This accounts for the differential distribution between weight and buoyancy forces. On the other hand, *quasi-dynamic* low frequency bending has been considered to occur in way of frequencies associated with the natural seaway. Considering that ship dynamics is primarily influenced by the time-dependent differential distribution between wave, buoyancy and hydrodynamic effects, it accounts for the majority of stress reversals during a ship's life time (Hirdaris et al. 2010).

However, market dynamics as well as advances in maritime technology and innovation have led to the development of new rules which are based to a larger extent on first principle approach. For instance, IACS CSR-BC&OT for bulk carriers and oil tankers suggests uniform safety margins and rationalise design assessment methods and criteria (IACS 2013a, b and IACS 2015). Accordingly, dynamic loads consider the influence of the characteristic vessel motions, accelerations and, as applicable, internal tank pressures. Dynamic loads associated with sloshing, local impact at the bottom forward, forward bow and green water on deck are also specified.

3.2.2 *Direct simulations for global quasi-strength assessment*

The design of a ship involves formulating an accurate model of the ship to analyse its response – internal and external – to its environment and the use of an optimisation method to determine system characteristics, while also fulfilling certain prescribed constraints on system characteristics and system response. A traditional rationally-based design according to classification society strength assessment procedure comprises of the following four key steps.

1. Stochastic prediction of external loads by quasi-static methods.
2. Estimation of the limit values of load effects for all load conditions and cases.
3. Evaluation of the minimum required margins between load effects and their limit values on the basis of a required degree of safety.
4. Analysis of the strength requirements based on design criteria that satisfy the design constraints.

For example, the above is well demonstrated by Payer & Schellin (2013) who presented an example for the case of a 13,000-TEU modern container ship. Their analysis and discussion concentrated on aspects related with the 3D overall FE idealisation of the ship structure and the mapping of quasi-hydrodynamic loads for the prediction of the overall response. More detailed hydro-structural modelling issues related with: (a) the application of quasi-hydrodynamic pressures, and (b) the combination of wave-induced dynamic loads, are discussed by Ma et al. (2014), Alfred Mohammed et al. (2012), and Papanikolaou et al. (2014). These methods use quadratic programming to calculate equivalent nodal forces so that the resulting hull girder sectional loads match those calculated by seakeeping analyses, either by strip theory methods or 3D panel methods. To validate the approach 3D panel linear codes (e.g. MAESTRO-Wave), may be useful. In the work by Alfred Mohammed et al. (2012) and Papanikolaou et al. (2014) a cross-spectral stochastic analysis methodology for the determination of the combination of global wave-induced dynamic loads by taking into account uncertainties associated with the wave heading, the joint probabilities of the wave environment and the correlations between different global wave-induced dynamic loads is introduced. This methodology considers the use of bivariate probability density functions or the covariances of two random variables with their associated derivatives and assumes only rigid body hydrodynamic actions under steady forward speed conditions. The design extreme values of principal global wave-induced load components and their combinations for a container ship progressing in irregular seaway were predicted using these two cross-spectral methods together with the short-term and long-term statistical formulations. It is shown that in general terms both cross-spectral analysis methods can be employed to assess the effects of loads in ship design and reliability analysis. However, the cross-spectral method predicted slightly higher load combinations than the cross-spectral probabilistic approach.

In all existing individual or common classification society quasi-dynamic strength assessment procedures the randomness of the ocean wave system is idealised in a statistical manner and in accordance with IACS Recommendation 34 (IACS 2001). Accordingly, standard wave spectra and directional spreading factors are used to describe the seaway mathematically and extreme lifetime loads are estimated from the seaway distributions. However, individual classification society direct simulation procedures differ on the basis of the quasi-design wave selection and evaluation of wave loads (see Table 1). Some classification societies use stochastic analysis to decide for the effects of long-term statistical analysis on the equivalent design wave loads (e.g. ABS 2006, BV 2006, DNV 2003, and KRS 2008). Others (e.g. LR 2013, 2014) use the design wave loads of the rule formulae, in which the combined dynamic effects of wave and ship motion are reflected, to apply equivalent static loads on the structural model. GL (2007) selects design waves satisfying the rule design wave loads, using seakeeping analysis for the evaluation of motions and employs an artificial static heeling for the additional torsional moment in the forward region of the ship. The following key fluid structure idealisation aspects remain common in all classification society approaches.

1. The structural analysis is performed for the extreme lifetime loads and the global strength is assessed.
2. The dynamic loads including inertia forces, the hydrodynamic pressures and, where applicable, internal pressures of liquid cargo induced by ship motions are transferred to the structural model.
3. In those cases that the pressure distribution over the hydrodynamic model is too coarse to be used for the structural analysis the pressure is interpolated linearly.
4. The unbalanced forces resulting from the difference between the hydrodynamic model and the structural model should be minimised.
5. The accelerations at the centres of elements, solid cargoes and liquid cargoes are calculated by the combination of critical motions.
6. The loading conditions are determined based on the loading manual. The most severe cases are selected for the global analysis.
7. The FE models used are discrete and follow the arrangement of primary structure like decks, stringers, bulkheads webs and girders. Strength response is verified against strength criteria of yielding, buckling, ultimate strength and fatigue strength. Since these criteria are the same in all cases, there is a unified safety level of structure all over the ship.
8. The hydrodynamic model comprises the hull form and weight distribution. The weight of the ship structure can be calculated from the global structural FE model using appropriate structural density. The structural density sometimes needs to be tuned to achieve the total weight of the ship structure taking account of local members, such as brackets, which are not contained in the global structural model.
9. Transfer functions are obtained through hydrodynamic analysis. Short-term analyses are performed for each irregular wave condition, namely modal period and significant wave height. For overall strength evaluations, i.e. long-term analysis, the wave loads are imposed using waves a vessel may encounter based on a probability of exceedance of 10^{-8} (IACS 2001).

10. The dynamic loads are represented by a series of load combination factors which represent the superposition of the various dynamic load components at a given point in time when the major dynamic load component is being maximised.
11. For fatigue evaluations, representative characteristic loads are used to represent the large number of modest fatigue-inducing fluctuating load ranges, which are based on a probability of exceedance of 10^{-4} . Since fatigue calculation results are very sensitive to load and corresponding stress range applications, the most representative characteristic loads are applied which strive to eliminate any large conservative assumptions. It should be noted that the follow-on fatigue calculation methods impose safety margins later in the applied method and acceptance criteria itself; hence, imposing additional conservatism at the load determination stage is not necessary.

Table 1. Design wave selection and wave load evaluation.

Classification society	<u>Design wave selection</u>		<u>Evaluation of wave loads</u>	
	Rule	Stochastic analysis	Rule	Ship motion program
ABS		X		X
BV		X		X
DNV		X		X
GL	X			X
KRS		X		X
LR	X		X	

3.2.3 Loads extracted from experiments and testing

The validation of loads on intact or damaged ship structures by model experiments and performance-based assessment is crucial within the context of design optimisation and design decision support. Within the reporting period there seems to be a strong trend in the area of developing and validating performance-based methodologies for the design assessment of damaged ship hulls operating under harsh or extreme environmental conditions using quasi-static methods. For example, Saydam & Frangopol (2013) presented a probabilistic framework for performance assessment of ship hulls under sudden damage accounting for different operational conditions. Their work considered the combined effects of sudden damage and progressive deterioration due to corrosion. The performance of ship hull was quantified in terms of ship reliability and robustness. The longitudinal bending moment failure was evaluated within the context of quasi-static response and was considered as the limit state. The longitudinal bending moment capacities of the intact and damaged ship hulls were assessed using an optimisation-based version of the incremental curvature method. In addition, aging effects on ship reliability were investigated. In a similar type of study Begovic et al. (2013) presented a study on the prediction of motions of a frigate hull. Their experimental campaign was conducted for two geosim models, 1:100 and 1:51 scales, at zero speed in head, beam and quartering seas. All experimental results for the 1:51 model were presented as 1st and 2nd order response amplitude operator, commenting on physical reasons for second-order response occurrences. The results show the changes in motion responses when a ship hull is in damaged condition. They highlight the model scale effects and demonstrated the comparisons between the tests in which the model may freely drift and those in which the mean position of the model is restrained.

More recently, Kukkanen & Matusiak (2014) presented numerical and experimental studies on nonlinear wave loads. The results from a nonlinear (transient) time domain Green function method were compared against experiments for a Wigley hull form in regular head waves. The influence of ship motions on vertical shear forces and bending moments in regular and irregular head waves and calm water were shown to be significant.

In response to wind farm vessels, Augener & Krüger (2014) realised a study about the computation of wave drift forces in regular and irregular waves for offshore wind farm installation vessels. In their study the longitudinal and transversal drift forces and the yaw motion induced wave drift moment were calculated using potential flow theory. Augener & Hatecke (2014) analysed the seakeeping of an offshore wind farm installation vessel during the jack-up process. The numerical computations were done with the seakeeping code E4ROLLS (Petey 1988). Besides the limitations through the dynamic positioning capability of an offshore wind farm installation vessel, there are structural limits for the legs of the vessel. The paper presents an analysis of the operational limits caused by the maximum acceptable impact loads on the legs from the sea bottom during the installation or retrieval conditions of the jack-up vessel, due to the motions of the vessel caused by the seaway. The design loads that were used were the axial and radial impact forces acting on the bottom of one leg, while the impact itself resulted from the ship's motion in a seaway. The results showed that the operational limits of these vessels are not necessarily dependant on impact loads.

3.2.4 *Loads from seakeeping codes*

A discussion for the different types of hydrodynamic idealisations was given in Section 2.1 of this report. In addition, Peng et al. (2011) proposed an effective prediction method for the slamming loads of trimaran structures based on model tests and the similarity theory. To investigate the slamming load distribution and its relation to the impact velocity, the authors performed drop tests of a trimaran cross sectional model. It was concluded that the peak pressure is proportional to the square of the impact speed and the effects of nonlinear factors, such as air cushion and splashing, are quadratically declining as the speed of impact increases.

3.3 *Structural modelling*

In recent years advances in computer technology enabled the development and implementation of improved FE modelling methods for the design of ships and offshore structures. This section presents a brief overview and examples of studies dealing with FE modelling, models for global and detailed analyses, and composite structures.

3.3.1 *Finite element modelling*

Element type

Within the reporting period considerable research efforts have been devoted into developing simple, robust, generalised and efficient element models. The use of conventional shell elements such as 4-noded or 8-noded quadratic shell elements is still broadly used. Rotation-free shell FE models have also been developed. In such idealisations the curvatures over an element are approximated in terms of deflection of nodes in way of the adjacent element patches.

Avi et al. (2013) presented an equivalent shell FE that may be used for the assessment of ship global and local static and vibratory response in the early stages of the design process. Their hybrid idealisation comprises of three layer laminate elements that represent the plate, the stiffener web and the stiffener flange. Accordingly, it accounts for in-plane membrane bending coupling and additionally shear stiffness. Numerical comparisons with 3D fine mesh FE idealisations demonstrated good agreement.

To address the issue of localised response, Gannon (2013) used FE analysis to simulate the weld overlay procedure for corrosion repair of pressure vessels considering especially resulting residual stresses and distortions. Their study investigated three different model types for the weld connection with changing element type, mesh configurations and material properties. It was demonstrated that the model with a high mesh density in the vicinity of the weld had the greatest accuracy regarding maximum distortion and residual stresses.

Model generation

In FE analysis a considerable portion of the total effort is still dedicated to model generation. In order to speed up this process the shipbuilding industry and classification societies are investing in sophisticated 3D CAD systems with automatic mesh generators such as the Sesam GeniE software (DNV-GL 2015).

3.3.2 *Models for global and detailed analyses*

Objective of global FE analysis is to identify:

- the stress levels on the plating of longitudinal hull girder structural members, and
- the buckling capability of plates and stiffened panels.

Meier & Lehmann (2012) investigated the accuracy of different (global) coarse FE approaches for modelling large openings such as holes in way of ship's floor. They concluded that, in order to have a more accurate behaviour under shear loads, it is necessary to represent the hole instead of reducing the thickness.

Fricke et al. (2014) discussed the importance of FE mesh idealisation used to model walls with window cut-outs. They concluded that modelling the correct shear stiffness of bulkheads in way of window cut-outs is critical. The authors highlighted that in FE modelling the fidelity of the mesh is quite important. Accordingly, rounded corners and/or insert plates should be modelled in detail unless shear stiffness is pre-determined either by FE computation or an analytical calculation.

Fine mesh models may be used at the detailed analysis stage to determine (a) the stress concentration factor of a complex structural geometry under a multi-axial loads or (b) hot spot stress in way of fatigue corners. Refinement methods were evaluated by Fischer et al. (2011), who presented the computation of the averaged strain energy in a cylindrical volume. The authors concluded that the most efficient approach to compute the Strain Energy Density (SED) is to perform a p -extension on a geometric mesh. If

FE computations are limited to low-order elements, geometric or radical mesh increase the efficiency significantly. Although in 2D the SED can be also computed with h -refinement strategies, the efficiency of high-order FE is very important. This is because 3D methods are not numerically efficient (Babuska et al. 1981).

3.3.3 *Composite structures*

Traditionally the application of composite materials relates to the constant need for weight reduction. Kunal & Surendran (2013) presented a work on the scope of using composites as major structural parts of large commercial ships. This work focused on the evaluation of quasi-static and impact loads by FE commercial analysis solvers (ANSYS and ABAQUS). Yang (2015) presented semi-analytical models that can be used for prediction of post buckling response and ultimate strength of imperfect composite plates. The models are based on a Rayleigh-Ritz method and can account for initial geometric imperfections, post-buckling deformations, out-of-plane shear deformations, and failure and degradation models for composites.

Jelovica & Romanoff (2013) carried out a theoretical investigation on the difference in the load-carrying behaviour between a web-core sandwich plate, a stiffened plate and an isotropic plate. Their study was carried out using two approaches, both solved with the FE method. The first method is based purely on the deterministic 3D idealisation of a sandwich plate. The second is based on the principle of the so-called equivalent single-layer theory of Reddy (2000). The results show that buckling loads of sandwich plates range from 42% to 65% higher than those of stiffened plates. This is because a sandwich plate is essentially a symmetrical structure for the cases where the coupling between in-plane and out-of-plane displacements does not exist. Furthermore, breadth-to-thickness ratio (representing local plate slenderness) is about two times lower in sandwich plates than in stiffened plates. Whereas the latter prevents local buckling, buckling loads may also reduce by increasing the transverse shear stiffness. Within the reporting period another emerging field of application is the use of composite modelling idealisations for the repair of damaged structures. For example, Avgoulas et al. (2013) studied the repairs in a cracked structural component on an Aframax tanker. According to IACS CSR-BC&OT, cracks of different lengths in two locations around the manhole of a hopper tank transverse web frame were evaluated. Different composite patch configurations were applied and studied for each crack case. Results showed that stresses are significantly reduced. It was demonstrated that the reduction of stress intensity factor after repair may range between 51% and 93% compared to the unpatched case.

3.4 *Structural response assessment*

3.4.1 *Buckling and ultimate strength*

Ozdemir & Ergin (2013) investigated the overall collapse of stiffened panels with imperfections under compressive loads, by considering the influence of different stiffener type, web height and plate idealisations on ultimate strength. They concluded that: (1) for angle type stiffeners the stiffness of stiffener components becomes more evident as the influence of nonlinear buckling becomes dominant; (2) when a torsional deformation of a flat or deep tee bar panel structure becomes large it is difficult to predict the stress in the stiffened plate with the beam-column model and it is necessary to consider the stiffener as a plate structure. Yanagihara & Fujikubo (2013) derived an analytical solution based on the elastic large deflection analysis to simulate the elastic behaviour of an isolated plate and stiffener under axial compression. The accuracy of their approach was validated by comparison with FE analyses and the buckling software PULS introduced by DNV (2002). Santos Rizzo et al. (2014) developed a simplified model based on nonlinear FE analyses to predict the ultimate loading capacity of stiffened panels under pure shear stress. Their parametric model allowed for variations in geometry and initial imperfections. Results compared to those calculated using DNV rules (DNV 2013b) and other studies (for example, see Santos Rizzo et al. 2014 for details), were found to be in good agreement. It was confirmed that the ultimate shear strength is sensitive to the magnitude and distribution shape of initial imperfections, except in cases when the material yield shear stress is achieved.

Tekgoz et al. (2013) discussed the effect of residual stress on the ultimate strength assessment of stiffened panels. The ultimate strength was evaluated for three FE models accounting for different residual stresses and boundary conditions in order to develop modified stress-strain curves which can be used directly for assessing the ultimate strength of stiffened panels. It was concluded that residual stresses decrease the first yielding point of the structure response and initial geometrical imperfections may also lead to strength reduction. While the structural capacity increases, the effect of residual stresses on the ultimate strength decreases. Beznea & Chirica (2011a, b) presented an investigation of post-buckling behaviour and estimation of global buckling ultimate strength of delaminated rectangular plates under shear. Their study considered the influence of the position and geometry of elliptical delamination on the changes in

the buckling behaviour of composite ship deck plates. The authors made use of a delamination model out of the software COSMOS/M, which represents damaged and undamaged part of the structure as layered shell elements, separated by a hypothetical plane containing the delamination. The two sub-laminates were modelled separately, with a surface to surface contact option, using 3-node shell composite element (SHELL3L in COSMOS/M). FE analysis was thought to predict well global buckling loads of composite plates on either side (i.e. sub-laminate) of the model.

Branner et al. (2013) worked on the numerical modelling of the buckling strength of composite laminates with delaminations. Nonlinear buckling and post-buckling analysis were carried out to predict the critical buckling loads. Their innovative modelling approach made use of 20-noded solid elements for every layer and results compared well with the multilayer shell element approach. Xu & Guedes Soares (2011) conducted a numerical study to analyse the influences of boundary conditions and geometry on the ultimate strength of stiffened panels under compression. Nine geometric configurations of stiffened panels were investigated including different boundary conditions for each case. It was concluded that clamped boundary conditions on plate edges may slightly increase the panel ultimate strength.

Silva et al. (2011) investigated the effect of nonlinear randomly distributed non-uniform corrosion on the ultimate strength of unstiffened rectangular plate that is subject to axial compressive loading. A series of plate surfaces representing different degrees of corrosion, its location and ages were generated by a Monte Carlo simulation. The results from nonlinear FE analyses were used in a regression analysis. Empirical formulae were derived to predict strength reduction because of corrosion with good accuracy to FE analysis results. To address the importance of imperfections such as initial deflection and welding residual stresses, Li et al. (2013a) developed simplified simulation methods based on equivalent loads. In these methods, the equivalent load of initial deflection is derived by coupling mathematical models describing shell bending and the equivalent load of welding residual stress. Their study showed promising results of the ultimate limit load in comparison to traditional direct calculation approaches and an experiment.

Wu et al. (2013) investigated the ultimate strength characteristics of a river-sea ship with large deck openings. An experimental research has been carried out for a model ship hull which was designed on the basis of the similitude theory. By means of the dimensional analysis, the similitude laws for both bending and torsion were derived. The numerical analysis results of the ultimate bending strength under a desired torque and the collapse behaviour at the ultimate limit state of the model ship hull from ABAQUS agreed well with experimental tests. It was concluded that the influence of torsion on the ultimate vertical bending strength may be significant. A similar study by Pei et al. (2014) showed good agreement between the test and the numerical models for the collapse behaviour and the ultimate strength.

Li et al. (2013b) presented a new approximate calculation method for the evaluation of ultimate bending moment of ship structures. For a typical stiffened panel a limit state analysis of strains and deflections was carried out. The ultimate bending moments of example ship-sections evaluated using this method showed relatively good agreement against experimental results, the simplified method introduced by Smith (1977) and nonlinear FE analysis. Yamada (2014) evaluated the residual Ultimate Longitudinal Strength (ULS) by comparing explicit FE analysis using LS-Dyna against Smith-type simplified analysis (Smith 1977) using the code MARS2000 of BV (2000). It was concluded that in intact conditions, the results for ULS are in good agreement. Residual ULS estimated by 3D FE analysis and that by the 2D Smith-type simplified analysis showed fairly good agreement in case of a damaged condition where the damage opening was included. However, in order to accurately predict residual ULS under high speed collision it was recommended to use a 3D FE model of the struck vessel to calculate a realistic damage opening size which thereafter is used in the following residual ULS analysis.

3.4.2 *Fatigue strength*

Within the reporting period research on fatigue strength using quasi-static methods concentrated on fatigue life predictions of cruciform joints with weld toe and weld root failure. For example, Fischer & Fricke (2013) evaluated the initial crack shape and its influence on the crack propagation analysis when using FE analysis. In this work different crack faces and shapes for weld toe and root failure arrangements have been simulated and compared against common approximate solutions. Sumi et al. (2013) investigated the effect of welding residual stress on fatigue crack growth lives of fillet weld with and without preloads. The as welded and after shakedown residual stress distributions were predicted by 3D uncoupled thermo-mechanical FE analysis. A crack propagation life of toe crack located at fillet welded joints was predicted based on a crack opening and a closure simulation method. Huang & Xiao (2013) investigated the fracture failure of longitudinal members including cracks. They employed the failure assessment diagram methodology to assess the conditions of failure at the crack tip, establishing an analytical formulation of the crack-tip condition. In their approach, which was validated against FE analyses, the material toughness is expressed in terms of crack-tip opening displacement. The failure stress of rep-

representative cracked members is evaluated as a function of the crack length. This enables determining critical crack lengths corresponding to the maximum stresses derived from extreme loads.

Pinheiro et al. (2013) studied the effect of deformations on the determination of Stress Concentration Factors (SCFs) for the case of low speed collision of a supply vessel with an FPSO's side panel. Accordingly they developed an FE model to simulate the side structure and the striking bulbous bow and conducted a parametric study considering different penetration depths. Based on these results they developed an analytical expression which gives SCFs as a function of the dimensions of the damage and the panel. The SCFs obtained were used in a theoretical fatigue life study to estimate the duration of residual fatigue life of a side panel collided by a supply vessel as a function of the damage magnitude. A similar type of study was carried out by Pasqualino et al. (2013). Their FE model was used in a parametric study considering different penetration depths of the supply vessel on the side panel, resulting in different damage magnitudes. The SCFs were estimated under the application of an in-plane compressive load in the panel, reproducing the loading undergone by the vessel beam. Results were used to develop an analytical expression, with the aid of the Buckingham theorem, that linearly fits the numerical data and gives SCFs as a function of dimensions of damage and panel.

Giuglea et al. (2011) developed an approach for fatigue assessment at early design stage using FE analysis. To overcome the challenges due to limited information in the early design stage, generic structural elements and pre-defined fatigue critical details were chosen. This allows for the development of a common approach for different ship types. Tanaka et al. (2011) adopted a shell-solid mixed analysis using semi-auto Rigid Body Element 3 (RBE3) in MSC.Nastran and the Virtual Crack Closure Method (VCCM) for quadratic tetrahedral finite elements, to evaluate Stress Intensity Factors (SIFs) in surface cracks of welded cruciform joints of a three cargo hold carrier. The shell-solid mixed analysis using the semi-auto RBE3 connecting technique was performed on the ship's structure. The SIFs were calculated using the VCCM for the quadratic tetrahedral finite elements. The solutions were compared with the SIFs calculated by the J -integral calculations of MSC.Marc. Thibaux & Cooreman (2013) determined SCFs for tubular joints using solid quadratic elements. In this work results from computations were compared with experiments and analytical expressions reported in literature and by ABS, DNV, the International Institute of Welding (IIW), and Lloyd's Register. It was concluded that whereas existing SCFs are not always conservative in way of the crown toe of the weld chord they tend to be over-conservative at the weld chord saddle.

3.4.3 Ship dynamics - vibrations

Boote et al. (2013) developed a detailed, global FE model for a 60 m super yacht with the aim to predict the critical vibration areas. In their work, resonances from the propeller forces were considered to affect the dynamic behaviour of the hull and superstructure. Comparisons of velocities, accelerations and frequencies to the maximum allowable levels from Bureau Veritas, Lloyd's Register and RINA were presented for both global and local vibrations. It was concluded that the FE idealisation presented considers most important parameters given by the classification societies. Mattioli et al. (2013) developed a new method for establishing the load history at a site in case of metocean climate including combination of several (up to 3 or 4) sea state components, such as those of main swell, secondary swell and wind sea. Their method is applicable to both extreme conditions and fatigue assessment. They also showed that long- and a short-term analysis with deterministic and probabilistic computation of vessel heading provide a reasonably conservative estimate of the vessel responses.

Rostami & Oskouei (2013) simulated the effect of seismic isolation (steel rubber bearings) installed on offshore jacket platforms (between the topside and jacket structures) located in seismic regions, by using the ANSYS FE software. A nonlinear FE model was applied for seismic assessment of isolated and unisolated platforms. Further on parameters for simulating isolators were defined. Their computational results demonstrated a reduction in displacement from 20% to 73% when real earthquake excitations were considered (El Centro 1940, Kobe 1995 etc.)

3.5 Validation of calculation results

Enhancing safety at sea through the specification and quantification of uncertainties related with the description of the environment and predictions of loads and responses is currently one of the main concerns of the shipping and offshore industry. These uncertainties play an important part in risk assessment for the design and operation of marine and offshore structures. Whereas measured values are used in the process of validating modelling techniques and associated assumptions both measurements and predictions in principle have errors associated with them. For example, high uncertainty of environmental description may lead to risks related with the seaworthiness of a ship. On the other hand uncertainties in the modelling of loads and responses may adversely influence design assessment.

As part of the mandate of ISSC and ITTC to encourage cooperation in areas of mutual interest and in order to address the subject matter of uncertainty qualification by the end of the last reporting period a workshop was organised by the ISSC I.1 Committee on Environment, ISSC I.2 Committee on Loads as well as the ITTC Seakeeping and Ocean Engineering Committees in 2012. Selected papers from this workshop have been recently published (Hirdaris et al. 2014b). The topics discussed by the workshop included:

- model testing,
- full-scale measurements,
- load prediction techniques,
- experimental validation techniques,
- utilisation of satellite measurements,
- extreme environmental phenomena,
- risk assessment and mitigation, and
- goal-based standardization.

In validating modelling techniques and associated assumptions, measurements, predictions and theoretical models are critical (Hirdaris et al. 2014b). Based on review by the committee the following sections discuss recent developments that relate with the evaluation or validation of quasi-static/dynamic loads by model experiments and full scale testing. Special emphasis is attributed to methods that may be used with the context of modern FSI idealisations, fatigue and ultimate strength assessment as well as loads modelling under extreme environments (e.g. ice).

3.5.1 *Model scale experiments and testing*

Coupling of different simulation approaches allows for the simulation of complex systems. One interesting combination was to simulate rigid bodies moving in a fluid. For example, Beck et al. (2013) demonstrated that a pendulum moving in a water tank is a simple example of a complex system for which several effects have to be taken into account in order to reproduce the dynamic behaviour. In this work, the simulation results for different immersion depths are compared against experimental data. The authors demonstrated that when using a coupled simulation it is possible to merge several advantages of different simulation techniques in one common simulation.

Bashir et al. (2013) presented results of towing tank tests carried out to predict the wave loads in regular wave conditions on a Deep-V hull form catamaran model. The experiments were carried out at the Newcastle University towing tank using a segmented model of the university's new research vessel, "The Princess Royal". The vessel is a twin hull with a Deep-V shape cross-section. The model, divided into two parts at the cross-deck level, was fitted with a 5-axis load cell at the position of the vessel's centre of gravity in order to measure the motions response and wave loads due to the encountered waves. The longitudinal, side and vertical forces, along with the prying and yaw splitting moments were measured. The results obtained were further compared with those from numerical predictions carried out using a 3D panel method code based on potential flow theory that uses Green's function with the forward speed correction in the frequency domain. The results highlighted reasonable correlations between the measurements and the predictions as well as the need for a proper understanding of the response of the multihull vessels to the wave-induced loads due to the nonlinearity that have been observed in the experimental measurements of wave loads.

Sloshing

Within the reporting period research on sloshing loads has been ongoing due to the absence of fully validated unified methods. An overview of the actual status of engineering developments in this area is presented by Malenica & Kwon (2013). According to the authors the methodologies proposed by the classification societies for the practical design verification containment systems are based on the so-called comparative approach which relies on the use of small scale model tests simulating intact ship operational conditions and target ships (e.g. LR 2009). The former are used to deduce the conservative pressure scaling factor and the same scaling factor is applied to the target ship. The resulting pressure loading at full scale is deduced and compared to the capacity of the containment system. Uncertainties relate with the scaling factor which does not have clear rational justification since it reduces hydrodynamic phenomena into a single number. Hence, challenges relate with: (a) how to scale the model test results, and (b) properly account for the structural elastic reactions considering that laboratory experiments are based on rigid models.

Recent research work that attempts to shed some light into the afore-mentioned problems has been carried out by Kim et al. (2012c, 2013a, 2013b, 2013c). The authors performed comparative study on

model-scale sloshing tests using a state-of-the-art 6 degree of freedom experimental rig as part of the International Joint Industry Project (JIP) PRESLO. This JIP was led by the Advanced Marine Engineering Centre of Seoul National University in association with IACS Classification Societies (ABS, Class NK, KRS, and Lloyd's Register) and Korean major shipyards (DSME, HHI, SHI, and STX). Sloshing experiments were carried out using a state-of-the-art 6 degree of freedom experimental rig able to evaluate the coupled influence of motions with sloshing loads under functional excitations corresponding to realistic sea state conditions. Comparisons of the statistical quantities from 1:50 and 1:70 model scale tests demonstrated that uncertainties at model scale may relate with peak pressures, sensor types and sensing diameters. A simplified method for the pre-screening of sloshing severity has also been developed based on comparisons between experimental and computational data.

Whipping and springing

Within the reporting period work on whipping and springing responses mostly relates to specific ship types such as Ultra Large Container Ships (ULCS). This is mainly due to their slenderness, operational speeds, and large bow-flare. Whereas the evaluation of the hydroelastic responses mostly aligns with the remit of the ISSC Committee I.2 on Loads, incorporation of the influence of such loads and load effects in the Rules for Ships implies the need to overall appreciate the influence of design innovation on design margins. Within this context the committee considered important to reference two key developments supported by IACS Classification Societies and academics namely: (a) the International JIP WILS (Wave Induced Loads on Ships) project initiated and led by MOERI (Maritime & Ocean Research Institute) (e.g. Kim et al. 2014, Lee et al. 2012, Lee et al. 2014, Southall et al. 2014, Tiphine et al. 2014) and (b) the EU FP7 project TULCS (Tools for Ultra Large Container Ships) (see IWWF 2012). Based on the committees' consensus it is recommended that based on these studies further publications demonstrating systematically the departure of key design assessment criteria from the quasi-static/dynamic to the hydroelastic region should be pursued further. For example, an experimental study on the bow-flare slamming loads of a 10,000-TEU container ship was carried out by Hong et al. (2014a). In this study slamming loads, vertical bending moment, and torsional moment were measured in regular waves and irregular seaways and for various speeds using a 1:60 scale model comprising of six segments connected by a U-shape steel backbone. Strain gauges were installed to measure structural responses and fourteen load cells were distributed in way of the critical locations of the bow-flare area. It was concluded that: (1) the fluctuation in the magnitudes of slams may be decreased when the impact forces are normalised by the instant surge velocities, (2) as the ship speed is decreased critical slamming induced loads are observed in way of the peak of the bow instead of the side cell bow waterline area, and (3) the magnitude of slamming loads is proportional to the square of wave amplitudes.

Fatigue strength

The rapid enlargement of the size of container ships has also led to the application of extremely thick plates in deck structures. This may grow concerns about the fracture toughness at the butt-weld with large amount of heat input, and the arrest toughness of brittle crack propagation in the base metal of such thick plates. Slamming induced whipping stresses might affect the fatigue crack propagation and the initiation of brittle cracks in container ships. Based on results from a relevant JIP on this subject run by the Japan Ship Technology Research Association (JSTRA), Sumi et al. (2013) presented two practical recommendations, that may prevent the brittle fracture of large container ships. Those are: (1) Ultrasonic Testing (UT) during ship construction should be used to detect and remove harmful flaws of welding joints, and may also confirm minimal fatigue growth in way of the welding flaws, and (2) sufficient brittle fracture toughness of the welding joints for the prevention of brittle crack initiation.

Engineering experience suggests that brittle fracture may lead to large-scale hull fractures. Accordingly, it is important to ensure the hull structural integrity by preventing brittle cracks from being initiated and also by providing proper means for arresting the brittle crack for those cases that crack propagation occurs. Recent work by Kubo et al. (2012) attempted to shed some light into the subject by carrying out a number of large scale and middle scale fracture tests for ULCS. They concluded that the required brittle crack arrest toughness value should be more than $6,000 \text{ Nmm}^{-3/2}$ to arrest brittle cracks in way of steel plates with thickness exceeding 50 mm.

The structural longevity of marine structures where anti-corrosion measures are inadequate is another area where understanding of uncertainties and their influence on quasi-static response may be important. Common repair methods aim to primarily replace damaged steel structures. Alternative repair methods suggest the use of patches made of composite materials. These methods account for the majority of the problems faced by conventional renewal repairs. For example the paper by Karatzas et al. (2013) demonstrates an experimental study of artificially corroded steel plates repaired with composite patches. The authors carried out tensile tests for eight specimens. The effect of aging was taken into consideration by three different aging scenarios. Part of the experimental results was subsequently validated with the use of

numerical simulations that encompassed cohesive elements so as to simulate the debonding procedure. Results showed that composite patch repairing was able to rehabilitate the defected steel plates and improve their load bearing capacity. The numerical results presented were found to be in good agreement against experiments.

Ultimate strength

An experimental investigation into the collapse behaviour of a box-shape hull girder subjected to extreme wave-induced loads was presented by Xu et al. (2012). Experiments were performed using a scaled tank model and sacrificial specimens with circular pillar and trough shapes. Prior to the tank tests, static four-point-bending tests were conducted to detect the load-carrying capacity of the hull girder. It was shown that the load-carrying capacity of a ship including reduction of the capacity after the ultimate strength can be reproduced experimentally by employing the trough type specimens. It was also shown from the multiple collapse tests that the increase rate of collapse becomes higher once the load-carrying capacity enters the reduction path while the increase rate is lower before reaching the ultimate strength.

Xu et al. (2013) presented a study on ultimate strength analysis of tanker hull. In order to obtain appropriate stress-strain curves for FE analyses, experiments on the collapse behaviour of stiffened panels were carried out using geometrically similar scaling from small-scale specimen to full-scale stiffened panels. The stiffened panel compressive ultimate strength test was designed according to geometrical scaling laws so that the output of the test could be used as representative of the stiffened panels of the compressive zone of a tanker hull subjected to vertical bending moment. The ultimate strength of a case study tanker hull was analysed by FE analysis using the experimentally developed master stress-strain curves obtained by the beam tension test and the compressive test of the stiffened panel. The results from the analysis were compared with results achieved by the progressive collapse method. Although not all parameters are scaled completely, for the full and smaller scale panels having the same collapse mode, the difference in the ultimate strength is less than 12% which indicates that the similitude of stiffened panels is still possible and practical.

In Wu et al. (2011), a structural model test method was introduced to study the ultimate strength of a high speed trimaran model structure. They applied similarity theory with FE analysis as input to the structural model design. To simulate the peak wave bending moment of the trimaran, three point bending was applied by hydraulic jacks during the ultimate strength test. Load stress and load displacement curves of the model and the global failure mode were obtained for the validation of FE analysis results.

Ice

The procedures to determine ice-induced global loads on a ship using full-scale data in accordance with the method proposed by the Hydraulics Centre of the National Research Council of Canada (HNRC) are described by Lee et al. (2013b). In this work 6 degree of freedom ship motions were found by processing the measured linear accelerations and angular rates (using the commercial sensor named Motion Pak II) under the assumption of rigid body motion. In addition, an algorithm and an analysis tool to estimate global ice load based on LabVIEW using the ship motion was developed. Full scale data were acquired while the ARAON rammed old ice floes in the high Arctic. Estimated ice impact forces for two representative events show 22-29 MN when ships operate in heavy ice conditions. In Ringsberg et al. (2014a), a similar model was presented that uses recorded motions of a ship that collided with a heavy ice berg or ice ridge. Results from predictions were found to be in good agreement with experimental measurements.

The other significant set of experiments includes improvements in lifeboat design. Full-scale field trials of a conventional lifeboat in pack ice have yielded insights into the design and operation of evacuation craft in ice. The multi-year trials program used an instrumented lifeboat to investigate design considerations such as powering and propulsion, hull form, manoeuvring, ice loads and ergonomics, as outlined by Simões Ré & Veitch (2013). Operational issues that have been examined include ice management for emergency evacuation, coxswain competence and training. Local loads were measured on an instrumented panel near the waterline on the port shoulder of a lifeboat during a field trials campaign that spanned several days. This panel was subjected to impacts with ice during a series of transit tests in reasonably well-controlled field conditions. The lifeboat experienced impacts on other, un-instrumented parts of the hull, which included the stem where the largest loads were likely experienced. Most of the measured loads were well below the estimated ultimate strength of the lifeboat hull material. The highest measured load was less than 40% of the estimated ultimate strength. By the end of the test program, which included ramming and backing cycles, there was no evident damage to the hull. Hence, under the ice conditions to which the lifeboat was exposed in the field campaign, the fiberglass structure was adequate. To increase knowledge about how ice loads affect the performance and safety of ships, Suominen et al. (2013) manipulated data from a full scale ice trial data on S.A. Agulhas II that took place in the Baltic Sea in 2012. These measured ice load data were compared with load prediction approaches given by the Finnish-Swedish Ice Class Rules (FSICR) and the International Association of Classification Societies' (IACS). For the bow areas, measurements and class predictions were found to be at the same

point of magnitude. This was not the case for the stern area during manoeuvres where load values from Class Rules (FSICR 2010, IACS 2011) were found to be too low.

Collision

Knowledge about the level of structural damage after a collision is necessary for designing ships and offshore structures operating in ice-infested waters. An understanding of the physical processes during such a collision is necessary to prevent (or limit) accidents, causing loss of life, the loss of a ship or environmental pollution. Accidental Collisions with Ice Masses (ACIM) laboratory tests are sensitive to structural design, i.e., the design of a structure that is flexible enough in relation to the ice mass. In such cases both ice and structure should be able to deform during the collision event. Kim et al. (2013d) address issues related to the planning of ACIM at laboratory scale with special emphasis on the choice of process of ice manufacturing and ice mechanical properties, flexibility of impacted structure and scaling of the experiment.

Schöttelndreyer et al. (2013) reported on the current state of the SideColl JIP. Based on recent developments from this project for the case of a ship-ship collision, the struck vessel normally reacts as the weak collision partner. The influence from uncertainties in material characteristics and collision scenario-related parameters on the damage opening size and shape was investigated by Hogström & Ringsberg (2012). In Hogström & Ringsberg (2013), four ship structures were assessed with regard to their crash-worthiness. Most of them need a general redesign of the ship structure; hence it is difficult to implement them only in critical parts of a ship. As a result, the Institute of Structural Mechanics of the University of Rostock proposed an alternative stiffening system for double hull side. The basic idea of this design was to connect the bulbs or face plates of two neighbouring profiles with a curved shell without changing the conventional structure. This alternative stiffening system was shown to significantly increase the collision resistance, but requires further investigations with respect to manufacturing as well as experimental and numerical investigations which demonstrate the influence on collision safety. In addition, Buldgen et al. (2013) presented a simplified analytical model of collision between two ships. By use of “super-elements” they developed a new formulation for the estimation of impact resistance in way of inclined ship side panels. They defined a super-element that may give the crushing resistance with respect to the penetration of the striking ship. It was concluded that the numerical approach may lead to crushing forces that are lower than those obtained using the FE software LS-Dyna. This could be attributed to the strain hardening and the bending of the uppermost deck which are not taken into account by the numerical model.

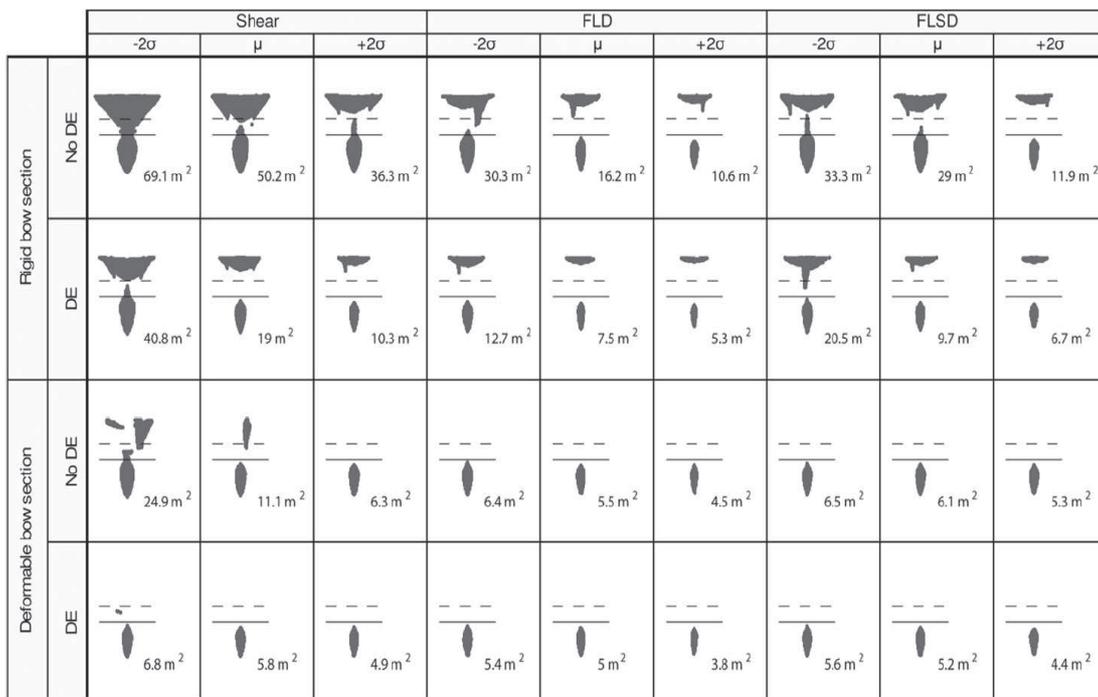


Figure 2. Results from FE analyses presented in Hogström & Ringsberg (2012) on how material characteristics modelling, uncertainty in material parameters and striking bow stiffness influence the size and shape of the struck vessel’s damage opening in the inner side shell.

Evaluation of ship collision safety is traditionally carried out with the striking ship assumed to be rigid. This approach is in line with the approach of classic safety assessments (NORSOK 2004). In a recent study Hogström & Ringsberg (2012) demonstrated that by systematic FE analyses the stiffness of the striking and struck vessels may also have significant influence on the size and shape of the damage opening (see Figure 2). Hence, the safety level can be increased significantly if the design of bulbous bows considers the influence of the aspect ratio of the bulb over the hull depth under the state of collision. In a similar type of study Tautz et al. (2013) reported on collision experiments, with rigid and deformable bulbous bows driven against double hull side structures, carried out in the test facility of the Institute for Ship Structural Design and Analysis of TUHH in Hamburg, Germany. Their work may be considered as good reference with regards to the level of maturity of numerical models against experimental results.

3.5.2 Full scale hull stress monitoring

Larger and larger ships are built and their ship motions and dynamic structural responses must be better understood. Most new advanced ships have extensive data collection systems to be used for continuous monitoring of engine and hull performance, for voyage performance evaluation etc. Information from these systems is also a valuable source for the further development of quasi-static response design methods for future larger ships. Nielsen et al. (2011) recommended that such systems could be expanded to include procedures for stress monitoring and for decision support, where the most critical wave-induced ship extreme responses and fatigue damage accumulation can be estimated for hypothetical changes in ship course and speed under real operational conditions.

During full scale measurements it is impossible to measure directly the hull girder loads. Bigot et al. (2013) demonstrated that different procedures may be used to obtain the internal loads from strain measurements and the process of data processing can be carried out in two steps: (a) the distortion modes should be incorporated in the structural model, and (b) a conversion matrix may be used to project the measured values on these distortion modes and the internal loads may be obtained by recombination of their modal values. The slamming behaviour of a large high-speed catamaran has been investigated through the analysis of full-scale trials data and presented by Jacobi et al. (2013). This work presents sea trials carried out by the US Navy in the North Sea and North Atlantic region on the 98 m wave piercer catamaran, HSV-2 Swift, designed by Revolution Design Pty Ltd. and built by Incat Tasmania. For varying wave headings, vessel speeds and sea states the data records were interrogated to identify slam events. An automatic slam identification algorithm was developed, considering the measured rate of change of stress in the ship's structure coupled with the vessel's pitch motion. This helped with the identification of slam occurrence rates over a range of operational conditions. The slam events have been further characterised by assessing the relative vertical velocity in way of slamming impacts. Since the ship was equipped with a ride control system, its influence on the slam occurrence rates has also been assessed.

A slightly different approach was applied by Storhaug & Hareide (2013) who assessed the responses of an ocean going vessel. Due to experience with whipping and springing, special attention to these effects was also made during the design and approval. The vessel was consequently strengthened beyond the minimum industry standard. It was concluded that since the measured fatigue life based on SCFs of 2.0 has been estimated to be well below the design life, special attention on cracks need to be taken from now on if the trade remains the same in the future. However, no cracks have been identified so far during inspection. The maximum loading level has been higher than ever assessed by DNV before based on hull monitoring data of blunt vessels. The rule of thumb value of 20% increase on extreme loading for blunt vessels due to whipping has been exceeded. The wave bending moment according to IACS URS11 has also been exceeded without whipping. The ultimate collapse strength has been assessed and compared to the measured dynamic loading and allowable still water loading. When whipping is assumed fully effective to contribute to collapse, the safety margin is still above 1.0, but on the borderline of what is desirable. However, if the vessel had not been strengthened beyond the original design due to the concern of whipping and springing, the safety margin would have been below 1.0. This may be the first documentation of a vessel that has been saved from breaking in two due to addressing springing and whipping properly during design.

Söder et al. (2012) presented a method for monitoring of racking-induced stresses in Ro-Ro ships. Their approach assumed that racking stresses are mainly induced by roll and sway motions and therewith related inertia and gravity forces. The method has been applied to full-scale measurement data from the Wallenius Lines PCTC Mignon. Derived stresses showed good agreement with stresses derived from strain gauge measurements, indicating that the method may be used as an alternative to conventional strain-gauge-based monitoring. Motion-based stress monitoring has several potential areas of application such as providing data for decision support, for live assistance and short-term route planning, structural condition reports and for supplying feedback to the design process.

4. UNCERTAINTIES ASSOCIATED WITH RELIABILITY-BASED QUASI-STATIC RESPONSE ASSESSMENT

4.1 *Uncertainties associated with loads*

The uncertainties of loads and structural responses are important parts in the development and application of the reliability-based design, assessment, inspection, maintenance, and repair methodology for marine and structural engineering. Therefore, the studies on uncertainties and their assessment methods have been and continue to be a large area of active research in marine structures; see Section 3.5 for a review of work on validation of calculation results. This chapter focuses on the recent developments in uncertainties associated with reliability-based quasi-static response assessment since ISSC 2012.

4.1.1 *Still water and wave loads*

Chen et al. (2013) presented a rational reliability-based assessment procedure for hull girder ultimate strength assessment of ship-shaped FPSOs. The stochastic model of still-water bending moment was established based on the loading conditions from the operation manual of FPSOs. A stochastic model was proposed to represent the probabilistic characteristics of the extreme value of Vertical Wave-induced Bending Moment (VWBM) based on its long-term distribution and the extreme value theory. The effects of the return period of the VWBM, environment severity factor, and corrosion effects on hull girder reliability index were also investigated. Through sensitivity analysis it was concluded that the most uncertainties relate with the ultimate strength bending moment. Garrè & Rizzuto (2012) developed a model for the assessment of the still water bending moment of a tanker after collision. The position and extent of the damage was modelled probabilistically. Results were compared in the light of the different features of the input probabilistic models, and interpreted in terms of a ranking of the various situations according to their probability of occurrence, the magnitude of the generated load effect and the spatial correspondence between the maximum bending moment and the damaged area. The method was also used to provide information for the selection of accident scenarios and design values for the maximum still water bending moment.

Karmakar et al. (2013) estimated the long-term joint probability distribution of extreme loads for different types of offshore floating wind turbines by using the environmental contour method. In this work the FAST code was used to simulate the wind conditions for various return periods and the design loads of various floating wind turbine configurations. Rajendran et al. (2013) investigated the relative motion and bending moment of a cruise vessel in extreme seas, looking in particular at the probability distribution functions of ship responses in irregular seas by comparing time domain simulations with model tests. Accordingly, the quality of numerical predictions was assessed by validation of empirically derived probability distributions. Zhang et al. (2013b) employed the Weibull distribution fitted method and the stack method to estimate the statistical value of wave loads induced by irregular incident waves and obtain the long-term extreme value under a particular exceedance probability. Their work identified that the main factors which may influence the long- or short-term prediction of quasi-static loads are the wave spectrum, the wave scatter diagram, the incident wave angle interval and last but not least the frequency interval. On the other hand, Si & Chen (2012) developed a method which could predict slamming pressure directly for a vessel of unconventional hull form based on the probabilistic method proposed by Ochi (1964). In this work long-term slamming pressures are predicted by a Monte Carlo method that makes use of the instantaneous values of ship motion responses and slamming coefficients. Numerical results show that slamming excitations in way of the peak and the trough of a wave will generate higher pressures. The effect of relative velocity between the ship and the wave on the slamming coefficient varies with different waves.

Abu Husain et al. (2013a) presented an efficient time simulation method to predict the probability distribution of the extreme values of quasi response based on the correlation between the response and its corresponding linear response extreme values. Their method seems to be efficient for both low- and high-intensity sea states. Wang et al. (2013b) investigated the suitability of three different probability distributions for modelling of extreme responses by comparing them with empirical distributions obtained from extensive Monte Carlo time simulations. A mixed probability model consisting of both the generalised extreme value and the generalised Pareto distributions was introduced to model the extreme responses.

Mallahzadeh et al. (2013) proposed a very efficient time simulation procedure to predict the probability distribution of the extreme responses based on a simple algebraic relationship between extreme responses and their corresponding wet surface elevation. The case study demonstrated that accurate predictions of the probability distribution of extreme responses can be obtained by a limited number (< 200) of short response records (say, about 2-minutes each). A similar type of research was carried out by Kurian et al.

(2013). They developed the statistical models based on the collected data of jacket platforms which were under construction at an ISO certified fabrication yard in Malaysia. The statistical analysis of the data was performed and a Monte Carlo simulation technique was used to generate values for fundamental resistance variables using statistical distributions. The authors issued recommendations on the reliability analysis of tubular members and joints. It is thought that their approach would be useful within the context of assessing the ultimate limit state design of jacket platforms.

4.1.2 *Ice loads*

Ji & Liu (2012) presented a state-of-the-art literature review on the area of ice loads on ships. They identified a number of strategic research directions related with: (a) the evaluation of pressures due to local and global ice loads using numerical models, (b) the importance of comparing numerical approximations against full-scale field observations and model tests, and (c) the need to understand the influence of operations such as manoeuvring and mooring on the global and local ice loads.

In a more focused type of work, Zhang et al. (2013a, 2014a) presented a mathematical model for calculating the geometric probability of ship-ice collision and carried out the studies of ship-ice collision loads by using numerical simulation and model test. Taylor & Richard (2014) developed a probabilistic ice load model to simulate ice loads during level ice interactions with a rigid structure based on the ensemble behaviour of empirical high pressure zones. The relationships between individual high pressure zones and the spatial-temporal distribution of high pressure zones during an interaction were presented. Preliminary results obtained from the proposed model were compared with the existing empirical models of local and global ice loads acting on offshore structures. Zvyagin & Sazonov (2014) presented an ice load model based on a stationary stochastic process with a lognormal distribution. In this work the simulation algorithms for the correlated lognormal processes was described in detail. It was concluded that the proposed theoretical model and simulation algorithm provide fast way for probabilistic modelling stationary ice loads process with lognormal distribution.

4.1.3 *Combination factors*

Mohammed et al. (2012) presented a cross-spectral stochastic analysis method for the combination of global wave-induced dynamic loads by taking into account uncertainties associated with the wave heading, the joint probabilities of the wave environment and the correlations between different global wave-induced dynamic loads. The design extreme values of principal global wave-induced load components and their combinations for a container ship progressing in irregular seaways were predicted by using two cross-spectral methods together with the short-term and long-term statistical formulations. The comparative studies of cross-spectral probabilistic method and cross-spectral Hamilton's method showed that both cross-spectral analysis methods can be employed to assess the effects of loads in ship design and reliability analysis. However, the cross-spectral Hamilton's method predicted slightly higher load combinations than the cross-spectral probabilistic approach. Papanikolaou et al. (2014) presented recent advances in modelling the combined hydrodynamic responses of ship structures using cross-spectral combination methods and in implementing uncertainty models used for the development of modern decision support systems as guidance to ship's master.

Huang & Xiao (2013) performed a comparative study on the extreme values of the combined still water and wave load effects of oceangoing ships obtained by the Monte Carlo simulation and the theoretical methods. The obtained results show that there is very good agreement between the numerical simulation and theoretical methods. The empirical distribution of the combined extreme values simulated and numerical theoretical distribution based on a load combination analysis can both be well fitted to an analytical extreme value distribution model of Type II. Teixeira et al. (2013b) calculated the probabilistic characteristics of the load combination factors for still water and wave-induced longitudinal bending moments of double hull tankers. The predictions of the different load combination methods were assessed based on the sample of five oil tankers adopted during the IACS-CSR design rules development process. A parametric and an uncertainty propagation study were then performed to identify the range of variation and the probabilistic models of the load combination factors that are applicable to double hull tankers. The obtained results have shown that: (i) the average load combination factors of the tankers decrease rapidly when the design period T decreases from 1 to 10 years, then tend to stabilize and that the mean voyage duration demonstrates a strong influence on the load combination factors; (ii) the average load combination factors of still-water bending moment and wave-induced bending moment is 0.97 and 0.85 for double hull tankers in full load for the design period $T=1$ and 20 years respectively; (iii) the average load combination factors of wave-induced bending moment is 0.84 and 0.81 for large and small tanker in full load for a reference time period of 20 years, and reduce to 0.8 and 0.76 in ballast load, respectively.

4.2 *Uncertainties in structural modelling*

4.2.1 *Corrosion*

Corrosion is a process of uncertain nature governed by many variables. Therefore, only probabilistic models can describe the corrosion process itself and its effect on the strength of structural components. Melchers (2012) presented a review of recent developments in the prediction of the likely future corrosion losses and of the maximum pit depth for steels exposed to marine environments. The review was made for some typical applications, including marine corrosion of ship ballast tanks, corrosion of sheet piling in harbours and corrosion of offshore platform mooring chains. A robust mathematical model based on corrosion science principles was calibrated over a range of immersion conditions published in open literature. These comparisons provided useful explanations for the effects of steel composition, water velocity, depth of immersion and seawater salinity and it also facilitated new interpretations of data for long-term pitting corrosion.

Jiang & Guedes Soares (2012) performed a series of nonlinear FE analyses on plates with partial and through thickness corrosion pits. The effects of the radius, depth and location of corrosion pits and the slenderness of plates on the ultimate capacity of mild steel rectangular plates under uniaxial compression were investigated. The results obtained show that the volume loss dominates the degradation of the compressive capacity of pitted mild steel plates in addition to plate slenderness. Single side distributed pits affect plates more than the double sided pits. Teixeira et al. (2013a) and Teixeira & Guedes Soares (2013) proposed the probabilistic model for the ultimate strength of corroded plate. The spatial variability of corrosion wastage of plate was represented by a random field generated by using Monte Carlo simulation.

The corrosion addition methods are widely adopted in structural design of individual classification societies, including CSR-BC&OT. Paik et al. (2013) investigated the historical trend in corrosion additions in the structural design of ships and the effect of corrosion additions on the ultimate strength performance of four double hull oil tanker structures, including Panamax, Aframax, Suezmax and VLCC. The ultimate strength of hull girders was investigated in terms of the gross, half-corrosion margin deducted, and net scantlings. The corrosion addition models specified by DNV Rules (DNV 2005) and CSR (IACS 2006) were compared with a time dependent corrosion wastage model and the corrosion models suggested by the Union of Greek Shipowners. Empirical formulas were proposed for the ultimate longitudinal strength performance of double hull oil tankers for the different corrosion addition rules. In a follow up study Kim et al. (2014) developed a Residual strength-Damage index (R-D) diagram by taking into account the time-dependent corrosion wastage effects. The method was tested for an Aframax class double hull oil tanker that had sustained grounding damages and suffered from corrosion at selected time intervals. The influence of those on net scantlings as specified by CSR was applied to gross scantlings using ALPS/HULL (2006).

Kwon & Frangopol (2012b) analysed the reliability of ship hull girder structures by considering uncertainties in ultimate bending capacity and sea loads. The ultimate bending moment capacity was predicted by time-variant random functions associated with corrosion and fatigue cracking. Still water and wave-induced bending moments were calculated using design-oriented and simplified direct methods considering different sea states as well as different ship operating speeds.

Mohd et al. (2013) developed a time-dependent corrosion wastage model for aging subsea gas pipeline. The proposed empirical model gives simplification on the prediction of the pit depth of a gas pipeline at any given age by manipulating the scale, shape and location parameter of the probability density distribution with respect to time. It was found that the pit depth of gas pipeline structure at subsea condition significantly increases with time and its corrosion progress can be modelled by 3-parameter Weibull distribution.

As an alternative to the traditional uniform corrosion model, Htun et al. (2013) introduced a random field model based on the Karhunen-Loeve (K-L) expansion method, introduced by Ghanem & Spanos (1991), to represent the stochastic properties of corroded plates. The stochastic properties of the minimum cross-sectional area of a corroded plate generated by the random field model were estimated as a reference index. In a similar type of work Htun & Kawamura (2013) employed the random field model based on K-L expansion method to generate the hypothetical corroded surfaces. The random characteristic of minimum cross sectional area of the plate with random field corrosion is calculated as a reference index of strength reduction by using polynomial chaos expansion method as well as Monte Carlo simulation. The results showed that the strength reduction of the plate with random field corrosion was smaller than the one obtained for uniform corrosion. Kim et al. (2012a) studied the ultimate longitudinal strength of five different sizes of container ships to investigate the impact of considering aged corrosion effects throughout a ship's life. The motivation to the study was to show the necessity of corrosion

addition application to container ships and the relevant predictions regarding decreases in the longitudinal strength of new-building container ships after corrosion.

Mohd et al. (2014) assessed the reliability of ageing gas pipeline structures due to corrosion pits. Measurement data for gas pipeline corrosion pit depth were collected and the statistical characteristics were quantified by statistical analysis. The authors also reviewed available mathematical tools for the reliability assessment of marine structures presented by Garbatov & Guedes Soares (2011). It was shown that these models may allow for the existence of multiple cracks both in way of stiffeners and plating. Within this context corrosion growth may be realistically presented as a time-dependent process. This study recommended that greater emphasis should be given to the use of structural monitoring systems, not only for decision support but also within the context of life cycle ship design and condition maintenance schemes.

Saydam & Frangopol (2013) presented a probabilistic framework for performance assessment of ship hulls under sudden damage (grounding and collision accidents) accounting for different operational conditions. Aging effects on ship reliability were investigated, i.e. the combined effects of sudden damage and progressive deterioration due to corrosion. The performance of ship hull was quantified in terms of ship reliability and robustness.

4.2.2 *Structural characteristics*

Akpan et al. (2012) presented a methodology for reliability assessment of damaged ships. The methodology recognises the existence of uncertainties when dealing with damaged ships and suggests a six-step process, including: (i) definition of ship characteristics and operational profile, (ii) determination of damage size and scenarios by 2D/3D model representation of the damaged vessel, (iii) estimation of loads on the damaged ships; (iv) estimation of the ultimate strength of damaged ship sections, (v) estimation of the deterministic structural integrity of the damaged vessels, and (vi) estimation of the probabilistic reliability of the damaged vessel. Ivanov (2013a) did a probabilistic calculation of the hull girder strength of a bulk carrier. The calculation was based on a probabilistic representation of wave-induced and still water bending moment and resulted in the development of a probabilistic model of the hull girder section modulus (elastic and plastic) including the influence of corrosion. In another paper (Ivanov 2013b), presented a simplified method for the calculation of hull girder section modulus that was compared with his probabilistic approach when also accounting for the influence of corrosion.

Decò et al. (2012) presented a framework for the assessment of structural safety of ships under different operational conditions by evaluating performance indicators such as reliability and redundancy. Reliability and redundancy were based upon the evaluation of the flexural capacities associated with the ultimate hull girder failure and the failure of the first stiffened panel of a selected cross-section. Aging effects due to corrosion were also investigated. The approach was applied to a naval catamaran vessel (Joint High Speed Sealift) and results were presented in the form of polar representations of reliability and redundancy for different operational conditions. In extending this work Decò & Frangopol (2013) discussed the development of a risk-informed decision tool for the optimal mission-oriented routing of ships. In this work hull strength was computed by FE modelling of the midship section. The approach considered the influence of different levels of damage and the response surface methodology was used to model the uncertainties associated with geometry and material properties under different operational conditions. Saydam & Frangopol (2013) further developed the methodology for performance assessment of ship hulls that have undergone gross damage due to grounding or collision incidents. The combined effects of damage and progressive structural deterioration due to corrosion were also investigated and applied for the case of an oil tanker. The variation of reliability and robustness indices for different operational conditions are again presented in polar plots with one half of the plot associated with performance in sagging and the other half associated with performance in hogging. The methodology is used in a number of case studies. In one of them, it is shown that some operational conditions result in significant reduction in the performance of a damaged hull. In general, the worst performance is obtained under head sea, and the effect of the sea state becomes more dominant when ship speed is increasing.

Zhu & Frangopol (2013) presented an approach for reducing the uncertainty in the performance assessment of ship structures by updating the wave-induced load effects with the data acquired from Structural Health Monitoring (SHM). The initial information on the wave-induced load effects was calculated based on strip theory. Bayesian updating was used to estimate the parameters in the Rayleigh and Type I extreme value distributions which were in turn used to model the peaks of wave-induced vertical bending moment and the largest values of the peaks, respectively. Time-variant reliabilities before and after updating were evaluated. The study concluded that use of SHM data may reduce epistemic uncertainties.

Teixeira et al. (2013b) presented an approach for the assessment of the response of a structure with random properties. Their approach considers the so-called “level of certainty” method that uses all of the input random parameters and a more accurate first-order second moment sensitivity approaches to predict

the percentiles of the response. The ultimate strength of a corroded steel plate with random initial distortions and random material and geometrical properties predicted by semi-empirical design equations or by means of nonlinear FE analyses was adopted as a case study to demonstrate the accuracy of the proposed approach. The percentiles of the ultimate strength of the plates calculated using these simplified approaches were compared with the ones obtained by Monte Carlo simulation. Hull girder reliability assessment based on ultimate hull girder collapse of the midship cross section or its local failure due to yielding or buckling of one of its structural elements was discussed by Gaspar & Guedes Soares (2013). The geometric and material properties of the midship cross section elements were modelled as random variables.

Zayed et al. (2013b) studied the lifetime reliability of ship hull structures subjected to corrosion degradation, including the effects of inspection and repair actions. The uncertainties in an inspection were accounted for by a practical probabilistic model. Accordingly ship loading uncertainties were modelled based on the time ratio spent under each loading condition during the ship's service life. Prestileo et al. (2013) studied the hull girder reliability of a crude oil tanker with bottom damage. They examined a number of possible flooding configurations, each one caused by a group of damage cases, characterised by different location and extent. Static loads, wave loads and residual structural resistance were determined for each damage case, with the objective of obtaining a prediction for the probability of the hull girder's failure. A probabilistic Bayesian Network model was generated to deal with the interdependencies of different variables.

4.2.3 Reliability and risk-based structural assessment

Risk-based ship design is based on risk and reliability analysis as opposed to rule based ship design, which is based on prescriptive, empirical rules (Papanikolaou 2009). When risk-based design is applied, the safety of novel concepts can be quantified, even if they are not covered by formal design rules. Risk-based design can also be used for optimising an existing design with respect to safety. A pre-requisite is that a consistent measure of safety is defined and can be quantified. When methods for risk and reliability analysis are integrated, they can be used to balance requirements to safety and other design factors, e.g. performance, life-cycle cost, and functionality. Risk-based methods gain more acceptance as decision support tools in engineering applications. Today, all main elements of risk-based ship design and approval are being developed and early applications demonstrate their feasibility in practice.

4.2.4 Methods and criteria

An analytical method for the control of the strength of a grillage (gross panel) under unidirectional in-plane axial load was proposed by Lokshin et al. (2013). The method was developed to: (i) calculate the critical stiffness of transverse girders, (ii) calculate the maximum unidirectional in-plane compression load when a structure's scantlings are known, and (iii) calculate the required structure's scantlings when the unidirectional in-plane compression load is given. A probabilistic method for control of the strength of ship's deck structure under unidirectional in-plane axial load was proposed, which can be employed to assess the effect of deterioration due to corrosion on the deck's buckling strength. Faber et al. (2012) presented a generic framework for consequence assessment and risk analysis of FPSO systems for the purpose of establishing structural design criteria. Their work considered the output of the Joint Committee on Structural Safety (JCSS) addressing the issue of system representation through exposure events, direct and indirect failure consequences.

Patelli et al. (2012) presented and discussed efficient approaches for stochastic analysis and their applications to large FE models for the solution of realistic engineering problems. A general purpose software was developed to provide integration between deterministic solvers for FE equations, efficient algorithms for uncertainty management and high performance computing. It can be widely used for optimisation analysis, life-cycle management, reliability and risk analysis, fatigue and fractures simulation, and robust design. Mulder et al. (2012) presented a user-friendly method to model and visualise uncertainty in an environment where little is known about the uncertainties involved. In this work uncertainty is defined at particular nodes or elements of the FE model by using the interval or fuzzy logic method. Several case studies were carried out to demonstrate the practical use of distance-based interpolation.

Zhu & Collette (2013) presented a new iterative inference algorithm for more accurate and efficient reliability evaluation of a dynamic Bayesian network-based deterioration process. The proposed algorithm appeared to be robust and efficient in comparison to static discretisation procedures. Barltrop et al. (2012) and Hifi & Barltrop (2014) have presented a methodology that has the potential to combine detailed analysis of long-term experience from large numbers of ships with reliability and risk-based analysis methods at both component and whole ship system levels. The methodology developed under the EU FP7 funded project RISPECT considers the influence of hydro-static and dynamic pressures, extreme events,

motions, fatigue induced global and local member forces, crack propagation, coating breakdown and corrosion modelling, structural reliability and fleet operational risk factors.

Li et al. (2013c) proposed acceptance criteria for fixed offshore platforms in the northern South China sea under extreme storm events based on reliability analysis. The long-term distribution of extreme environmental loads was investigated. The role of ultimate strength analysis and reliability assessment in the structural integrity management of fixed offshore structures was demonstrated by a pushover study for an aging platform. Bai & Qian (2013) calculated one limit state equation of an unstiffened panel by using MATLAB software and given the partial safety factors for the load and resistance factor design of the panel under different reliability index levels. Žanić et al. (2013) presented an efficient method for ultimate load capacity and safety calculation with inclusion of reliability and robustness-based design criteria, including multi-criteria topology/geometry optimisation of the ship structural model and scantlings/material multi-criteria optimisation of structural panels. The method was verified with respect to accuracy and speed on the box girder design and panel design with CalREL methods based on Monte Carlo First Order Reliability Methods (FORM). Zavoni et al. (2012) presented applications of the framework for generic risk assessment for FPSO systems. The consequence models for structural risk assessment were developed for failure of hull girder sections, hull components and mooring lines using Bayesian probabilistic networks. The target reliability levels were estimated by: (a) optimising the expected life-cycle costs, and (b) verifying compliance within the context of risk acceptance criteria.

4.2.5 *Structural capacity*

Yu et al. (2013b) proposed a method to calculate the relative angular deformation between arbitrary positions in the hull based on the simulation of irregular waves. The method was used in a case study where spectral and reliability analysis methods were used to calculate the probability of peak response deformation beyond the critical value for the studied vessel. Ibekwe et al. (2013) carried out the hull girder ultimate strength reliability assessment of a damaged frigate by using the interactive-numerical method (Ibekwe et al. 2011). A parametric analysis that considers different load cases obtained from experimental wave measurements demonstrated the increased risk of failure of damaged ships. Pasqualini et al. (2013) carried out a statistical analysis of the cross-correlation between geometrical parameters of a welded joint and the spatial correlation along the weld. Jia & Moan (2012) studied the effect of sloshing in tanks on the hull girder bending moments and the failure probability of an oil tanker in various damage conditions. It is concluded that in certain tank resonance conditions, sloshing effects cannot be neglected.

Branner et al. (2013) presented a probabilistic approach to reliability assessment of fatigue critical welded details in jacket support structures for offshore wind turbines according to ISO (2007) and DNV (2011b). The fatigue stress cycles on the jacket members were computed by applying tower top loads from an aeroelastic simulation with superimposed marine loads and in accordance to the IEC-61400-3 (IEC 2005) guidelines for operational conditions. The uncertainty in the fatigue stresses was taken into account by using probabilistic S-N curves and a stochastic model to predict the failure in one chord/leg intersection type weld. Differences in calculating and applying hot spot stresses in tubular welded joints have been analysed and discussed. Mao (2014) proposed and validated an efficient spectral method for the prediction of crack propagation in ship structures by taking into account the stress response amplitude operators. A case study on the deck longitudinal stiffener of a 2,800-TEU container ship was carried out to demonstrate the application of the method. The scatter of crack propagation associated with the wave environment was also investigated. The results indicated the potential of crack inspection and maintenance optimisation to enable more efficient ship operation.

Cerkovnik et al. (2013) developed a method for the assessment of fitness for service of risers and flow lines by using a Monte Carlo simulation. The authors evaluated the probability of failure based on incomplete in-line inspection data (from e.g. magnetic flux leakage to ultrasonic testing) and the statistical characterisation of other pertinent parameters. The case study results showed that these methods can be useful in providing a basis for determination of fitness without the need to resort to arbitrary factors of safety. It was concluded that using deterministic analysis may lead to conservative estimates in comparison to the method developed. In fact a safety factor between 2.0 and 3.0 may be more appropriate where the target annual probability of failure is of the order of 10^{-5} .

Maes et al. (2013) carried out studies by the stationary and ductile probabilistic Failure Assessment Diagrams. Based on this work it may be concluded that failure probabilities allow for an objective comparison of different cracks across a wide range of operating characteristics and therefore can be used to establish a reliability-based integrity management plan. Mousavi & Gardoni (2014) presented a simplified method for the reliability- and the integrity-based optimal design of engineering systems that directly involves the system annual failure probability as a measure of system safety. By calculating the probability of system failure, their method could be used not only for risk-based decision-making but also for structural inspection.

Faber et al. (2012) introduced a generic framework for consequence assessment and risk analysis of FPSO systems based on the recent work by the Joint Committee on Structural Safety (JCSS) addressing the issue of system representation through exposure events, direct and indirect failure consequences. The scenarios considered for risk-based calibration of a design code safety format for FPSO systems were outlined. Human factor related risk acceptance criteria have been determined based on the concept of the Life Quality index. The consequence models were established by Bayesian Probabilistic Networks and the target reliability indices were determined for structural design of FPSO components. Kawamura et al. (2013) carried out life cycle structural optimisation of the midship section of a double hull tanker to minimise construction costs and maximise life cycle benefits. Yang & Wang (2012) proposed a method for fatigue reliability-based design optimisation of a bending stiffener, which may be employed to protect the upper connection of umbilical/flexible risers against damage. Three meta models were constructed by the optimum Latin Hypercube method (Stocki 2005) and the feasibility of the method was verified by a case study of beam. The results demonstrated that the method is rational and improves the fatigue reliability of bending stiffeners. Yang et al. (2013a) applied a stochastic approach to the design of stiffened composite panels for which typical applications can be found in composite ship structures. A parametric study was conducted using the Navier grillage theory (Blake et al. 2009) and FORM to investigate any detectable trend in the safety index with various design parameters. The reliability of the panels was found to be sensitive to uncertainties in component thickness and fibre content. The fatigue reliability of fixed offshore platforms was investigated by Gholizad et al. (2012) by analysing different failure scenarios. In order to evaluate the occurrence probability of a special scenario, it was divided into a finite number of sub-scenarios and evaluated separately followed by a comparison of them. Based on the calculated values, the probability of occurrence was obtained for each scenario, and finally, the failure probability of the entire system was calculated.

Yu et al. (2013a) conducted reliability analysis and reliability-based optimum design of thin-walled structure as the stochastic structural system. The stochastic variables were categorised into two groups. One is allowable stress and loading and the other is plate thickness and cross-sectional area of beam. The failure probability of structural system was calculated considering beam cross-section area and plate thickness are stochastic variables or not, separately. The optimum design for plane frame structure solves the light weight problem of structure under constrain of reliability. Liu et al. (2014) performed the fatigue life reliability analysis of submarine pressure shell butt weld by using the probability density evolution method. The crack propagation growth probability density evolution equation was obtained by introducing extended state vector into crack propagation rate model with random initial conditions. The example shows that results from the proposed method are in good agreement with the Monte Carlo method and that the crack size probability density function evolves with loading cycle.

Present ship building rules follow the S-N curve approach to evaluate the fatigue damage at identified locations while the use of fracture mechanics approach is yet to receive due attention. In Doshi & Vhanmane (2013), a methodology of evaluation of fatigue life of the longitudinal stiffener and transverse web frame connection using fracture mechanics was demonstrated. The approach can be useful in application to risk-based inspection of ship structures. This is because factors such as crack dimensions, crack growth law parameters and applied loads are random in nature; hence, they were accounted for considering their randomness. Examples of numerical results are presented for fatigue life of an oil tanker using the proposed method and IACS-CSR. The fatigue reliability of fixed offshore platforms was investigated by Gholizad et al. (2012) by analysing different failure scenarios. In order to evaluate the occurrence of probability of a special scenario, it was divided into a finite number of sub-scenarios and evaluated separately followed by a comparison of them. Based on the calculated values, the probability of occurrence was obtained for each scenario, and finally, the failure probability of the entire system was calculated.

Another example study on the reliability-based investigation of fatigue damage was presented by Sørensen (2012). The required safety factors (namely Fatigue Design Factors - FDF values) were used for fatigue design of steel substructures of offshore wind turbines. Design and limit state equations were formulated and stochastic models for the uncertain strength and load parameters were described. The effect of possible inspections during the design lifetime was investigated. The results indicated that, for fatigue critical details, where the fatigue load is dominated by wind load, FDF values equal to 2.5 are required. Further, if the wave load is dominant, slightly larger FDF values are required.

4.3 Risk-based inspection, maintenance and repair

4.3.1 Inspection

Condition monitoring and maintenance management of marine structures are continuously being improved. The ever increased awareness of maritime safety and risks has contributed to the development of risk- and reliability-based methods as a basis for inspection, maintenance and repair strategies. Hence,

marine structures can be operated safely and be maintained cost-efficiently in accordance with the established rules and regulations. This section presents a selection of recent work and methods that have contributed to reliability-based inspection, maintenance and repair, and their influence on uncertainty prediction of structural capacity and response. Ku et al. (2012) developed a systematic framework to assist operators in laying out inspection planning for semi-submersible structures using the structural reliability analysis and risk assessment techniques. The inspection timing and frequency for various structural components can be determined based on the time-varying reliability index of the structural components under consideration. Guédé et al. (2013) presented a framework of risk-based inspection for a park of offshore wind turbines taking into account the fact that only a sample of wind turbines is inspected at the scheduled inspection dates. The failure of a wind turbine is driven by the fatigue crack of one of its critical structural detail and the uncertainties in the operation and maintenance costs due to the possible change of maintenance strategies with respect to the number of wind turbines are considered. The numerical example of a wind farm shows that the proposed risk-based strategy significantly reduces the computational effort required by the complete risk-based inspection analysis.

Guo et al. (2012) introduced a reliability-based procedure for effective inspection planning in order to avoid the ultimate failure of deck plate of aging tankers. The time-variant failure probabilities of deck plate were calculated by using the Latin Hypercube sampling method in the Monte Carlo simulation and the time for thickness measurement of deck plate was predicted by comparing the calculation results with target values. A total of 1,080 cases for 9 sample tankers were analysed to illustrate the procedure, including sensitivity and parametric studies. Frohbös & Lampe (2013) described some of the major aspects of the methodology developed to estimate the risk to offshore pipelines and presented the results of a general risk assessment of 22 aged offshore pipelines. The assessment reveals different governing threats and failure modes for pipelines and risers, like ageing, free span or corrosion. The obtained results of the risk assessment were used for the optimisation of the inspection intervals within the proposed risk-based inspection framework. It was concluded that the combination of remaining life time with index procedure was able to cover all relevant failure modes. When only using the remaining life time approach threats like impact damage, which is the reason for 30% of all pipeline damages, are not covered.

In order to optimise the inspection and repair schedules for structural components on ships, Vasconcelos de Farias & Netto (2012) conducted two case studies on corrosion damage of an FPSO due to its high incidence among the observed damages. With the results from Bayesian inference, necessary “subsides” were developed for the next field inspection, establishing the basis for determining the regions where survey is needed the most, and the corresponding inspection intervals. Goyet et al. (2013) presented a study on risk-based inspection for offshore structures with the FPSO as an example. The study presented strong insights about all the ingredients which have to be used to support the development of risk-based inspection practices. In further, preserving the integrity of any system depends on predicting, assessing, and preventing risks while any existing failure mechanism is mitigated. This depends on forecasts, technological innovations and finding appropriate solutions to prevent or deal with emergencies. Tammer & Kaminski (2013) discussed an eight-step procedure for risk-based inspection (RBI) and its application for safeguarding the hull integrity of floating structures (FPSOs), with primary focus on fatigue degradation mechanism. The main steps included: (i) determination of asset integrity policy, (ii) functional decomposition and asset screening, (iii) assessment of probability of failure, (iv) assessment of consequences of failure, (v) relative risk ranking, (vi) determination of inspection programme, (vii) implementation, data evaluation and feedback, and (viii) conditional updating of the model. It is suggested that RBI be preferably used in combination with hull monitoring to gain the most of the benefit.

4.3.2 *Maintenance and repair*

A relevant problem nowadays that influences (decreases) the structural capacity with the operational period of marine structures to sustain loads is corrosion. In order to protect marine structures from corrosion protective coatings are applied. The coating life is limited and hence it must be maintained or substituted regularly following maintenance management programs. In Ulfvarson (2011), a state-of-the-art description concerning corrosion protection systems was presented which focused on the localised strain-induced coating failures and some methods under development. Coatings and corrosion protection in ballast tanks, quality requirements, coating breakdown and degradation resulting in corrosion were studied by Heyer et al. (2013). Baere et al. (2013) presented an economical modelling approach which for a ship’s life-cycle reduces the cost of ballast tank coating applied in double hull space ballast tanks of modern merchant vessels. The proposed method was recommended to be used in inspection planning and evaluating the life extension of existing offshore platforms. Examples of other studies where risk- and reliability-based procedures that can contribute to more efficient maintenance strategy and repair were presented by Guo et al. (2012) who studied ultimate failure of deck plate by considering life degradation effects using the Latin Hypercube sampling method in Monte Carlo Simulations. Kwon & Frangopol (2012a) estimated lifetime

maintenance costs due to fatigue damage based on reliability-based analysis. Obtained results show that by tailoring the maintenance strategy to the design of the structure significant savings can be found in the lifetime costs associated with the component. Temple & Collette (2013) developed a framework to estimate the lifetime maintenance cost of a naval structure based on an uncertain operational lifespan and an associated maintenance schedule. The framework accounts for damage to the ship's structure due to both corrosion and fatigue. The maintenance schedule is optimised to minimise the total lifetime structural costs for the ship based on global and local strength requirements.

5. SHIP STRUCTURES

Rising oil prices and stronger emission regulations have influenced the trend in ship design to emphasize on energy saving, slow speed operation, dual-fuel engine ship and LNG fuelled large commercial ships. Furthermore, to reduce transportation cost of unitary container, designs of large container ship's size are still requested larger to increase the container capacity that a ship carries. Several 18,000-TEU container ships were delivered from 2013 are now in service. For such designs, its more flexible hull and deflection characteristics must be considered in the strength assessment, especially for whipping and springing phenomena that have a negative impact on the structural integrity. The design of 22,000-TEU container ships which are approximately 450 meters in length will be the next challenge for designers and approval engineers. For bulk carriers and oil tankers, the CSR-BC&OT (IACS 2015) will enter into force on the projects contracted for construction on or after 1 July 2015. The important change in the direct strength analysis, compared to the current rules, is that a cargo hold structural strength analysis will be requested within the cargo hold region including the aft bulkhead of the aftmost cargo hold and the collision bulkhead. This also means that more accurate assessments are requested to ensure the structural safety of commercial vessels.

Section 5.1 presents a historical background and an overview during the reporting period of the developments in international rules and regulations divided into sections for IMO Goal-Based Standards, IACS-CSR and the development of structural design software systems. In Section 5.2, recent developments for ship concepts are highlighted with focus on container ships and LNG/LPG tankers.

5.1 *Developments in international rules and regulations*

5.1.1 *IMO Goal-Based Standards*

Goal-Based Standards (GBS) have been discussed by various ISSC committees over the last 10 years (e.g. ISSC 2009, ISSC 2012). For this reason this section mostly focuses on key points and recent developments that have already impacted or will impact the implementation of unified or individual classification rules and design procedures relating with the prediction of loads on tankers and bulk carriers.

GBS were introduced in IMO at the 89th session of the Council in November 2002 through a proposal by Bahamas and Greece (C 89/12/1), suggesting that IMO should play a larger role in determining the standards to which new ships are built. The submission argued that the Organization should develop initial ship construction standards that would permit innovative designs. At the same time it should ensure that ships are constructed in such a manner that, if properly maintained, they could remain safe for their economic life. The IMO MSC 80 in May 2005 agreed on the basic principles of GBS as follows: "GBS are: (1) broad, over-arching safety, environmental and/or security standards that ships are required to meet during their life cycle, (2) the required level to be achieved by the requirements applied by Classification Societies and other recognised organisations, administrations and IMO, (3) clear, demonstrable, verifiable, long standing, implementable and achievable, irrespective of ship design and technology, and (4) specific enough in order not to be open to differing interpretations". For bulk carriers and tankers the GBS consist of five "Tiers" namely:

- *Tier I – Goals:* high-level objectives to be met.
- *Tier II – Functional requirements:* criteria to be satisfied in order to conform to the goals.
- *Tier III – Verification of conformity:* procedures for verifying that the rules and regulations for ship design and construction conform to the goals and functional requirements.
- *Tier IV – Rules and regulations for ship design and construction:* detailed requirements developed by IMO, national Administrations and/or recognised organizations and applied by national Administrations and/or recognised organizations acting on their behalf to the design and construction of a ship in order to conform to the goals and functional requirements.
- *Tier V – Industry practices and standards:* industry standards, codes of practice and safety and quality systems for shipbuilding, ship operation, maintenance, training, manning, etc., which may be incorporated into, or referenced in, the rules and regulations for the design and construction of a ship.

The GBS Tiers I to V constitute the IMO GBS, which became mandatory on 1 January 2012 under the SOLAS Convention (new SOLAS regulation II-1/3-10), subsequent to the adoption of the following instruments at MSC 87 in May 2010:

- New SOLAS regulation II-1/3-10 “Goal-based ship construction standards for bulk carriers and oil tankers” (resolution MSC.290(87)).
- International GBS for bulk carriers and oil tankers (resolution MSC.287(87)) (the Standards).
- Guidelines for the verification of conformity with GBS for bulk carriers and oil tankers (resolution MSC.296(87)) (the Verification Guidelines).

SOLAS regulation II-1/3-10 makes the GBS applicable to oil tankers and bulk carriers of 150 m in length and above:

- for which the building contract is placed on or after 1 July 2016,
- in the absence of a building contract, the keels of which are laid or which are at a similar stage of construction on or after 1 July 2017, or,
- the delivery of which is on or after 1 July 2020.

5.1.2 IACS Common Structural Rules for Bulk Carriers and Oil Tankers

IACS Common Structural Rules for Bulk Carriers and Oil Tankers (CSR-BC&OT) is applicable for self-propelled oil tankers and bulk carriers with length greater than 150 m and 90 m, respectively, with unrestricted and worldwide navigation. The rules consist of two parts namely: (a) Part I that provides requirements common to both Double Hull Oil Tankers and Bulk Carriers, and (b) Part II that provides additional requirements applied to either ship type. The Consequence Assessment (CA) that was completed in 2014 (IACS 2014a, b, c) looked at scantling increases with no design changes and no design optimisation was carried out to find increases as well as decreases. Some of the key output of the CA can be summarised as follows:

- In general, CSR-BC&OT are more conservative than the CSR, for both oil tankers and bulk carriers.
- CSR-BC&OT require that the cargo hold structural strength analysis is mandatory within the cargo hold region including the aft bulkhead of the aftmost cargo hold and the collision bulkhead. The scope covers five regions, including the midship, forward aft end, foremost and aftmost cargo holds (see Figure 3). The implementation of boundary conditions, loads and equilibrium, and permissible stresses, criteria for yielding, buckling and fine mesh have been harmonised.
- The increase estimates calculated are approximations of the scantlings that may be needed to satisfy the CSR-BC&OT requirements. In the computation of the estimates approximate methods have been used to arrive at the scantling estimates, and the design have not been modified. Therefore, the final scantlings will not become apparent before new designs have been generated.
- The original CSR net scantling approach is retained and the corrosion margin values have in general been left unchanged. This is because corrosion data collected from bulk carriers and tankers have been extensively re-analysed, verifying that existing corrosion margins are well on the conservative side.
- The general tendency for oil tankers and bulk carriers is that the scantlings will increase when CSR-BC&OT apply.
- The newly introduced FE analysis for fore and aft cargo hold will generally not increase scantlings due to the yielding assessment.
- The additional class notation and assignment of the GRAB notation is intended to handle heavy grabs. For bulk carriers the GRAB requirements lead to scantling increases in several holds. The FE buckling requirements will generally increase scantlings for oil tankers and bulk carriers.
- In general, fatigue analyses for both ship types give lower fatigue lives in the CSR-BC&OT than in CSR.

With regards to the stress acceptance criteria, in most of the current classification rules criteria are implemented for the yielding check of local stress concentrations assessed by means of direct calculations and modelled by fine meshes. However, due to differences in approach not all stress acceptance criteria are the same. An overview of the stress criteria as defined in the main class rules is given in Table 2. It should be noted that the table only contains an excerpt from the actual stress criteria and is therefore not complete. What can be observed is that there is a variety of mesh sizes to be used. Furthermore, stresses are in most rules to be taken at the element’s mid-plane. Only ABS (2014) explicitly allows incorporating plate bending stresses in the analysis. The CSR-BC&OT stress acceptance criteria are identical to CSR-OT,

except that an additional 20% of stress may be allowed for details that comply with the fatigue assessment criteria, which in other rules is not possible.

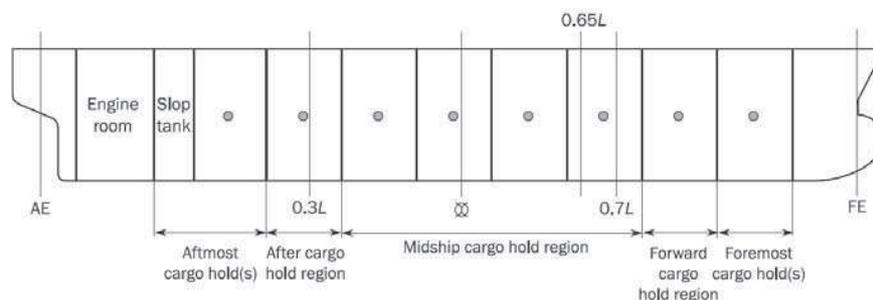


Figure 3. Definition of cargo hold regions for FE structural assessment.

Table 2. Stress criteria defined in main class rules (*DNV (CSA), see DNV (2013a)).

Rules	ABS	DNV	DNV*	KRS	LR	BV	CSR-BC	CSR-OT	CSR-BC&OT
Probability (1)	10^{-8}	10^{-4}	10^{-8}	10^{-8}		10^{-5}	10^{-8}	10^{-8}	10^{-8}
Scantling (2)	gross	net	net	gross	net	net	net	net	net
Mesh (3)	$s-t$	suitable	t	s	$1-1.5 \times t$	50×50	$s/4$	50×50	50×50
Element length (4)	15-800		15	800	22.5	50	200	50	50
σ_{all} (5)	382- 224	245	400	282	353	294/ 335	280	353/ 400	353/ 400
*Notes	(7)	(8)		(9)	(10)	(11)		(12)	(13)
Reference (6)	ABS (2014)	DNV (2014b)	DNV (2013a)	KRS (2013)	LR (2014)	BV (2014)	IACS (2012a)	IACS (2012b)	IACS (2014a)

*Notes:

1. Probability of exceedance of load case for which the yielding check is performed.
2. Modelling of the scantlings, either by including (gross) or excluding (net) the corrosion margin of the plating.
3. Mesh size to be used in way of local stress concentrations. "s" indicates the general frame spacing, "t" plate thickness. Otherwise the element size is given in mm (e.g. 50×50 indicates an element size of 50 by 50 mm).
4. Typical length of element side considering the mesh criteria and a typical spacing of 800 mm and typical plate thickness of 15 mm.
5. Allowable equivalent stress for mild steel in N/mm^2 .
6. Reference to the appropriate rules and regulations.
7. Non-tight structures, or tight structures with tertiary stresses accounted for.
8. For end bracket of stiffeners of unproven design.
9. Various general criteria depending on location.
10. Applicable to the stress analysis of hatch corner radii onboard container vessels.
11. The allowable stresses given are for elements respectively adjacent or not adjacent to a weld.
12. The allowable stresses given are for elements respectively adjacent or not adjacent to a weld and only for load cases where static and dynamic loads are combined.
13. The stress criteria in the CSR-BC&OT are equal to those for CSR-OT, except that for details complying with fatigue assessment criteria stresses increased by a further 20% can be accepted.

Harmonised common structural rules introduce hull girder residual strength assessment of the hull in damaged conditions. They provide a calculation formulation using an incremental and iterative Smith-type procedure. Various researches have proposed alternative methods for the calculation of the ultimate strength of hulls with non-symmetric sections. FE codes have been also employed for the calculation of residual strength. When using FE the main concerns of the users are: (a) the selection of mesh, (b) the selection of the appropriate solver, i.e. implicit or explicit, and the parameters related to it, (c) the boundary conditions, and (d) how to apply the action, i.e. bending moments with or without external loads or rotations of the end sections. An essential issue is also the description of the actual properties of the hull including the effect of corrosion on the thickness of the structural members.

For evaluating different ship structural crack arrest technologies, Zilakos et al. (2013) proposed a methodology that combines CSR fatigue loadings with the FE method for the study of cracks on actual marine structure subjected to high-cycle (low-stress) fatigue. An Aframax tanker's mid-hold model subjected to different fatigue scenarios were investigated. The proposed method is simple and based on rules

and regulations widely accepted in the ship industry. For the residual strength of hull in damaged conditions, CSR-BC&OT provides a calculation formulation using an incremental and iterative Smith-type procedure (for details, see Zilakos et al. 2013). The FE method has been also employed for the calculation of residual strength.

Samuelides et al. (2013) investigated the sensitivity of the FE analysis results from the modelling parameters. Guidance for the selection of modelling parameters so as to obtain convergence is provided. Finally, the determination of the residual strength to a bulk carrier and a tanker subjected to collision damage using ABAQUS/Explicit was presented.

Nam & Choung (2013) investigated the accuracy of average compressive strengths of stiffened panels on ultimate longitudinal strengths of hull girder. Average compressive strengths based on simplified CSR formulae and FE analysis were calculated for stiffened panels. Then hull girder ultimate strengths have been calculated using the in-house software UMADS which is based on the progressive collapse method with a new convergence criterion. It is concluded that average compressive strengths from FE analyses induce conservative prediction of hull girder ultimate strength, because CSR formulae estimate less conservative shortening behaviours of stiffened panels than FE analysis results.

5.1.3 *Development of structural design software systems*

Structural design software systems including class rules calculation, FE assessment, combination of hydrodynamic analysis and structural analysis gradually become very important tools for ship designers and classification societies. This is because of the maturity of FE technology and the advancement of the rule requirements that now require the application of advanced direct calculation procedure for the prediction of quasi-static loads. For ship structures that may be prone to structural damage because of environmental loads that arise from impact loads (e.g. slamming, sloshing, green water on decks, etc.) most methods account for the instantaneous peak pressure. With this in mind Kim & Paik (2013) developed an advanced design formula that predicts the permanent deflection of plates and stiffened panels in the time domain. Their work proposed the use of two parameters that can describe the impact loads namely peak pressure and duration time. However, further comparisons with nonlinear FE methods of stiffened plate structures under impact loads are required.

Ma et al. (2013) suggested that multi-objective optimisation methods can be used to determine the Pareto optimal solutions of a stiffened panel based on the ALPS/ULSAP (2006) algorithm. Objective of this work has been to solve a design problem by simultaneously minimising the weight/cost of a stiffened panel, and by maximising its buckling and yielding stresses. Two methods, namely Pareto Simulated Annealing (PSA) and Ulungu Multi-Objective Simulated Annealing (UMOSA) were presented for a single panel optimisation. The loads applied to the panel were assumed to be constant. An iterative procedure was used to optimise stiffened panels. The numerical results showed that the proposed method is very useful to perform ultimate strength based ship structural optimisation with multi-objectives, namely minimisation of the structural weight and cost and maximisation of structural safety.

For large ship structural design, the Direct Load Analysis (DLA) for strength assessment of hull structure is adopted to strengthen the initial design based on rules or to satisfy the requirement for a specific notation. However, this analysis is too complicated for designers because it includes quite a number of FE analyses and corresponding parameters to be considered. To satisfy the requirements of the various classification societies and to consider the designers' needs, Won et al. (2013) developed a process of the structural assessment using direct load analysis which was standardized to consider various rules and the calculation procedure is automated to reduce the calculation effort. The system is mainly composed of four parts according to the general procedure of the dynamic load analysis such as the interface to ship motion, load transfer module to the finite element model, global to local mapping module in the FE analysis and fatigue life estimation modules.

Brindley et al. (2013) presented two approaches for the practical fatigue strength assessment of container carriers. Those reflect the industry demands for design and design assessment. In the former a simplified stress concentration factor is defined to evaluate the hot spot stress range. This is directly compared to an allowable hot spot stress range/mean stress curve that may be used to assess the fatigue strength. The latter records the hot spot stress directly from a local fine mesh model. Mean stress, material strength and plate thickness effects are incorporated to evaluate an equivalent hot spot stress range. The authors presented one possible concept concerning the influence of the so-called shakedown stress on material strength effect and the expected S-N curve modification. Fukasawa & Mukai (2013) discussed the effects of hull girder vibration on fatigue strength for a Post-Panamax container ship. In this study the container ship under investigation was assumed to encounter 100,000 sea states according to the occurrence probability of the short-term sea state given in the IACS North Atlantic wave scatter diagram. When the influence of hull flexibility was considered in the calculations the total cumulative fatigue damage factor doubled. They concluded that a stress range around 100 MPa may have a significant effect on

the fatigue damage in the ship. It is important to confirm whether this phenomenon can be observed or not in the actual fatigue damage of a ship taking account of the nonlinearity in crack initiation/propagation stages. When the smaller amplitude component of higher frequency vibration is superimposed on the larger amplitude component of lower frequency vibration, the enlargement effect of the total amplitudes of superposed stress may significantly affect fatigue life. However, the number of cycles of the small amplitude component cannot be disregarded.

In a study by Jeong et al. (2013b), fluid coupling effects in tanks with stiffened plates were investigated by experimental measurements and FE numerical analysis. The results demonstrated that the differences of natural frequencies between in- and out-of-phase modes may increase depending on the fluid depth. The reason is that the fluid effect on out-of-phase modes affects the mass of tank structures. The influence from natural frequencies depending on water level in way of the adjacent tanks is small, while the influence of mode shape can be significant. Yang et al. (2013b) estimated the slamming impact loads and dynamic structural responses of container ships at an initial design stage using a direct analysis method. The slamming impact pressures and dynamic structural response were studied using the commercial CFD program STAR-CCM+ and the structural analysis software ABAQUS. These two programs were coupled using the co-simulation function of STAR-CCM+, known as the one-way coupled FSI scheme. Numerical simulations were carried out for the bow bottom and the stern slamming impact loads of a container ship in extreme design wave conditions.

5.2 *Special ship concepts*

5.2.1 *Service vessels for wind mills and offshore platforms*

Offshore structures are designed for certain accidental scenarios. This is done to guarantee a sustainable level of equivalent safety. Accordingly, accident scenarios are defined to prevent that the consequences of an accident are disproportional to the original cause. Within the reporting period a suitable example of application is presented in Storheim & Amdahl (2014). They investigated the damage of offshore platforms that may be subject to ship collisions. In their analysis they considered bow and stern impacts of a supply vessel having 7,500 tonnes displacement against the column of the floating platform, jacket legs and braces. The effect of ship-platform interaction on the distribution of damage has been studied by nonlinear shell FE simulations. For bow collisions the crushing behaviour and potential penetration of the bulbous section into cargo tanks or void spaces of the floating platform was studied in detail. For the jacket braces the study was focused on whether it is possible to penetrate into the ship bow without significant plastic bending or local denting. At post-processing stage the collision forces were compared against the NORSOK (2004) standards. In a similar type of study by Notaro et al. (2013), they studied the collision between the offshore installation and a modern 10,000 Offshore Service Vessel (OSV) with a bulbous bow. The residual hull girder strength of the unit was assessed to identify potential threats to hull integrity.

5.2.2 *Container ships*

The contribution from springing and whipping on fatigue and extreme loading may be significant for long slender ships with large openings such as container vessels. Therefore, within the reporting period a number of studies based on available full-scale measurement data attempted to quantify the influence of hull flexibility on the fatigue life of such vessels. For example, a study by Barhoumi & Storhaug (2013), utilised 4-year full-scale measurements to investigate the influence of whipping and springing effects, on an 8,600-TEU container ship. Their study demonstrated that fatigue damage initiates under head or beam seas conditions. Whipping contributes significantly to the increase of the dynamic extreme stresses in deck, hence doubling the dynamic extreme stress especially under hogging but also under sagging conditions in way of the aft quarter length of the vessel. Whipping-induced loads lead to amplification of the dynamic stresses which may exceed the quasi-static IACS rule by up to 48% in hogging. A similar type of study was conducted by Renaud et al. (2013) and Andersen & Jensen (2013) on a 9,400-TEU container ship based on full-scale measurements over a 6 year period. These studies concluded that the inclusion of the effects of hull girder flexibility may have a negative influence on the fatigue life. In particular the work by Andersen & Jensen (2013) investigated the efficiency of spectral fatigue analysis methods to capture the influence of non-Gaussian/narrow banded frequency components that emerge in way of hull girder induced resonances. The authors suggest that such approaches are not accurate. Notwithstanding, the agreement between the spectral methods and rain flow counting methods is generally good and the narrow-band approximation seems to yield a fast and fair estimate of the fatigue damage.

In a recent study, Fricke & Paetzold (2013) carried out fatigue tests of a welded detail subject to variable amplitude loading. They investigated the effect of whipping stresses on fatigue damage and the suitability of the Palmgren-Miner rule for fatigue life assessment. Their study has been based on theoretically

derived/idealised sinusoidal stress histories and stress histories from onboard measurements. The results showed that most of the fatigue damage is caused by the low frequent stress cycles, which may be enlarged by whipping, as long as the whipping stress amplitudes are smaller than the wave-induced stress amplitudes. The contribution of the additional small stress cycles due to whipping is rather small. This validates a simplified approach proposed by the authors where only the enlarged wave-induced cycles are considered by a correspondingly modified cumulative distribution of stress ranges.

Tsai et al. (2013) carried out a frequency domain weakly nonlinear seakeeping/linear sloshing coupled analysis for an 8,000-TEU container ship under ballast and full load conditions. At first instance, their analysis highlighted the influence of resonant frequencies that correspond to roll motions by scatter diagrams. Consequently, the structural strength in way of the boundary of ballasted cargo holds was assessed. The risk induced by resonance of ship motion and sloshing water in cargo holds were confirmed in the design stage. A frequency domain model was utilised in a hydrodynamic numerical code HydroSTAR (see Tsai et al. 2013 for details), and the analysis included nonlinear seakeeping, linear sloshing, and the coupling calculation of the motion equation. The additional resonant frequencies, especially for the rolling motions, induced by the motion-sloshing coupling effect were clarified. The structural strength of the boundary of the ballasted cargo holds was assessed for those critical rolling motions by the BV numerical code HOMER (BV 2010). Further, Yang et al. (2013b) estimated the slamming impact loads and dynamic structural responses of container ships at an initial design stage using a direct analysis method as mentioned in Section 5.1.3.

5.2.3 LNG / LPG tankers

In recent years there has been increasing demand for energy efficiency, green shipping and reduced emissions. Considering that LNG fuel is considered as one of the most promising alternatives with low environmental footprint it is not a surprise that within the reporting period research and development efforts concentrated mostly on understanding the influence of quasi-static loads on the global integrity of LNG ships and their Cargo Containment Systems (CCS) as well as vessels that carry LNG as fuel.

Bang et al. (2013) developed the design of an enhanced 56,000 m³ IMO type B LNG cargo tank and assessed their design against DNV rules (DNV 2008, 2009). A study by Lee & Zhao (2013) revealed that the maximum von Mises stresses of every CCS component exceeded the reference values in the horizontal and vertical CCS members, except for the top and bottom R-PUF in the horizontal CCS member. Even though longer duration of shock pressure responses could be obtained using large water shooting water model, response to shock and fluid flow may be more severe compared to those of small water shooting models. Chun et al. (2013) evaluated the structural capacity of a corrugated membrane, against hull deformation, sloshing and thermal loading. Their study suggests the introduction of a failure criterion based on the rupture strain of the material considering in way of the first CCS barrier. Paik et al. (2014) have also studied sloshing loads in the storage tanks of LNG FPSOs and proposed a new method for the determination of nominal values of sloshing loads.

Hwang et al. (2013a, b) studied the structural responses due to sloshing loads of membrane type LNG CCS. A three step numerical assessment is proposed which incorporate: (a) linear static, (b) transient dynamic, and (c) localised FSI analyses. In a case study on a small-scale insulation box that represented a LNG tank, the approach was compared against results obtained from small scale model tests. Considering the uncertainty of sloshing impact loads, the results between the numerical simulations and the experiments show satisfactory agreement with regard to e.g. pressure history acting on the wall of the box.

Rudan et al. (2013) studied the crashworthiness of a typical LPG ship. Nonlinear FE analyses were used in parametric studies to compare the collision resistance of a conventional side-shell structure design with an innovative space-saving sandwich hull structure. The results show that the sandwich hull structure is more collision-resistant in terms of more energy-efficient absorption, however, the sandwich concept should be further studied. Ehlers (2013) proposed a particle swarm optimization-based procedure to obtain a crashworthy ice classed LNG tanker. The procedure utilised a number of selected arctic materials, which further improved the collision resistance at sub-zero temperature. As a result, the LNG tanker scantlings were optimised for local impact and compared to standard rules based concepts to identify the potential gain in collision resistance. In Ehlers et al. (2013), the ultimate strength of an intact and damaged LNG vessel subjected to sub-zero temperature (SZT) due to cold climate was investigated. This temperature influence is included by explicitly characterizing the material properties down to -90 degrees Celsius. A ship collision simulation introduced damage to the hull girder and thereby allowed for a comparison between the ultimate strength of an intact and a damaged hull girder. A simplified method was used to calculate the ultimate strength based on the individual panel contributions, both for the intact and damaged conditions.

Low temperature problems in structural assessment of LNG carriers were studied by Biot et al. (2013). In order to suggest a procedure for the structural design of a type C tank and its supporting structures,

they compared different approaches for numerical simulation of the interaction between tanks and ship structures. The outcome of the study was an FE-based simulation procedure for heat transfer analysis applicable on LNG carriers. Wang et al. (2013a) developed a procedure for thermal analysis and strength evaluation of cargo tank structures in offshore FLNGs and LNG carriers. In the study, a heat transfer analysis methodology was employed, and a computational tool was developed for application on hull and tank structures of both membrane-type and independent Self-supporting Prismatic type B (SPB) LNG vessels. Using this method, the temperature distribution and corresponding heat transfer coefficients (HTCs) in the hull structure can be estimated so the appropriate steel grade can be selected for the inner hull and the boil-off rate (BOR) can be calculated. FE results, from numerical simulations where the temperature range during operation was -170 to 20 degrees Celsius, were used for assessing the yielding and buckling strength of a tank structure.

Jeong et al. (2013a) proposed a strength assessment procedure of Mark III CCS plates which incorporates FE analysis together with various strength-based failure criteria for composite materials. The strength assessment in the study was performed within the initial failure state of a Mark III CCS plate. Failure details like failure locations, loads and critical stress values can be identified by the proposed approach.

Storhaug et al. (2013) studied strain measurement data of structural members onboard two LNG vessels. The data has been collected for a period of 5 years which enables the analysis of whipping and springing fatigue-related-effects of LNG carriers during different seasonal and weather conditions. The two vessels have been sailing in the world wide trade except for the North Pacific area, and the time spent in the North Atlantic is about 40%, which is higher than for typical LNG vessels. The vessel speed has been relatively low in average and well below the service speed. The results show that whipping and springing have resulted in a significant increase in accumulated fatigue damage in the two vessels.

5.2.4 Other ship types

Passenger ships

Modern passenger ships and mega cruise liners have high and long superstructure that comprise of several decks supported by pillars, longitudinal and transverse bulkheads on the hull and large openings. These characteristics generate nonlinear strain distributions in way of the midship section and raise the demand to understand the usefulness and practicality of applying advanced structural analysis techniques. Melk et al. (2013) investigated the shear-induced secondary normal stresses in the balcony openings of modern passenger vessels with narrow superstructures. The investigation was carried out using the FE method. In their study two quasi-static loading schemes were considered: (a) a cosine shape loading simulating the wave actions, and (b) a four-point bending load enabling deeper analysis on the shear-induced responses. It was demonstrated that the shear-induced normal stresses have considerable effect to the overall stress state around openings. Romanoff et al. (2013) presented a study of the interaction between the hull and the superstructure for a passenger ship exposed to bending loads. An advanced beam theory model that takes into account the influence of vertical and shear stiffness between various decks was employed and a Pareto optimisation procedure was followed to establish the significance of different weight and vertical centre of gravity distribution on overall quasi-static response. It was demonstrated that vertical and shear coupling between different decks may significantly affect the hull girder response of passenger ships. The authors concluded that the vertical bending moment is shared equally by the hull and the superstructure, while an optimal vertical centre of gravity may considerably increase the share of load carried by the superstructure.

Korhonen et al. (2013) studied the influence of surface integrity on the fatigue strength of high strength steel used in balcony openings of cruise ship structures. The fatigue test specimens, having a dog-bone shape and yield strength of 355 MPa, 460 MPa or 690 MPa, were cut by plasma. After cutting, the specimens were treated by grinding or by grinding followed by sandblasting, i.e. using post-cutting treatments suitable for shipyard conditions. The resulting surface roughness and hardness profile were measured. Fatigue tests with load ratio 0.1 were carried out and the investigation demonstrated that post-cutting treatments suitable for shipyard conditions can considerably increase the fatigue strength of high strength steel.

Sailing yachts

Shimell et al. (2012) presented the Dream Symphony project which is a 4-mast staysail schooner. With a length of 141 meters (463 feet), she will not only be the largest private sailing yacht ever constructed, but also an all Glued Laminated Wood (GLT) construction, incorporating some composite materials and steel. The requirement to use laminated wood as the main building material for a yacht of this size posed several challenges. However, the first aim was to make sure that the structural arrangement provided suf-

ficient strength and stiffness to withstand the forces imposed by hydrodynamic and rigging loads. Due to the unique nature of this project most calculations were done using first principles. An extensive material testing program was also conducted to determine the material design properties and account for the very specific nature and variability of wood. After an initial design using a two-dimensional approach, full FE analysis of the boat was carried out; see Shimell et al. (2012) for details. By presenting the design methodology, specific aspects of the laminated wood construction and key findings of the FE analysis conducted, the study illustrates how modern design methods and tools can be applied to design such a unique yacht.

Due to the increasing demand of methods and tools for the analysis of yacht behaviour in a realistic environment and in particular the development of time domain approaches able to simulate yacht motions in a seaway, a number of Dynamic Velocity Prediction Programs have been developed. For example, Fossati & Muggiasca (2012) presented an opening simple model with the aim to reproduce unsteady sail aerodynamics taking into account three dimensional effects and unsteady mainsail-jib interaction. The authors assumed that the yacht design scale and its wave pattern are short compared with the time and length scales of the wave motion. Consequently, it was modelled as a single point mass constrained to move on a surface governed by the equations of wave motion and the equations of vessel motion were derived.

The racing yacht design process, except the hull and appendages, involves the selection of sails, rigging and mast. Proper selection and scantling calculations of the mast and standing rigging is of crucial importance as it is the backbone and connection of sail induced loads on the hull. Zamarin et al. (2013) presented a novel methodology for the optimal selection of a mast and standing rigging based on the application of the Analytic Hierarchy Process (AHP) method on a 40ft racing yacht. Their approach consists of three phases. The first phase identifies possible design solutions. The second one specifies the best design for stability configuration. The third phase is used for load calculations, scantlings determination, and final approval of the project variables. Papantonatos et al. (2013) presented an experimental study on the dynamic performance of a BOC-50-foot sailing yacht model. A scaled model of the hull form with the keel-bulb configuration has been tested in the towing tank of the Laboratory for Ship and Marine Hydrodynamics of the National Technical University of Athens, Greece. During the tests the dynamic responses, as well as the added resistance were recorded. Results referring to the resistance, the side force, the centre of gravity displacement, the pitch as well as the vertical accelerations of the model at the bow, the centre of gravity and the stern were presented. Moreover, using a velocity prediction program, the polar and the stability diagram of the tested sailing yacht were calculated. Useful conclusions about the dynamic behaviour of the model were obtained.

6. OFFSHORE STRUCTURES

Within the reporting period research efforts concentrated on the assessment of the consequences from extreme, and accidental loads by advanced simulations such as nonlinear transient analysis, computational thermal-fluid dynamics, heat transfer analysis, gas dispersion simulation, thermal elasto-plastic analysis, etc. Advances in the use of probabilistic methods for risk and uncertainty quantification have also been significant.

6.1 *Types of analysis for various floating offshore structures*

Song et al. (2013) evaluated the effect of sloshing impact on the fatigue damage of an independent Type B LNG by sloshing model tests utilising a 2D rectangular tank with internal structures. Impact pressures were measured on stringers and a fatigue assessment was performed for a welded joint of the stringer on the side wall. By means of the experimental data, a procedure for the fatigue assessment of structural members inside such a tank was proposed and validated in a case study of a FLNG ship.

Pasqualino et al. (2013) and Pinheiro et al. (2013) developed a theoretical model for the evaluation of the SCFs and their influence on the fatigue life of FPSO side panels that have been damaged by collision. In this work a parametric study considering different damage magnitudes was carried out and the results obtained were used to develop an analytical expression to provide SCFs as a function of the dimensions of the damage.

High-frequency vibrations of Tension Leg Platforms (TLPs), commonly known as ringing and springing, have challenged TLP designers since the first full-scale TLP was installed in the North Sea in 1984. In Muehlner et al. (2012), a nonlinear time-domain model is presented of a TLP that exhibits the ringing and springing response of the vessel. The analysis model uses large displacement theory for the vessel and tendons and a semi-empirical wave model based on a modified linear wave theory. Predictions of vessel motions and tendon loads made with the analysis model were compared to model tests and were found in good agreement with the measurements. The analysis model was also used to investigate the fatigue damage in the tendons caused by the vessel's high-frequency response. Tendon stress time

histories were computed for nine different unidirectional sea states. The analysis showed that high-frequency response was present in all sea states even though ringing occurred only in sea states with significant wave heights above 3 m. Tendon fatigue damage contribution from high-frequency loads were found to be significant in every sea state.

Schmidt et al. (2014) performed a study on the fatigue reliability analysis for a brace-column connection of a semi-submersible hull. Three spectral methods were used to evaluate equivalent fatigue loads and fatigue damage. These included the Rayleigh method, the Modified Rayleigh method with bandwidth correction, and Dirlik's method, to estimate fatigue damage using Miner's rule. Uncertainties in the fatigue life assessment procedure were introduced in the analysis. The main sources of uncertainties in the fatigue analysis were those in a proposed "equivalent fatigue load" estimate in the short term, in the S-N curve parameters, and in the stress concentration factors. The results show that the frequency-domain methods did not lead to significant differences in predicted fatigue loads and damage. One reason could be that, for example, the cycle counting for Dirlik's method is based on the rate of peak occurrences, while the Rayleigh and Modified Rayleigh methods count cycles based on the zero up-crossing rates.

Ringsberg et al. (2014b) studied the importance of choosing a suitable fatigue calculation method for the design of offshore structures. In their work they used two different methods, the structural hot spot and effective notch stress method in a comparison study for two typical fillet welded joints. They found that local weld parameters, such as weld size, may have a considerable effect on fatigue life. They also concluded that wrong design criteria, including local weld parameters, may increase the chance of weld root failure, meaning that a local method, such as the notch stress method should be used for calculating the fatigue life for the critical area.

Gao & Low (2014) presented a new and efficient method for the simulation of long-term fatigue of deepwater risers. The method makes use of a statistical sampling technique, so that the results from the simulation of one sea state can also be used for other sea states. Application on a turret FPSO moored in 500 m water depth showed that the new method yields relative precise estimates of the fatigue damage, when compared with the classical Monte Carlo approach.

In offshore structures, collision and wave impact are important issues in terms of structural integrity. The residual strength of damaged structure as well as post-ultimate strength have been also treated as important. Ning et al. (2013) suggested a numerical approach for the evaluation of the structural integrity of a generic Spar hull in collision with a large supply vessel. Dynamic and nonlinear FE analysis were implemented using ABAQUS/Explicit module respectively for two collision scenarios namely: (a) a realistic simulation where the impact kinetic energy governed by an initial impact speed and total mass of a ship is gradually depleted during the collision, and (b) a simplified analytical method where the impact speed of a ship bow throughout the collision is constant or the total impact energy is unlimited.

Venzon et al. (2013) introduced an FE methodology that can be used to verify the structural integrity of damaged vertical webs of a semi-submersible, Mobile Offshore Drilling Unit (MODU). The methodology isolated one of the damaged vertical webs and applied the boundary condition on the adjacent structure where the web is located. The residual strength characteristics of damaged stiffened cylinders, namely, ring-stiffened and stringer-stiffened cylinders subjected to combined axial compression and radial pressure were investigated using the FE software package ABAQUS (Cerik et al. 2014). The damage process was explicitly simulated by means of quasi-static impact analysis in which cylinders were assumed to be dented by a rigid indenter. Subsequently, a series of the FE analyses were carried out for a number of damaged stiffened cylindrical shells. Closed-form expressions that may be useful for the prediction of the residual strength of damaged stiffened cylinders were derived. Those may be useful for reliability-based studies.

Amante et al. (2014) presented a study on residual compressive strength of dented FPSO side shell panels. Their FE analysis was carried out in two steps. First, collision damage by a supply vessel was imposed using the FE program ABAQUS/Explicit. After the indentation, a compressive load was applied and then the panel residual compressive strength was calculated. Moreover, in general, perforated plates containing cut-outs need to be carefully evaluated in terms of buckling failure. Park et al. (2013) carried out a series of nonlinear FE analyses to evaluate the buckling/ultimate strength according to various geometry and loading conditions, namely axial compression and in-plane edge shear. Based on these results, a simple formula was proposed that was found to give a reasonable estimate of ultimate strength of perforated plate with reinforcement under a variety of loading conditions (longitudinal/transverse compressive load and edge shear load).

For a wave slap of FPSO, a methodology for practical structural assessment of offshore structures was proposed by Moon et al. (2012). In this work the idealisation of impact loads was facilitated by the so-called pressure-impulse theory. Accordingly, time histories of impact pressures were generated along with the pressure impulses predicted. Nonlinear transient structural analyses utilising the time series of impact pressures led to the derivation of equivalent static pressure factors.

Hong et al. (2014b) studied the effects of steep wave-induced bow impact loads (so-called slapping loads) on FPSOs using model tests. For a measurement of the pressure and impact force on the frontal area, a bow-shaped panel was fabricated with the pressure and force sensors, and installed on the bow starboard side of the model FPSO. It was concluded that the impact loads acting on the FPSO bow may significantly increase with increasing steep waves ($H_w/\lambda > 1/16$) and in this sense they should be considered in the evaluation of seakeeping performance and structural design assessment.

Zhang et al. (2012b) established a corrosion forecasting mathematical model for a 3000 m deep sea semi-submersible platform. In their work the ultimate bearing capacities of a typical component and a node were evaluated and the evolution laws of the ultimate bearing capacity under various failure modes and various service years were summarised. It was concluded that as corrosion damage may have significant effect on ultimate strength, the corrosion damage factor should be taken into account in the design of offshore platforms.

Nonlinear structural simulations for an aluminium helideck of a floating structure were investigated by Koo et al. (2014). The aim of the study was to evaluate the buckling/ultimate strength of the developed pancake under helicopter landing impact and to compare the structural safety and stability in accordance with Eurocode 9 (CEN 2007). It was observed that the aluminium sandwich structure may be able to withstand the external forces induced by helicopter landing. However, results of global yield and buckling strength assessment led to the conclusion that Eurocode 9 design assessment criteria are significantly conservative.

Izadparast & Duggal (2013) studied the probability distribution of dynamic responses of turret-moored FPSOs and evaluated the effects of nonlinearity on the response distribution and the extreme statistics. For this purpose, sample data sets obtained from two experimental model tests studying the response of typical external turret mooring systems designed for deepwater and shallow-water conditions were utilised. Special focus was attributed on the extreme statistics of the mooring leg tension and vessel horizontal offsets. Accordingly, the probability distributions of measured data were estimated using common distribution models of linear and nonlinear random variables (Rayleigh, exponential, Stansberg, Weibull and 3-parameter Rayleigh distributions).

Wang et al. (2014) proposed a computationally efficient methodology for the long-term extreme analysis of FPSO mooring systems by the use of Kriging metamodel (Simpson et al. 2001). The paper showed that short-term extreme analysis over all sea states can be replaced by a long-term extreme analysis with a Kriging metamodel. The later can improve the efficiency of the long-term extreme analysis significantly.

Seakeeping capability of a floating type offshore structure is directly connected with operational profit, and the hull form is a dominant factor to the capability (e.g. column size, spacing and pontoon size) in the case of semi-submersible type unit. Therefore, it is important to design optimal hull form which has the best performance. In a study by Park & Jang (2013), a method for the hull form optimisation was presented. It consists of three modules: a panel generation module, a mass estimation module, and an analysis input generation module. In the first module, 10 design variables are defined to represent the hull form such as the width, length, height of the pontoon. Once the values of those variables are determined, the panel model for motion analysis is automatically generated. The second module, mass estimation module, enables to estimate hull lightweight by surface and volume of the model. Finally, a linear hydrodynamic motion analysis is performed to obtain response amplitude operator (RAO).

Construction practices of floating structures such as floating LNG terminals, container terminals, floating production storage offloading and floating breakwaters have increased worldwide. These types of structures are exposed to severe ocean environment conditions such as wave, hydraulic pressure, and impact loads. As a result, new types of floating structures with improved dynamic response and structural performance compared to existing ones have been proposed. One example of such a structure was presented in Lee et al. (2013a) where a regular pontoon-type structure was used as a reference and further developed to a hybrid-floating which has ballast compartments that includes separate space also for an air-gap. In their paper, it was demonstrated in a case study of three floating structures (with the same global dimensions) that the two analysed hybrid-floating structures had reduced motions compared to the conventional pontoon structure. Further, the structural characteristics of the new concepts showed satisfying results with low stresses in the elastic regime.

A number of model tests and theoretical computational methods have been developed during the reporting period with the aim to evaluate the quasi-static response of offshore structures in those cases that innovation impacts design choices. In the following paragraphs, some examples are presented. Qi et al. (2014) presented the engineering analysis, computer simulation, model test validation, and mooring system optimisation for a Dry Tree Submersible (DTS). To verify the correctness of the numerical time-domain analysis results, DTS model test was done over a scale 1:60 in an ocean engineering basin. Heave RAOs showed a significant benefit compared to traditional semi-submersible structure. In another investigation by Van't Veer & Vlasveld (2014), they studied the influence from green water on a twin-hull

FLNG concept. The green water problem was studied by model tests for a turret-moored midscale twin-hull FLNG. Numerical simulations were carried out and compared against experiments. The numerical results underestimated the freeboard exceedance. However, trends in the response over all sea states and locations were well captured.

Kvaleid & Kvillum (2014) performed a nonlinear air-gap analysis of a semi-submersible and compared the results with both linear analysis results and model test results. The representation of nonlinear platform motion was found to be vital for the accurate air-gap prediction. Results from the use of a 3D diffraction-radiation weakly nonlinear hydrodynamic approach resulted in a good agreement between the model test and the nonlinear simulation air gap results in a severe sea state. It was concluded that sufficient modelling of hydrodynamic damping in severe sea states may be important alongside the consideration of viscous drag effects. Furthermore, in Cao & Wan (2014), a numerical study of the strongly nonlinear extreme wave interaction with a floating structure based on the open source package OpenFOAM was presented. The numerical solver used in this study was based on the Navier-Stokes equations, and the Volume of Fluid (VOF) method was employed to capture the complicated free surface. The results of motion response of a floating body under extreme waves were much larger than that under regular waves. Under extreme wave, the motion of floating body became large suddenly when the wave component focused at the location of floating body. The free surface showed strongly nonlinear characteristics. The numerical results were found satisfactory when compared to experiments including motion responses and green water phenomena.

Lu et al. (2012) presented a numerical time domain simulation model using a VOF technique to capture the violent free-surface motion that may be used to study green water phenomena and its impact loading on structures. The incompressible Euler/Navier-Stokes equations, written in an Arbitrary Lagrangian-Eulerian (ALE) frame, were solved using projection schemes and an FE method on unstructured grids. Numerical simulations of green water problems were carried out for green water overtopping a fixed 2D deck, green water impact on a fixed 3D body without or with a vertical wall on the deck, and green water impact on the deck and deckhouse of a moving FPSO model. The numerical results obtained using the proposed models were compared with experimental measurements for each case. The agreement was fairly good and it was concluded that proposed numerical model can be used for simulating green water effects.

6.2 *Types of analysis for various fixed offshore structures*

Stress concentration factors for tubular joints were computed using solid quadratic elements and the results of the computations were compared with experiments reported in the literature and with expressions reported in the literature and in design codes (Thibaux & Cooreman 2013). Kajolli et al. (2014) investigated the effect of loading sequence on fatigue life of a steel jacket. A new damage indicator based sequential law was proposed to estimate fatigue life of offshore steel structures. A verification of the new damage model is conducted by comparing the theoretically predicted damage and fatigue life with experimentally observed damage and fatigue life respectively.

To model the joint flexibilities of the support structures of wind turbines, Tu & Vorpahl (2014) studied the use of a superelement modelling approach which includes the idealisation of detailed joints. Their results were compared to those obtained by a classic beam and shell idealisation for a generic 5 MW jacketed wind turbine. A static analysis including a reduced fatigue load case was conducted to pre-check the different load bearing behaviour of modelling approaches. It was concluded that the mass difference was more than 3% between the beam model and the shell model.

Probability distribution of extreme loads of offshore structures may be of great value for designs. The major obstacle in establishing the probabilistic properties of response is due to the nonlinearities of the wave load mechanism and/or the structural system which may lead to non-Gaussian distribution for the response. The problem is further compounded by current and intermittent loading on members in the splash zone, which have a significant effect on the statistical properties of extreme responses. The Conventional (Monte Carlo) Time Simulation technique (CTS) is frequently used for predicting the probability distribution of the extreme values of response. However, this technique suffers from excessive sampling variability and hence a large number of simulated extreme responses (hundreds of simulated response records) are required to reduce the sampling variability to acceptable levels. Three different versions of a more Efficient Time Simulation technique (ETS) were compared by exposing a test structure to sea states of different intensity (Abu Husain et al. 2013b). Further development of this technique was made for more accurate estimates of the long-term probability distribution of the extreme response (Abu Husain et al. 2013a). Abu Husain et al. (2014) validated the ETS procedure against results from CTS procedure by comparing probability distribution of extreme values of overturning moment from the two methods. Corresponding results for quasi-static responses were found to be in very good agreement.

The suitability of the Generalised Extreme Value (GEV), and the Generalised Pareto (GP) distributions for modelling of extreme responses, was presented in Wang et al. (2013b). They compared the GEV and the GP distributions with empirical distributions derived from extensive Monte Carlo time simulations. Mohd Zaki et al. (2013b) presented further development of the Finite-Memory Nonlinear System (FMNS) method which is an identification technique to establish a relationship between the output and input of some nonlinear systems. The computational effort using the FMNS method can be about 35 times more efficient than a conventional time simulation procedure. In their study, the response of an offshore structure exposed to Morison's wave loading was studied. The FMNS modelling technique was used to model the drag-induced component of quasi-static response, the inertia-induced component of quasi-static response, and the (total) quasi-static response of a case study offshore structure. The results from several FMNS simulations were compared against conventional time simulation method with good agreement between the two simulation methods.

Linear random wave theory is frequently used to simulate water particle kinematics at different nodes of an offshore structure from a reference surface elevation record. However, it is well known that linear random wave theory leads to water particle kinematics with exaggerated high-frequency components in the vicinity of mean water level. To avoid this problem, Mohd Zaki et al. (2013a) suggested that empirical techniques such as Wheeler and vertical stretching methods may be used to provide a more realistic representation of the wave kinematics in the near surface zone. A fixed platform in a water depth of 100 m was used as the case study. The structure was modelled as linear and its dynamic response was evaluated through mode superposition procedure. It was shown that the probability distributions of extreme responses based on the Wheeler and the vertical stretching methods can be significantly different from each other, leading to uncertainty as to which method should be used in design.

Baarholm et al. (2013) presented nonlinear time domain irregular wave simulations for the Kvitebjørn jacket platform located in the North Sea. The aim was to quantify the Equivalent Dynamic Amplification Factor (EDAF). It is the factor one has to multiply the q -probability quasi-static response with in order to obtain an adequate estimate of the q -probability dynamic response. For each of the selected extreme sea states, both quasi-static and dynamic response simulations were carried out for several wave realizations using different seeds. Based on the quasi-static response and dynamic response, EDAFs were calculated for different response measures in the jacket. These factors can subsequently be used in ultimate limit state (ULS) and accidental limit state (ALS) analyses of the platform.

Due to increased estimates of extreme wave crest heights and subsidence of seabed, many fixed offshore structures experience problems due to negative air-gap effects. Scharnke et al. (2014) studied wave-in-deck loads by model tests and simplified load models where the wave kinematics were estimated using the Stokes 5th order theory. Simplified models were found to underestimate the forces measured in the model tests. Iwanowski et al. (2014) used an industrial CFD tool to study the wave-in-deck loads obtained in model tests described by Scharnke et al. (2014). It was found that a careful setup of CFD simulations could reproduce the measured wave-in-deck force, if the incoming wave was close to regular/steady state excitations. For extreme events in irregular wave conditions, it was not possible to reproduce the measured wave-in-deck loads when a Stokes 5th order theory was used for the wave kinematics.

Lu et al. (2014) used a new wave maker based on New Wave theory to generate extreme waves at the inlet boundary with the aim to analyse the wave-in-deck loading. Accurate prediction of water surface elevation and wave impact force was reported using the proposed method. A unique advantage of the wave generating strategy presented is that it can produce the required waves at a prescribed time and location, and thus reduce the total simulation time as compared to conventional CFD methods.

Abdussamie et al. (2014) studied the wave-in-deck force on the bottom plate of a rigidly mounted box shaped structure that may be subject to unidirectional regular waves. An analytical momentum approach recommended by classification societies and a VOF method were utilised to study the wave-in-deck load. Numerical results were compared to results from model tests, and it was concluded that CFD techniques can be used for the solution of wave-in-deck problems provided that a convergence study is done against a representative tank experiment.

A Navier-Stokes code was employed in conjunction with the interface capturing level-set method for the prediction of wave impact on a jack-up structure under hurricane wave conditions (Chen et al. 2013). An overset grid system was employed to facilitate the simulation of complex flow around a generic jack-up structure with 3 supporting legs and simplified topside equipment. Time-domain simulation of green water and wave impact loads were performed for random 3D short-crested waves based on the directional wave spectra of Hurricane Katrina.

Design loads from breaking wave impacts towards a GBS platform were studied by Oberlies et al. (2014). Model tests of the structure in storm waves were executed to provide local wave impact load data

on the shaft of the GBS. An approach where probabilities of sea states and wave impacts were combined into a joint probability distribution was used to derive yearly exceedance probabilities of wave impacts. This method provided design values based on the probability of a particular response instead of the probability of a specific input (i.e., sea state return period).

An experimental and numerical evaluation of the impact response of ring-stiffened cylinders struck at mid-bay with a mass having a rigid knife-edge indenter was studied by Cerik et al. (2014). The experiments aimed at reproducing a collision scenario involving offshore installations with supply vessels. Dynamic force-displacement curves and strain measurements were presented. The results were compared with the nonlinear FE simulations performed using ABAQUS/Explicit software. It was observed that the presence of ring-stiffeners has a significant effect on the resistance against denting and also permanent deformation.

Wave breaking on structures induces a turbulent multi-phase flow and hence its characterisation represents a challenging task for both experimentalists and numerical modellers. Alemón-Arcos et al. (2014) investigated the simulation of offshore wave-structure interaction using OpenFOAM software for a tension-leg platform with a scale ratio 1:168. The numerical results suggested that the vertical velocity cannot be ignored because it can exert a large upward vertical load to equipment and facilities close to the frontal edge of the deck.

The ageing of offshore infrastructure presents a constant and growing challenge for operators. Ageing is characterized by deterioration, change in operational conditions or accidental damages which, in the severe operational environment offshore, can be significant. Nezamian & Altmann (2013) studied the structural integrity of thirteen identified platforms under existing conditions as these platforms are either nearing the end of their design life or have exceeded more than 50% of their design life. Information on history, characteristic data, condition data and inspection results were collected to assess the current state and to predict the future state of the facility for possible life extension. In-service integrity assessments, pushover analyses, corrosion control and cathodic protection assessments and weight control reports were completed to evaluate the integrity of these facilities for requalification to 2019 and life extension to 2030.

The existing knowledge on the structural integrity assessment of offshore platforms may benefit from case studies on the life extension evaluations of aging structures. A case study for the structural integrity assessment of an existing 8-legged aging drilling platform located in the Persian Gulf and now 42 years old was proposed. The objective of the study has been to check whether the offshore structure in question is fit for purpose for a life extension of 25 years beyond 2012 (Golpour et al. 2013).

Amdahl et al. (2012) and Amdahl & Storheim (2013) studied the scenario of broad side ship collision with jacket legs in accordance with the NORSOK standards (NORSOK 2004). Accordingly, a jacket leg and the shipside of a typical supply vessel were modelled, and various impact simulation scenarios were carried out with LS-Dyna software. The resistance to denting of the jacket leg and the resistance to indentation of the ship side were compared against the NORSOK recommendations. The distribution of energy dissipation and damage to the ship and the leg was studied for various leg thicknesses and two contact positions. Travanca & Hao (2014) evaluated the consequences of bow impacts for different collision scenarios between ship and jacket structures. Two different vessels and two jacket designs (three and four legs) were studied. The impact energy was in the range 59-74 MJ. Possible plastic deformation mechanisms were analysed and simplified approaches were considered for prediction in comparison with the numerical results carried out by FE analysis.

Ice-induced vibrations caused by moving ice have been monitored on some of the platforms deployed in north part of Bohai Sea of China. Zhang et al. (2012a) present field monitoring of ice-induced vibrations and full-scale measurements of ice force. The dynamic behaviour of ice-resistant jacket structure and potential failure modes provoked by ice-induced vibrations were discussed. It was concluded that for jacket structures, which are designed to satisfy criteria to resist a maximum ice force, the ice-induced vibrations may increase the risk for e.g. fatigue failure. Moreover, Wang et al. (2012) presented a new direct ice force measurement technology of jacket structures conducted in the Bohai Sea of China. In their paper, a description of specially designed ice load panels to be mounted on any type of floating offshore structure is presented followed by examples of measurements where the new ice force measurement panel has been successfully used.

Oberlies et al. (2014) presented a methodology to estimate iceberg impact loading, as well as analyses and design of exterior walls of the Hebron Gravity Based Structure to resist the 10,000-year return period iceberg impact loading. The iceberg impact load on the Hebron Gravity Based Structure was calculated using a probabilistic analysis including Type II uncertainty analysis with a logic tree. When subjected to the 10,000-year iceberg impact, the Hebron Gravity Based Structure was designed to be highly utilised, that is, the concrete and rebar were stressed to their specified strength. This was done by allowing internal redistribution of elastic forces and by using nonlinear FE analyses.

Zhang et al. (2014b) investigated two vibration-based methods for detecting damage for tripod type offshore wind turbine. These methods are the Modal Strain Energy (MSE) and the Modal Strain Energy Decomposition (MSED). The results indicated MSE performs better for column member while MSED does better for brace members. If the measured data is complete, damages can be localised easily in both two damage locations.

Li et al. (2014) studied the impact between a wind turbine monopile and the transition piece during installation. The transition piece makes the link between the fixed monopile and the wind turbine tower. Due to the random motion of the transition piece when installing from a floating vessel, vertical impacts is a function of the limiting crane tip motion, environment condition, as well as the dynamic behaviour of the installation vessel. The study gives indications about the maximum vertical impact velocity to be respected in such operations.

The optimisation of offshore wind mill's structure becomes today an important field of investigation. This task is generally done during the initial design stage, as for the ships' structure. The technical solution chooses for the submerged part of wind turbines is mainly influenced by economic reasons. During the last 3 years, it seems that the most economical solution is represented by the jack-up support types. Schafhirt et al. (2014) demonstrated the feasibility of the genetic algorithms optimisation for the jack-up support for wind turbines. A design and an analysis interface for the optimisation using genetic algorithms was developed. Using a simplified geometry and one load case, it was shown that the complexity of the optimisation model was the same as for a realistic application.

6.3 Uncertainty, risk and reliability in offshore structural analysis

Sources of uncertainty for pile-founded fixed steel jacket platforms can be divided into three different categories: (a) uncertainties associated with the soil-pile modelling parameters in clay soil, (b) the platform jacket structure modelling parameters, and (c) the uncertainties related to ground motion excitations (El-Din & Kim 2013). The main uncertainty arises from the soil-pile interaction. El-Din & Kim (2013) investigated the sensitivity of the seismic response parameters to the uncertain modelling variables of pile-founded fixed steel jacket platforms using tornado diagrams, first-order and second-moment approaches, as well as static pushover analysis techniques.

Reliability study of axially loaded jacket piles in sand was presented by Ronold et al. (2012) aiming at predicting their probability of failure in compression. A first-order reliability method (FORM) was used for probabilistic modelling calculations. It was concluded that the new design methods need further validation against large scale test results in order to serve as consistent design methods. Alternatively, as a minimum, they need to be accompanied with restrictions with respect to range of validity and extrapolation in use.

Khedmati et al. (2013) presented a concise reliability analysis of an offshore platform under fatigue loading conditions. The fatigue analysis was based on the S-N approach considering fixed supports of the piles and nonlinear simulation of soil reactions. A wide range of uncertainty parameters were included in the fatigue reliability analysis, such as hydrodynamic coefficients, marine sediments, stress concentration factors, stress intensity factors, and initial imperfections. The systematic procedure can be applied on other types of offshore structures.

The effect of soil-structure interaction is also important issue in jack-up rig. Mirzadehniasar et al. (2012) employed both the singular New Wave and multiple constrained New Waves to simulate random sea states in order to investigate the nonlinear dynamic response and collapse mechanisms of a jack-up platform subjected to extreme waves. Five different foundation types (pinned, fixed, and spudcans with 152 MN, 190 MN and 228 MN preloads) were investigated. The probability of collapse, the critical areas dominating the collapse mechanisms, the maximum deck displacements and the variation of the results for 100 randomly generated New Waves were discussed. It was also concluded that for assessment of the ultimate strength of the jack-up platform, neither pinned nor fixed supports can adequately substitute for a more sophisticated model that tracks the load-displacement behaviour of the spudcan foundations.

Dyanati & Huang (2014) developed an ultimate limit state function of a steel offshore platform based on base shear capacity and demand, and calculated seismic reliability of the prototype structure against collapse. A 3D FE model was used to calculate the values of limit state functions in terms of both capacity and demand.

A reliability-based methodology was presented in Li et al. (2013c) for an assessment of acceptance criteria of fixed offshore platforms in the northern South China Sea under extreme storm events. A structural reliability method was proposed to quantify the probability of platform failure subjected to extreme storms based on a long-term distribution of the extreme environmental load considering the joint occurrence of wave, current and wind.

There is research to mitigate computational burden of reliability analysis. Gholizad et al. (2012) investigated the fatigue reliability of fixed offshore platforms by analysing different failure scenarios. In order to calculate the occurrence probability of each scenario, a massive reliability analysis should be done for each of the corresponding sub-scenarios using an artificial transfer function instead of implementing time consuming traditional methods. Based on the calculated values, the probability of occurrence was obtained for each scenario, and finally, the failure probability of the entire system was calculated.

Uncertainty coming from fabrication process was treated. Steel circular hollow sections have been extensively used in fixed offshore structures because of their high strength-to-weight ratio, non-directional buckling and bending strength, and low wave resistance. In a tubular joint, circular hollow members are connected by welding the prepared end of the brace members onto the surface of the chord member. The tubular DKT-joint is the geometric configuration where the chord is welded with two outer braces and one central brace. Lotfollahi-Yaghin & Ahmadi (2012) studied the results of FE analysis on the 81 steel multi-planar tubular DKT-joints. These numerical results were used to determine the probability distribution of SCFs along the weld toe of the central brace under axial loads. The best fitted distribution was determined and its parameters were calculated based on the maximum likelihood method. It was concluded that the proposed probabilistic density function can be used for fatigue reliability analysis of such structures.

For a floating offshore structure, the random nature of the sea state is one of the main uncertainties in loading. To more confidently simulate wave loads, all of the randomness of water surface should be taken into account. Load history also plays an important role in the nonlinear dynamic response of structures. Accordingly, an appropriate way to consider these effects is dynamic analysis of offshore platforms using random time-domain generation of the sea surface over a long period of time. Chen et al. (2013) presented a rational reliability assessment procedure for hull girder ultimate strength assessment of ship-shaped FPSOs. The hull girder ultimate strength of FPSOs was calculated by a rigorous progressive collapse analysis using Smith's method. The stochastic model of Still-Water Bending Moment (SWBM) was established based on the loading conditions from the operation manual of FPSOs. A stochastic model for the extreme value of Vertical Wave-Induced Bending Moment (VWBM) was proposed based on the long-term distribution of VWBM and the extreme value theories. Hull girder reliability was measured by a first-order reliability method.

Helmers et al. (2012) developed an efficient Monte Carlo method for the stochastic analysis of slamming loads on marine structures. The probability distribution of the maximum impact force during slamming was established for a given stationary sea state. The method was demonstrated by using a uniform wedge and Wagner's flat plate theory. When the observed data are limited, statistical estimates can be used to supplement or even replace information based on the Bayesian approach. Vasconcelos de Farias & Netto (2012) applied these concepts to the study of the structural integrity of the hulls of FPSO units. Two case studies were conducted with a focus on corrosion damage due to its high incidence among the observed damages.

Fire accidents have been recognised as a major hazard of offshore facilities in oil and gas industries and many researches were focused on the consequence analysis to evaluate the severity of the accident. Kim et al. (2012b) presented a practical procedure for the nonlinear structural consequence analysis of structures under fire. The thermal and structural response analysis has been performed in this study using a commercial nonlinear FE analysis code. The results of the structural response analysis were then compared to the experimental results. Jin & Jang (2013) proposed a new probabilistic fire risk assessment procedure where structural cumulative failure frequency was calculated from CFD fire simulation and a heat transfer analysis. Transient effect of hydrocarbon release was also properly reflected by applying an effective method called "snapshot". In Jin & Jang (2014) the new procedure of fire risk analysis was further discussed and demonstrated on a specific case.

As a conventional measure to mitigate structural failure under fire, Passive Fire Protection (PFP) is widely used on main structural members. However, an excessive use of PFP can cause considerable cost for material purchase, installation, inspection and maintenance and long installation time can be a risk since the work should be done nearly at the last fabrication stage. Friebe & Jang (2013) presented a few case studies on how different applications of PFP have influence on collapse time of an FPSO module structure. A series of heat analysis and thermal elasto-plastic FE analysis were performed for different PFP protections and the resultant collapse time and the amount of PFP were compared with each other.

Gas explosion has been categorized as an important issue of the design of offshore structures. Han et al. (2012) presented practical considerations for the nonlinear dynamic structural analysis of offshore structures under blast loadings from gas explosion accidents. Numerical investigations including modelling of blast loads and idealisation of structural materials and members have been conducted for the overall topside structures. As a design step for offshore structures under blast loadings, an applicable guidance on the FE analysis was described in this study.

A practical procedure was presented for nonlinear structural response analysis of FPSO topside blast wall under explosion loads (Sohn et al. 2012, 2013). Two methods were adopted for nonlinear structural consequence analysis of FPSO topside blast walls. One has been computed based on the use of time-domain nonlinear FE analysis and the other was performed with single degree of freedom method based on resistance function. The relationships between blast pressures versus impulse of FPSO topside blast walls were developed.

Ahn et al. (2014) discussed methodology, conditions, and design consideration of dropped object analysis on a panel/deck structure using dynamic FE analysis. Results from direct FE analyses were compared against those from the simplified energy method described in DNV (2010). Parameter sensitivity analysis was carried out in order to study the influence from parameters and model uncertainty on energy absorption in the panel/deck structure. It was concluded that results were influenced by the application of failure criteria according to the rule requirements, application of material properties, dropping position, condition of the object etc.

Ren et al. (2014) investigated the use of a Risk-Based Inspection (RBI) plan combined with a fatigue failure analysis on a jacket platform located in the South China Sea. An RBI plan combines member failure consequence and probability and fatigue failure analysis in order to develop the final inspection plan. The paper presented also the methodology to establish a practical and reliable inspection plan for such offshore structures.

Valdman (2014) presented the results of risk assessment and a risk management analysis was performed as part of the environmental impact studies of offshore processing and transportation systems designed for Arctic seas. It was noted that in spite of overall improvement in the safety levels of offshore operations achieved over the last 10 to 20 years, the major accidents are still frequent and the safety barriers for efficient risk management and control remain to be an urgent issue.

7. BENCHMARK STUDY

Design against impact loads (slamming) can be challenging, time consuming and involve complex calculations. Application of simplified, quasi-static calculation approaches will make the design process much easier. The objective of this benchmark study was to evaluate the accuracy of such simplified approaches within the context of quasi-static impact load analysis. During recent years, much attention has been directed towards the structural integrity of free fall lifeboats when they are subjected to impact loads. The committee has received access to data, both structural drawings and data from drop tests (trajectory information, measured pressures, etc.); the committee acknowledges OLF, Schat-Harding, Statoil and Marintek for the permission.

7.1 Methodology

The case study lifeboat is a Schat-Harding FF1000 model. The main particulars of the lifeboat are presented in Table 3. The hull is made of Chopped Strand Mat (CSM) laminate. The hull shape and structural drawings were provided by Schat-Harding. Model tests of the lifeboat were carried out by Marintek using a 1:9 scale model, as illustrated in Figure 4. The skid angle was 50 degrees. Several force transducers for measuring of the pressure were installed in the model. Two of them were located on the bottom of the lifeboat and they were used in the case study. The locations of these transducers are defined in Table 4 and shown in Figure 5. An FE model provided by DNV-GL is shown in Figure 6 and Table 5 presents the material properties used in the FE model.

Table 3. Main particulars of case study lifeboat.

Parameter	Value
Overall length (L_{pp})	12.57 m
Overall width (B)	3.34 m
Displacement (105%: light vessel + 64 persons á 90 kg)	16.8 metric tonnes
Longitudinal centre of gravity (forward of stern)	5.29 m
Radius of gyration in pitch (% of LOA)	25%

Table 4. Definition of locations used in the benchmark study.

Location	x (from stern)	y	z
S1	2.25 m	1.0 m	1.1 m
S2	8.20 m	1.0 m	1.1 m

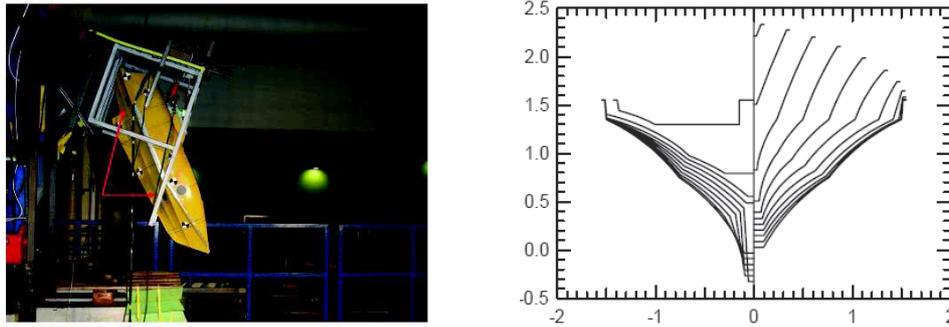


Figure 4. Model test at Marintek of a free fall lifeboat. (Left) Test setup and (right) body plan.

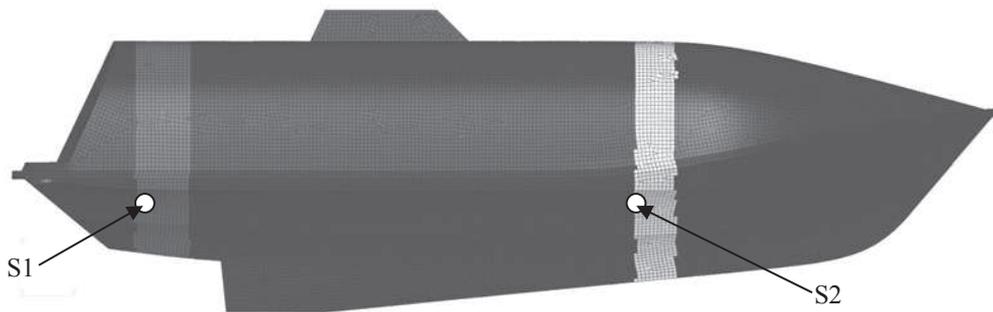


Figure 5. Location of the transducers S1 and S2 (see Table 4 for the exact locations).

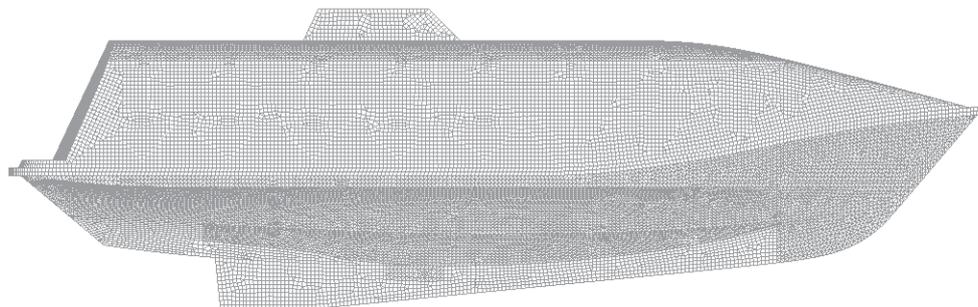


Figure 6. Illustration of the full finite element model.

Table 5. Material properties.

Property	CSM	Structural foam	Buoyancy foam
E_x [MPa]	7500	42	5
E_y [MPa]	7500	42	5
E_z [MPa]	5000	42	5
ν_{xy} [-]	0.32	0.3	0.4
$\nu_{xz} = \nu_{yz}$ [-]	0.32	0.3	0.4
G_{xy} [MPa]	3000	-	-
$G_{xz} = G_{yz}$ [MPa]	1500	-	-
ρ [kg/m ³]	1460	42	100

A high speed underwater video camera was used to record the underwater trajectory. It was used to estimate the relative velocity between the lifeboat bottom and the water surface. An example is shown in Figure 7 from a test performed in irregular waves, $H_s = 6.8$ m, $T_z = 6.8$ s. This test was used as the basis for the benchmark study.

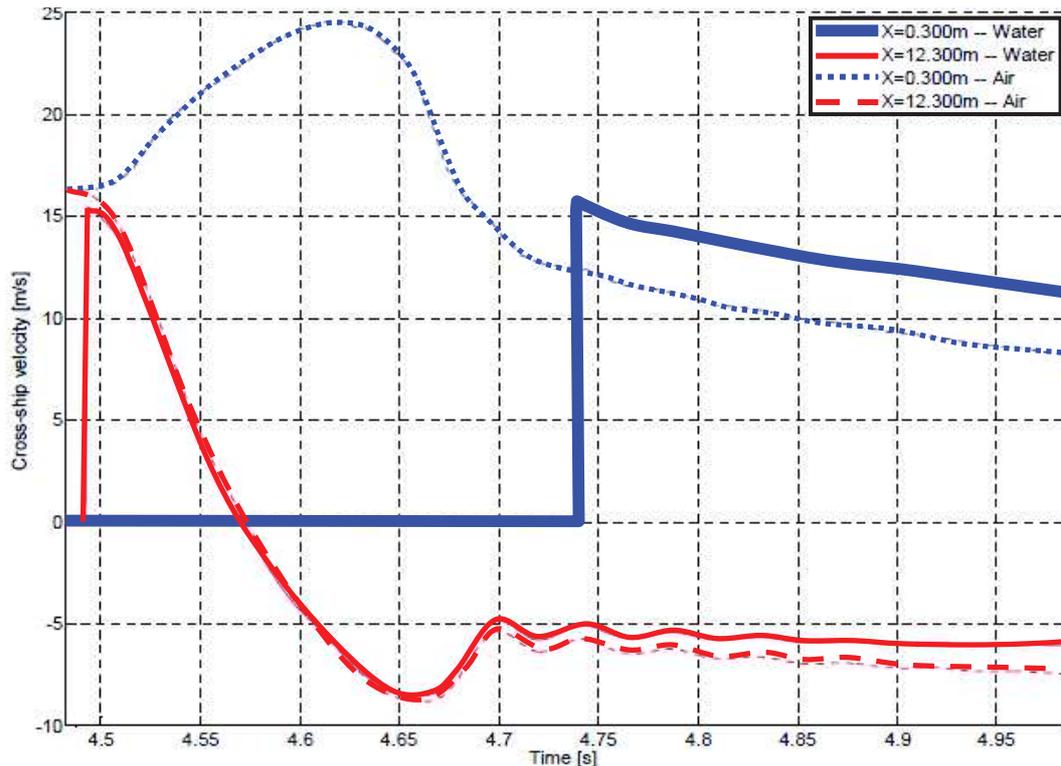


Figure 7. Cross-sectional velocities for aft (upper thick solid, 0.3 m from stern) and fore (lower dashed, 12.3 m from stern) section. Solid lines and dashed/dotted lines represent the velocities relative to the water (wave motion included) and to the air (earth-fixed coordinate system), respectively. Zero velocity relative to water means that the section bottom is above sea surface.

7.2 Simplified methods

The space average pressure was found as $p = 0.5\rho C_p V^2$, where V is the velocity taken from experimental data and C_p is the pressure coefficient taken from DNV (2014a) as $C_p = 2.5 \cdot (\tan(\beta))^{-1.1}$. This value represents the pressure over a broader area (i.e. several plate fields of a ship). The calculated pressure was compared with the measured pressure presented in Figure 8. It was found that the calculated peak values deviate significantly from the measured values. The main reason for these deviations may be due to the influence of 3D effects, which can be prominent in the bow area (ABS 2011). Another factor that affects the results may be the model test conditions. Model tests were performed in an irregular wave environment ($H_s = 6.8$ m, $T_z = 6.8$ s). This may complicate the calculation of impact pressure and can explain some of the deviation.

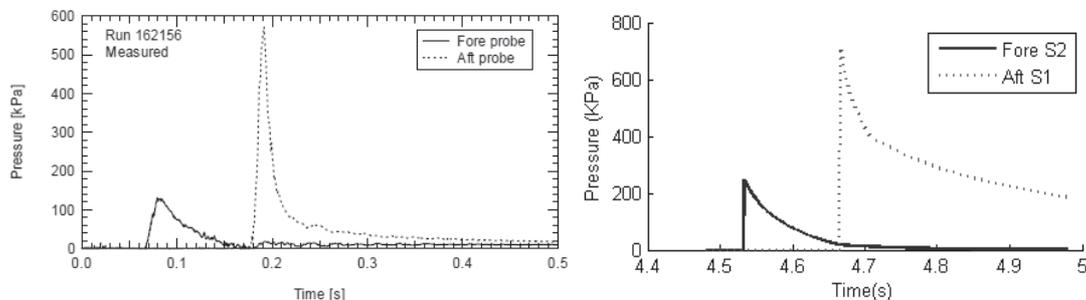


Figure 8. (Left) Measured and (right) calculated pressures.

The maximum strain in the middle of the plate field was found by modelling a strip of the composite plate as a beam, see Figure 9. The strain was calculated by two methods. The first was based on results from experiments with stiffened panels. These experiments were reported by Faltinsen (1999) and were performed using aluminium and steel panels. The results of these experiments are summarised in Figure 10, where the non-dimensional strain is plotted as a function of non-dimensional impact velocity.

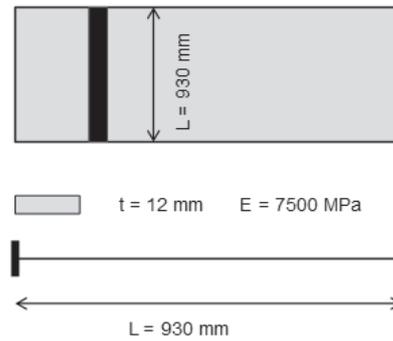


Figure 9. Plate strip model of lifeboat bottom.

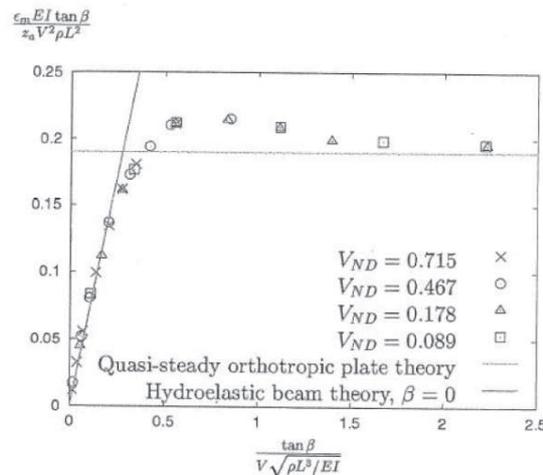


Figure 10. Maximum non-dimensional strain amplitude in the middle of a longitudinal stiffener (Faltinsen 1999).

For comparison, the response was also based on a pure static response combined with a dynamic amplification factor. The strain was found as $\epsilon = (Mt)/(2EI)$, where $M = (pL^2)/24$. The dynamic amplification factor was calculated from formulas in standard textbooks on structural dynamics (see e.g. Thomson 1972). The natural period of the plate strip was $T_n = 1.3$ s, whereas the duration of the pressure pulse was $t_1 = 0.01$ s. If it is assumed that the pressure pulse is triangular, the dynamic amplification factor is $D = \pi t_1/T_n = 0.0242$. The hydrodynamic added mass can be estimated as $A = 0.5\pi\rho R^2$. When it is included, the natural period becomes 4.7 s and the dynamic amplification factor is reduced to 0.007.

Hydroelastic effects are important when $\tan(\beta) < 0.25V(\rho L^3/(EI))^{0.5}$ (DNV 2014a). For this case, $0.25V(\rho L^3/(EI))^{0.5} \approx 0.1$, whereas $\tan(30^\circ) = 0.58$, i.e. hydroelastic effects are not important. The results of the simplified calculations are presented in Table 6 and Table 7. It is seen that when the effect of hydrodynamic added mass is included, the results from the simplified quasi-static method are quite close to the results based on experimental data presented in Figure 10; see Heggelund et al. (2015) for additional calculations and assessment of the results.

Table 6. Results based on experimental data.

Property	S1	S2	Comment
Velocity	17.6 m/s	12.8 m/s	From measurements (Figure 7)
Deadrise angle	30°	40°	-
Pressure	670 kPa	140 kPa	From measurements (Figure 8)
Pressure coefficient, C_p	4.2	1.7	Based on DNV (2014a)
Strain	1.07 μ s	0.540 μ s	Based on Figure 10

Table 7. Results from simplified quasi-static method.

Property	Dry		Including hydrodynamic added mass	
	S1 (aft)	S2 (fore)	S1 (aft)	S2 (fore)
Velocity	17.6 m/s	12.8 m/s	17.6 m/s	12.8 m/s
Deadrise angle	30°	40°	30°	40°
Pressure coefficient, C_p	4.6	3.0	4.6	3.0

Pressure	726 kPa	255 kPa	726 kPa	255 kPa
Dynamic amplification factor	0.02	0.02	0.007	0.007
Strain	3.57 μs	1.28 μs	0.97 μs	0.35 μs

7.3 Quasi-static linear FE analysis

FE analysis was performed using the FE model shown in Figure 6. The pressure was applied on two strips of the lifeboat as shown in Figure 11. Static pressure was assumed in the FE analysis. The impact pressure loads were represented by equivalent static pressures, which were applied separately on the specific strips of S1 and S2. Inertia relief was applied as boundary condition. The analysis was performed as pure quasi-static analysis, i.e. no dynamic factors were employed in the current results. Also 3D effects were neglected in the analysis. This simplification was considered to be valid since the hull profiles of the investigated sections were rather constant.

The quasi-static analysis was performed by two parties in the committee using different analysis codes. The results are presented in Table 8. It was found that stress/strain and deformation at these two points are rather small, especially in comparison with the peak values in the respective sections. The results presented seem comparable with the results from the simplified quasi-static method (see Table 6) when hydrodynamic added mass is not included. The agreement is quite surprising since the dynamic amplification factor is very low and the effect of dynamics is not included in the FE analysis.

Table 8. Results from quasi-static FE analysis.

Property	Chalmers		SNU	
	S1 (aft)	S2 (fore)	S1 (aft)	S2 (fore)
Analysis code	ABAQUS/CAE 6.13-3		Patran/Nastran	
Velocity	17.6 m/s	12.8 m/s	17.6 m/s	12.8 m/s
Pressure	726 kPa	255 kPa	726 kPa	255 kPa
Strain	3.92 μs	1.49 μs	3.42 μs	1.45 μs

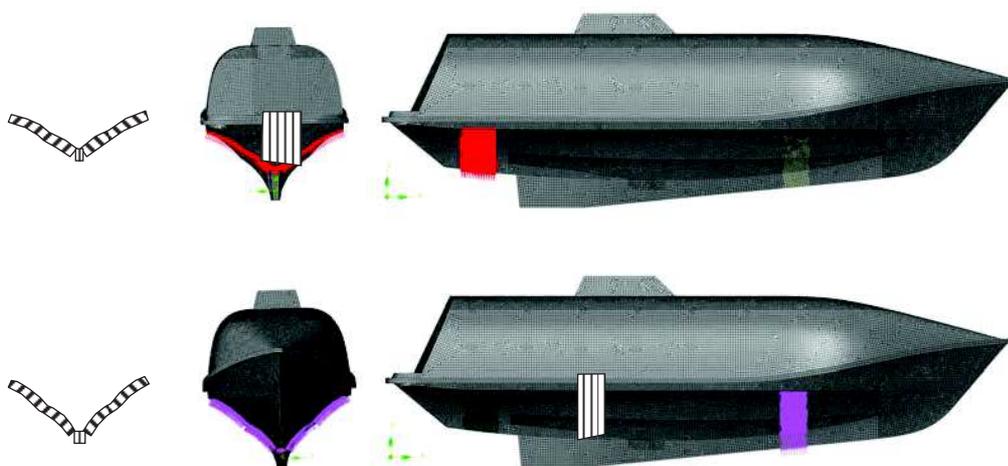


Figure 11. Pressure application to FE model. (Upper) Equivalent static pressure applied on S1 and (lower) equivalent static pressure applied on S2.

7.4 Nonlinear, transient dynamic FE analysis

The analysis presented in Section 7.3 has been based on a linear, static analysis. A complete analysis need to include nonlinear effects caused by large deformations (geometric nonlinearity). Also, due to the short time duration, dynamic amplification should be included. An investigation was carried out based on a transient dynamic analysis of a strip taken from the FE model. The position of the strip was at the fore sensor and the width of the strip was 0.1 m. X -symmetric boundary conditions were imposed on both the front and the rear sides in the longitudinal direction and y -symmetric at the transverse centreline. Additionally, the strip model was fixed at knuckles or corners where longitudinal structural members pass. Thus, only the local plate response is included.

The model was loaded with uniform pressure on the bottom as shown in Figure 12. Different analyses with different pulse durations, Δt , were also performed. The three shortest durations were comparable

with the duration from the experimental results (see Figure 8). For comparison with the quasi-static analysis, a dynamic analysis with long pulse duration (9 seconds) was also performed. The analyses were carried out using the commercial software LS-Dyna. All analyses included geometric nonlinearities, the material behaviour is linear (purely elastic) and strain rate effects of the material were not included.

The results from the long duration analysis are shown in Figure 13. The strains at the upper and lower surface as well as in the midplane of the plate are plotted. It is seen that the difference between these values is small. The maximum strain is $5.5 \mu\text{s}$ and the membrane strain is $5.0 \mu\text{s}$. This means that the load is carried mainly by membrane stress and that the effect of local bending is small. As the membrane stiffness dominates, the strain from the FE analysis is much less than the strain from the analytic plate strip model ($56 \mu\text{s}$).

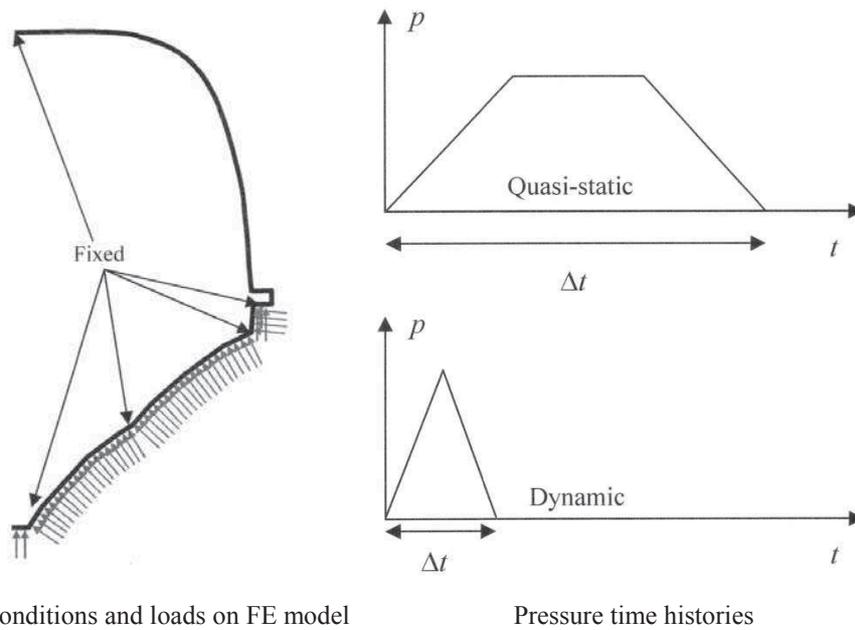


Figure 12. (Left) Strip model and (right) applied loads for nonlinear, transient dynamic analysis.

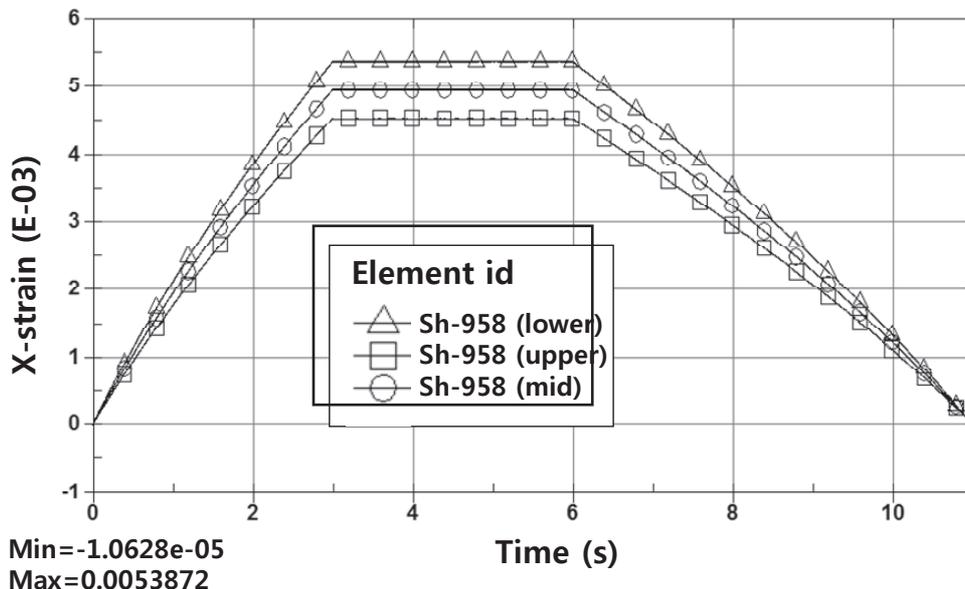


Figure 13. Response for long duration analysis ($\Delta t = 9 \text{ s}$).

The same pressure was applied to the global FE model shown in Figure 11, but, the applied area was extended in the longitudinal direction to be equivalent to the strip model. The resultant static strain was $2.6 \mu\text{s}$, which is about half of the strip model. The reason seems to be that the longitudinal stiffness of the plate between two neighbouring web sections is taken into account in the global FE model.

The strain from the short pulse duration run ($\Delta t = 0.05 \text{ s}$) is shown in Figure 14. Also here, the bending stress is negligible. Results for all pulse durations are summarized in Table 9. It is clearly seen that the

stiffness of the structure is so large that the dynamic response is almost the same as for the static analysis, i.e. the dynamic amplification factor is close to 1 and the response is quasi-static.

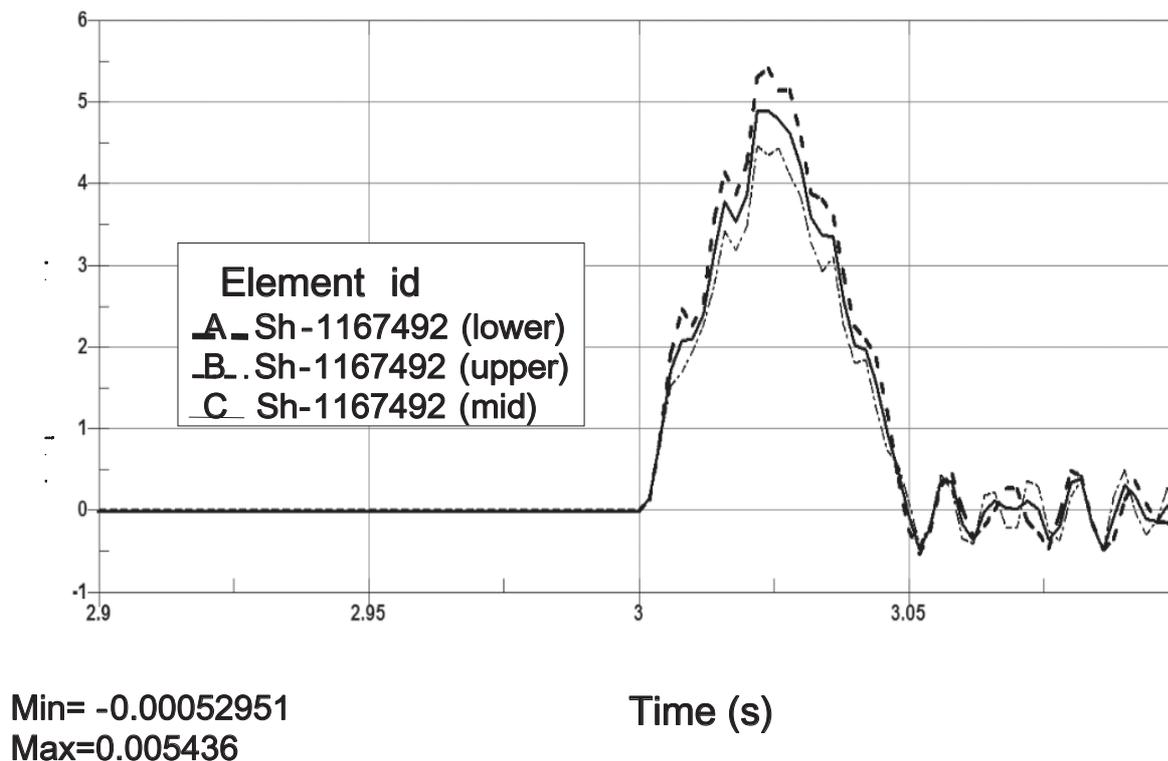


Figure 14. Transient dynamic response for $\Delta t = 0.05$ s.

Table 9. Maximum strain from transient dynamic analysis with $p_{\max} = 273$ kPa.

Δt [s]	Strain [μs]
9	5.53
0.1	5.57
0.05	5.45
0.01	8.16

7.5 Concluding remarks

Quasi-static prediction of structural response to impact loads was investigated based on basic mechanics, experimental results for steel and aluminium panels and quasi-static FE analysis. Slamming loads on the bottom of a free fall lifeboat during water entry was selected as the case study. It was found that results from simple beam theory combined with basic formulas for dynamic response assessment was in good agreement with the experimental results. It was found that hydroelastic effects were not important for this case.

The peak pressure calculated with the parametric formulas in DNV (2014a) deviates from the measured values. The main reason for this is believed to be due to 3D effects. The strain calculated by simple beam theory combined with basic formulas for dynamic response assessment was in good agreement with experimental results for steel and aluminium panels as long as the hydrodynamic added mass was included. Based on simple beam theory, it was found that the dynamic amplification factor was very small, approximately 0.01.

The strain calculated by nonlinear, transient dynamic FE analysis showed that the geometric nonlinearities were large so that the loads were carried mainly by membrane stress and that the effect of local bending was small. The effect of plate bending was of secondary importance. The additional stiffness was so large that the response was almost quasi-static, i.e. the dynamic amplification factor was close to 1. The maximum strain was of the same order of magnitude as the results from the simplified calculations, though.

Finally, linear FE analysis was also performed using inertia relief. The results were comparable to the results from the methods discussed above. However, this was believed to be a coincidence since neither the dynamic response or geometric nonlinearities were included.

8. CONCLUSIONS AND RECOMMENDATIONS

The committee reviewed recent works concerning topics identified by the committee mandate. The report presents a summary of current publications that are relevant to quasi-static analysis methods applied to ships and offshore structures. The summary presents a general introduction to strength assessment approaches followed by descriptions of progresses of calculation procedures, uncertainties associated with reliability-based quasi-static response assessment, ship structures, offshore structures, and a benchmark study of slamming loads on the bottom of a free fall lifeboat during water entry. The following paragraphs highlight conclusions and observations from the literature review and the benchmark study.

Research developments find their way more and more into industry standards and classification rules (e.g. IACS CSR-BC&OT). It should be the aim of classification societies to explicitly provide the possibility for applying rational, first principle-based analysis in the design of ships and offshore structures.

The analysis methods utilised for ships and offshore structures vary depending on the design stages of construction. This report provided an overview of these methods and the work being carried out to enhance these approaches. It touched on rapid first principles assessment methods for early stages, to design stages where more detailed modelling and analysis techniques are required to support production. It also addressed the evaluation of local and global behaviour utilising FE techniques. FE model methodology and assessments have become an integral tool in design of marine structures. This tool is used to assess various loading conditions encountered by ships and offshore structures, understand the impact from structural degradation, assess wave loadings, evaluate ice loading conditions, and address damage due to collisions. Further, for evaluation and validation of the calculated results, we will continue in the future rather have to rely on thoughtful experiments, either on model or full-scale, as they observed the appearance of a highly complex dynamic character whose accuracy solutions are not only linked to the increasing advancement of technology (e.g. computer performance), but above all for thinking in detecting neglected and/or forgotten effects.

The topic of structural reliability analysis is of special interest for quasi-static response of ships and offshore structures as this is related to uncertainties in quasi-static calculation models. The uncertainties in the environmental loads and structural resistance of marine structures can significantly affect the structural performance and safety. It is important that we understand the extent to which uncertainties associated with quasi-static response analysis influence design considerations and structural reliability. In the report, recent studies on uncertainties associated with the reliability-based quasi-static assessment of ships and offshore structures were reviewed. The focuses were on the uncertainties of loads and load combination factors, probabilistic modelling of corrosion and its effects on structural strength, reliability-based design and assessment method, and risk-based inspection, maintenance and repair.

In the ship structures chapter, a review of developments in international rules and regulations was presented. A review of recent developments of special ship concepts such as container ships, LNG/LPG vessels, service vessels for wind mills and offshore platforms, passenger vessel and sailing yachts in relation to quasi-static response was provided.

For an offshore structure, structural integrity is the most critical issue since it is operated at a fixed site for its life time and a regular inspection in a dry dock is not feasible like a ship. There has been a lot of research on wave impact loads under harsh condition such as bottom slamming, wave run-up, wave slap on bow structure, and green water. For a simulation of the strongly nonlinear extreme wave interaction with a floating structure, computational fluid dynamics (CFD) based on the Navier-Stokes equations and the Volume of Fluid (VOF) method or 3D diffraction-radiation panel based codes have been employed. Model tests are accompanied to verify those analyses. Structural integrity is assessed by a nonlinear transient structural analysis using the time series of impact pressures.

For an investigation of progressive collision damage characteristics for an offshore structure in collision with a supply vessel, numerical approaches based on dynamic and nonlinear FE analysis have been proposed. The spectral approach in frequency domain has been widely used for a prediction of extreme load for linear system. However, they are not valid for nonlinear environmental load such as Morison force imposed on jacket structure. There have been many researches to treat the nonlinearity in efficient way in place of Monte Carlo based time simulation technique such as efficient time simulation technique and finite-memory nonlinear system.

Probabilistic approaches have been adopted to handle with uncertainties existing in the assessment of fatigue strength or ultimate strength. For a fixed platform, the uncertainties mainly exist in soil-pile modelling parameters, marine sediments and seismic loadings. In a floating offshore structure, the uncertainty arises from the structure itself such as material property, initial imperfections, residual welding stress, etc., as well as the randomness of environmental load.

In the benchmark study presented in Chapter 7, quasi-static prediction of structural response to impact loads was investigated based on basic mechanics, experimental results for steel and aluminium panels and quasi-static FE analysis. Slamming loads on the bottom of a free fall lifeboat during water entry was selected as a case. It was found that results from simple beam theory combined with basic formulas for dynamic response assessment was in good agreement with experimental results for steel and aluminium panels as long as the hydrodynamic added mass was included. It was found that hydroelastic effects are not important for this case.

Future recommendations of topics for review are:

- advance methods for mesh generation of FE models and new FE techniques,
- advance methods to account for corrosion and fatigue in assessing structural strength,
- uncertainties of internal loads and load effects on structural strength,
- reliability-based life-cycle design,
- risk-based inspection, maintenance and repair,
- development of new rules and regulations by regulatory bodies, and
- structural aspects of specialised ships and offshore structures.

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