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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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CONTENTS

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 that encompasses serviceability, ultimate strength, fatigue and accidental limit states. For engineering economy in the early design stage, quasi-static approaches are commonly employed to evaluate loads. It is then important to have good understanding of the difference between quasi-static analysis and dynamic response analysis and available engineering techniques (e.g., empirical approaches, direct analysis methods, and reliability analysis), as well as the associated modelling procedures that can be applied for design assessment. In the development of innovative designs and unique marine structures, useful information can also be obtained from direct load, response, and strength analyses. In these cases, the relationship between limit states and the corresponding loading conditions should be clarified in a precise manner.

A convenient and useful computational tool for structural response analysis is the finite element (FE) method, which can efficiently model the complexity and interaction of components and parts of large structures and the maritime environment if properly employed. The knowledge and treatment of uncertainties that may relate to the modelling of loads and structures and constitutive material modelling can significantly impact the accuracy and reliability of the results. Recent advances in computer and software technology have enabled and almost standardised the analysis of complex ships and offshore structures during the design process under operational conditions using the FE method.

ISSC Technical Committee II.1 has presented thorough reviews of various strength assessment approaches with a focus on topics such as simplified analysis, direct-calculation reliability analyses, optimisation-based analyses (including reliability), composite structures, uncertainties, and design trends, and development and challenges of ship structures (refer to Aksu *et al.* 2006, 2009, 2012). A previous report by ISSC Technical Committee II.1 (Ringsberg *et al.* 2015) presented a comprehensive review of calculation procedures divided into (i) different levels of analysis related to design stages, (ii) recent work on the design of production load modelling with an emphasis on rule- versus rational-based ship design, (iii) structural modelling using the FE method divided into global analysis and detailed analysis, (iv) recommendations for structural response assessment with regard to the fluid-structure-interaction (FSI), buckling and ultimate strength, fatigue strength, and ship dynamics, and (v) validation of the results from numerical calculations in terms of model scale experiments and full-scale monitoring. One of the core chapters of the report addresses the uncertainties associated with reliability-based quasi-static response assessment, including methods and criteria for reliability and risk-based structural assessment in the context of the structural capacity. The report presented a summary and discussion of the developments in international rules and regulations for ship structures and specific ship types, such as service vessels for windmills and offshore platforms, container ships, and LNG/LPG tankers. Various types of floating and fixed offshore structures were addressed by a review of methods for uncertainty, risk, and reliability analysis. The previous committee performed and presented a benchmark study, in which design against impact loads (slamming) was investigated for a free-fall lifeboat case (refer to Ringsberg *et al.* (2017) for the complete benchmark study).

The mandate of this committee encompasses an extensive field of research topics. Following the discussions from the former ISSC congress in 2015, the committee decided that the report should prioritise and emphasise the most relevant issues during the reporting period. The report should highlight and present examples of the most important progress since the former two to three reporting periods. As a result, the committee's work presented in the current report is less detailed in some areas but fulfils the mandate of the committee. This committee also decided to omit subsea structures, such as pipelines, risers, and wellheads, as these structures were considered to fall outside of the scope of the committee's mandate.

The current committee report is organised as follows: the remaining sections of this chapter provide a general introduction to strength assessment approaches for the quasi-static response of ships and offshore structures. The objective of the chapter is to provide a brief overview of modelling of quasi-static loads and the procedures and available technologies for the evaluation of associated responses within the context of reliability assessment. Chapters 2 to 4 are the core chapters of the report with reference to the committee's mandate. Chapter 2 presents load modelling, including the categorisation of the loads imposed during operation and life. The chapter explores the loads that can be transmitted to structures during operations or accidental situations and outlines the recent research conducted in support of knowledge gain in these areas. Chapter 3 presents a review of structure modelling and response analyses and focuses on the development of structural modelling and response analysis methods that implement or facilitate implementation of a quasi-static approach to structural analysis. The chapter is divided into multiple sections to address structural modelling and response methods, failure modes and response analysis, new materials, ageing structures and experiments, monitoring and validation. In Chapter 4, recent studies and advances in awareness of the risks that relate to uncertainties in loads and structural modelling, which are crucial for safe design, are presented. The importance of uncertainties associated with reliability-based quasi-static response assessment is discussed. Methods and criteria for reliability- and risk-based structural assessment are presented in the context of structural capacity methods. A review of recent studies and methods that consider existing and aged vessels with regard to risk-based inspection, maintenance and repair is presented.

Chapter 5 presents recent developments in international rules and regulations, such as the IMO Goal-Based Standards, the new DNV GL rules, Lloyd's Register rules, materials and extra-high-strength steels, strength analysis of container ships, and the IMO Polar Code. This chapter also includes a review of class rule-related software developed by Classification societies as a support of early concept (first-principle) design to detailed design and manufacturing. One section presents the most recent developments during the reporting period in automatic mesh generation tools. Chapter 6 discusses specific marine structures, such as jacket platforms, FPSOs, very large floating structures, and livestock carriers. The latter are examples of structures that are very complex, require analysis methods that are not always easily identified in guidelines, regulations and rules. The chapter provides some examples from the literature during the reporting period to highlight advances in quasi-static analysis methods and the assessment of these specific marine structures.

All ISSC committees are encouraged to perform benchmark studies. During the reporting period, this committee decided to perform two benchmark studies, which are presented in Chapter 7. The first study explores wave load modelling and structure response analysis in a ship structure, whereas the second study investigates the design against impact loads (slamming) of a floating offshore structure. The conclusions and recommendations for future work and progress of the committee's work are presented in Chapter 8.

1.1 General introduction to strength assessment approaches

An extensive variety of strength assessment approaches can be employed in the design assessment and structural optimisation of ships and offshore structures. In the preliminary stage, simplified solutions, although conservative, are usually applied. For detailed design, more detailed, time-consuming and potentially precise methods are usually applied. Irrespective of their degree of fidelity, the available methods reflect three main aspects, namely, (a) modelling idealisations/assumptions, (b) process of load derivation and application to a model, and (c) uncertainty modelling and quantification. Each of these aspects is introduced in separate sections of this report.

Modelling of loads by quasi-static analysis

Within the reporting period, the trend is similar to the trend described in the previous report by Ringsberg *et al.* (2015). The development of suitable methods for the simulation and evaluation of quasi-static responses that incorporate the influence of nonlinearities by multi-physics methods has proved challenging, particularly within the context of industrial applications. This challenge is primarily attributed to the lack of unified validation studies or verification schemes that can limit the number of uncertainties related to the computation of wave-induced dynamic loads. As techniques become more sophisticated and assumptions become more complex, uncertainties may vary and increase. Equally, validation, computation time and complexity may become an issue when we try to understand, simplify or validate the modelling assumptions. 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; refer to Chapters 2 and 4.

Response calculation

The approaches in which the uncertainty of 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 the load and resistance factor design (or partial safety factor) approach. These methods are extensively employed in the design of ships and offshore structures. Within these classes of calculations, one can further distinguish between simplified, analytical or semi-analytical analysis and direct calculation methods, referring to either the way the quasi-static loads are derived or the complexity of the structural model. Classification rules provide guidance on modelling and acceptance criteria based on either beam theory or direct calculations using the FE method. FE analysis remains the principal approach for investigating the structural response under accidental loading scenarios that may be associated with grounding, collision, ice structure interaction, or design for crashworthiness; refer to Chapter 3.

Reliability analysis

Reliability can be defined as the ability of a structure to comply with given requirements under the operational conditions that it may experience throughout its service life. Due to their inherent variability, probabilistic analysis methods in principle are capable of idealising the influence of these effects. In this context, reliability analysis may be employed to measure the probability of structural failure by considering both the loads that act on a vessel and the resistance (strength) of the structure.

Strength assessment approaches can be classified into four categories (Ringsberg *et al.* 2015): (0) deterministic approach, (I) partial safety factor approach, (II) approximate reliability analysis, and (III) fully probabilistic approach. The first two approaches (0 and I) have been well implemented in design standards (refer to Chapters 4 to 6). Based on the allowable stress 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 may not necessarily consider load combinations or the use of different materials at the moment. Class II and III approaches have the potential to provide a better indication of the structural reliability at the expense of additional information and computational effort. In reliability-based design, the design value of the target reliability index can be derived by analytical probabilistic processes. The concept of probabilistic analysis can be used to calibrate the values of the partial factors in load and resistance factor design (LRFD) methods.

2. LOAD MODELLING

One critical aspect of the design of ships and offshore structures is the evaluation of the loads imposed during operation and life. These loads can then result in a structural response that can be assessed via the applicable criteria for the intended platform. This chapter explores the loads that can be imparted to structures during operations or in an accidental situation and outlines the recent research conducted in support of knowledge gain in these areas.

In general, loads applied on ships and offshore structures can be divided into two major categories: operational loads and accidental loads. Operational/design loads are typically loads that are derived from the intended day-to-day operations of a structure, including lifetime considerations for the occurrence of loads based on the expected operational scenario of a structure. Accidental loads are attributed to accidents; collisions and groundings are examples of these types of loads. This chapter also outlines research on items such as load combinations and experiments conducted in these areas.

2.1 Operational/design loads

This section explores the various types of operational/design loads and the research efforts conducted since the committee's last ISSC report in 2015. Operational/design loads can be defined as the loads that a structure is typically expected to encounter during operations and its lifetime, considering the statistical methodologies for factoring the occurrence of extreme loads (i.e., rogue waves) and providing safety mechanisms via probabilities of non-exceedance and appropriate safety factors.

2.1.1 Wave loads and extreme loads

A recent example of the evaluation of wave loads is a study of offshore structures by Elhanafi (2016). This research focused on the prediction of wave loads for a wave energy converter, in which the author explored the loading effects on an oscillating water column (OWC) by utilising two-dimensional (2D) and three-dimensional (3D) computational fluid dynamics (CFD) models that considered a matrix of wave characteristics, such as wave height and period. The author also considered pneumatic damping and obtained an adequate correlation for regular wave interactions. Future research is suggested for extreme environments and further exploration and validation of 3D modelling methods. Other studies of extreme loads have been performed by Vázquez *et al.* (2016), in which the authors conducted experimental and numerical investigations for the vertical moments of bulk carriers and roll-on/roll-off vessels. The authors demonstrate that the vertical bending moment is the basis for the design of mid-ship sections and that vessels can experience abnormal waves, such as the New Year's Eve Wave (NYW) and the Single Abnormal Wave North Alwyn (SWNA). Model testing and numerical methods can be employed to evaluate regular and irregular waves, including abnormal waves. The studies revealed that the bow flare and freeboard characteristics of the two vessel types affected the estimation and comparison of the bending moments, including the linear assumptions of the numerical models that affected the comparisons with experimental data. Exploration of the area of the extreme loads on the dynamic collapse of bulk carriers was also performed (Xu *et al.* 2015b) to address the nonlinear behaviours of structures, in which a one-frame space model was utilised to conduct the analysis. The results indicated that the load-carrying capacity of the hull girder decreases after the ultimate strength is reached and provides data on the effects of the 1/1000 probability of exceedance load effects on the hull girder. Overall, wave loading efforts have focused on utilising CFD techniques to model the loads, evaluating the structural response under extreme loads and gaining a deeper understanding of the behaviours of structures when extreme loads are encountered. These efforts are especially critical when considering that weight and cost have to be assessed when designing a ship according to a desired operational profile.

2.1.2 Wind loads

The wind loads applied to ships and offshore structures represent another ongoing area of research. Wnęk and Guedes Soares (2015) conducted experimental testing in a wind tunnel and compared the results with the results of CFD models. Their study was performed in a wind tunnel in the Instituto Superior Técnico (IST) in Lisbon (Portugal) and included scaled models of a floating LNG platform and an LNG carrier. The scaled models were set up to measure resultant forces/moments along three Cartesian axes that are derived from wind loads applied at various angles of attack. Numerical simulations that utilise the commercial software ANSYS ICEM CFD were also conducted to perform a comparison with the experimental results, including mesh density studies for the air boundaries. Their results noted mesh density effects and wind angle of incidence effects, which indicate that methods should be addressed to best capture the boundary layer effects along the walls of the model; these results demonstrated reasonable agreement for certain conditions. Other researchers, such as Bentin *et al.* (2016), have focused on the wind impacts with regards to the optimisation tools for routing and evaluating wind-assisted propulsion devices. In this case, experimental data were collected for more than a year to apply towards the development of a model that can save up to 53% of energy when route optimisation is combined with wind propulsion. This process is route-dependent and subject to the prevailing wind directions. Future application of this technology may include dependency on fuel cost and regulations outlined by governing bodies. Although winds affect routing, a different area of interest is the wind loads on moored ships, especially as they exert external pressure loads on the hull, which need to be properly accounted. Redondo *et al.* (2016) evaluated the wind and wave combinations on moored ships by capturing mooring forces on the ships and mooring devices. The authors developed a scaled model that captured the characteristics of the port, including sediment conditions, and evaluated the effects of water and wind parameters, individually and combined. The combination of these forces reveals an increase in ship motion and amplitude. Future studies were suggested in areas where a loaded container ship is subject to these combined effects, including their influence on the safe operation of industrial equipment on the loading and offloading cargo. Wind loads continue to be an area of interest, in which CFD tools, computer models, and model testing are helping to characterise these coupled effects and provide data that can be employed in areas such as weather routing for improved efficiency.

2.1.3 Ice loads

Operational ice loads on the hulls of ships and offshore structures may be categorised as “stationary” or “moving”. Stationary loads act at one point on a hull structure, whereas moving loads exhibit tangential motion along the hull. In Kim and Quinton (2016), the force-displacement curve, variation of contact area and pressure distribution for moving ice loads that act on an elastic plate were determined. The study presents the results of moving ice load experiments on an elastic plate and compares them with previously published results for similar experiments involving stationary ice loads. The experiments and numerical analysis suggest that the difference in the magnitude of an ice load and trend of the pressure distribution between stationary and moving loading conditions is negligible if the structure remains elastic during the ice-structure interaction.

The constant added mass (CAM) method and the FSI method are extensively employed to simulate ship-ship and ship-ice collisions. In the CAM method, the hydrodynamic effect of the surrounding water is treated as a constant added mass, whereas the surrounding fluid flow is explicitly modelled in the FSI method. In Song *et al.* (2016a), the two methods are compared, and the causes of the differences in the results are explained. The comparisons indicated that the FSI method yields better results for the motion of the floater and the CAM method was faster but predicted a higher peak contact force and more dissipated energy in the ice mass than the FSI method.

Park *et al.* (2015) undertook an accidental limit state-based ship collision analysis to identify the operability of aged non-ice classed ships in the Arctic Ocean. Internal collision mechanics analysis of the struck vessel structures was performed at a right angle with an initial velocity. The striking ship and struck ship were the same ship—a 157,500 DWT Suezmax class double hull oil tanker. Various Arctic ambient temperature conditions—room temperature to -80°C—

were applied to the ambient exposed plating of the struck ship. Time-variant corrosion wastage was employed in the case of age-related damage. The FE software LS-Dyna was conducted to apply the nonlinear constitutive curves of the materials from a series of tensile tests at low temperatures. The operability of aged ships in the Arctic condition was estimated based on the results.

The ice interaction of a structure is an ongoing area of research and a subject of in-depth study of other ISSC committees. Numerical approaches are being evaluated to determine the methodology to address ice-related effects, especially for ships that are not initially designed to operate in high-latitude conditions.

2.1.4 Sloshing and slamming loads

Sloshing effects are typically observed across various vessels. Cheon *et al.* (2016) performed a study of an LNG-FPSO, in which the research efforts were devoted to conducting a scaled test to investigate the sloshing effect on tanks. A sloshing scaled tank was placed above a test fixture excited with six degrees-of-freedom (DOF) motion time histories that were derived from numerical simulations and piezoelectric pressure sensors were installed on the wall of the model. The model included several pressure sensor arrays and average methodologies to overcome a travelling pressure wave problem, and a test matrix including various tank filling heights. The test predictions were larger than expected and dependent on the tank-filling conditions. Additional research and full-scale experimental data are needed to provide additional data points and better understand the scaling factors of pressures. In the area of slamming and whipping, numerical and experimental work was conducted by Kim *et al.* (2015a) to assess a fully coupled hydroelastic model. The authors utilised an 18,000 TEU container ship for the investigation, conducted a 1/60 model test in the Samsung Ship Model Basin under head sea conditions, and compared the results with the results of a one-dimensional (1D) beam and 3D FE model with a Generalised Wagner Model coupled with a 3D Rankine panel method. The results indicated that fully coupled 3D models provided the best results for slamming assessments compared with de-coupled analysis, which tends to lean towards conservativism.

Slamming was also explored for the bow sections of a wave-piercing catamaran in a study by Swidan *et al.* (2016). A notional hull form for a wave-piercing catamaran similar to INCAT Tasmania designs was developed and equipped with load cells and pressure transducers to measure the slamming events at maximum impact velocities of 4.45 m/s during a drop test. Several tests were performed to alleviate uncertainties from velocities and randomness. The results indicated that the maximum slam pressure occurred when the interior archway is filled with water, which is affected by the immersion of the demi hulls. This finding suggests to the designer that the air gap can be increased to reduce pressures, and experiments also highlighted a pressure/velocity relationship for these conditions. However, the pressure transducer location is critical; their data suggested that the application of a quasi-2D approach can provide invalid data when investigating the slamming effects of catamarans.

2.1.5 Turret loads, mooring loads, and towing loads

FPSO ships utilise turret mooring systems. Recent studies have emphasised the prediction of the ship heading (e.g., Milne *et al.* 2016), especially wind, waves, and current effects, leveraging full-scale data from the Raroa FSPO, a 3D boundary element code Nemoh, and met-ocean predictions utilising a SWAN model. Reasonable estimates of the heading within 5% of measured values were obtained, which provides supporting data that indicates that Nemoh can be used to develop estimates of the lateral drift force and yaw moments. Towing is typically associated with the movements of other naval structures. A novel approach to towing was investigated by Yulmetov and Løset (2017) to gain knowledge in the area of towing icebergs to clear areas of ocean traffic. The authors proposed a model for towing ice; this research focuses on experimental validation of this model coupled with simulations. The experimental evaluation was performed at the Hamburg Ship Model Basin, and non-smooth discrete element method codes were utilised for the numerical efforts. The broken ice concentration on the basin was varied as the iceberg was towed, where the ice concentration influenced the towing force to its greatest extent. The breath of the tow tank was another parameter, as the rigid boundaries created effects that may not be present in open areas where broken ice can be pushed but not crushed out of the way of the towed iceberg. The authors outlined the limitation of the model as a pre-decisional support tool and improvements in towing that was set up to capture more realistic conditions. The wind effects on mooring are another subject of experimentation (e.g., Redondo *et al.* 2016); the authors coupled wind with waves in a controlled experimental study to evaluate their combined effects. The authors utilised a unique system to develop force and moment loads on a scaled vessel using linear springs and actuators. The spectral results of the coupled ship and wind motions indicated that the ship motion across the frequency range is amplified by the inclusion of wind loads and that special considerations are needed when the sail area of a vessel is large, such as in the case of cruise ships and container ships. This spectral characteristic has also been examined by Kumar *et al.* (2016) in Pohang New Harbour. The harbour was designed to protect moored vessels from typhoon-type events; however, small portions of waves continued to radiate through the entrance. The simulations and numerical models are developed to analyse the wave field around each vessel in the harbour, evaluate local resonance, identify the safest location for mooring, consider irregular geometry within the harbour, and develop a computationally effective model to predict moored ship motions.

2.2 Accidental loads

The previous section addressed operational loads, whereas this section explores accidental loads from collisions and groundings, as well as fire/explosive loads. Although explosive loads are adequately addressed in other ISSC committee reports, this content is limited to quasi-static response applications.

2.2.1 Collision and grounding

Collisions and groundings are a fairly severe set of accidental loads that sometimes cause detrimental damage to vessels. The work presented in Marinatos and Samuelides (2015) aimed to define a procedure that outlines the numerical simulations conducted to evaluate the responses of ship structures in accidental loading conditions. Ship structures experience different modes of failure, such as tension, bending, tearing and crushing. In these conditions, the particular effects of material curves, rupture criterion, mesh size, and strain rate have a profound effect on the results. Different material models and simulation techniques were employed for the simulation using the explicit FE software Abaqus, which consists of eighteen indentation tests conducted by different research groups. The tests refer to the quasi-static, dynamic transverse and in-plane loading of various thin-walled structures, which represent parts of a ship structure. Consistency in the numerical results was observed with the use of an equivalent plastic strain criterion, in which a formulation of cut-off values for tri-axialities below 1/3 was included.

The effect of a new highly ductile steel material on the crashworthiness of hull structures in oblique collisions was investigated by Yamada *et al.* (2016), who used nonlinear ship-to-ship collision simulations. A series of nonlinear FE analyses were performed using two Very Large Crude Carriers (VLCCs) with changing striking speed and collision angle. A comparison of absorbed energy and critical striking velocity for both conventional ship and new ship were discussed. Lee *et al.* (2016b) present ship collision analysis results for the world's first FLNG. The purpose of the analysis was to ensure that its hull structure has sufficient strength against collision events. Storheim and Amdahl (2014) present collision scenarios with bow and stern impacts against the column of a floating platform and the jacket legs and braces. The effect of the ship-platform interaction on the distribution of damage was investigated by modelling both structures using nonlinear shell finite elements. The numerical analyses were utilised to develop a novel pressure-area relation for the deformation of the bulbous bow and stern corners of the supply vessel. Procedures for the strength design of the stiffened panels were discussed; refined methods and criteria were proposed. Travanca and Hao (2015) present a series of FE numerical simulations with the aim of providing a comprehensive understanding of the strain energy dissipation phenomenon, particularly for the ship-structure interaction. Ships of different dimensions and layouts are modelled for impact simulations. From the FE analyses, simplified approaches are derived in terms of the relative stiffness of the two structures for assessing the responses and energy absorptions of the two structures. The conclusions can be applied to a broader range of collision assessment of offshore steel jacket platforms that are subjected to high-energy ship impacts.

The damage caused by accidental frontal collision of a supply vessel with an FPSO unit is examined in dos Santos Rizzo *et al.* (2015). This damage has a negative influence on the ultimate shear strength of the platform and stiffened side panels and should be carefully assessed. Nonlinear quasi-static FE analyses using the software Abaqus are presented. Geometric imperfections are introduced by considering the first buckling mode shape of the panel. A displacement loading control is imposed to the bulb to evaluate the plastic deformation and spring back effect. The ultimate shear strength is assessed considering the geometric imperfection and the residual stresses from the collision. A parametric variation is performed to investigate the influence of bulb displacement, initial imperfection amplitudes and plate thickness.

Liu and Guedes Soares (2015) present a simplified analytical method to examine the crushing resistance of web girders subjected to local static or dynamic in-plane loads. A theoretical model, which was inspired by existing simplified approaches, is developed to describe the progressive plastic deformation behaviours of web girders. The elastic buckling zone, which absorbs almost zero energy, is captured and confirmed by the numerical results. In addition, the analytical method derives expressions to estimate the average strain rates of the web girders during the impact process and evaluate the material strain rate sensitivity with the Cowper-Symonds constitutive model. These adopted formulae, which are validated with an existing drop weight impact test, can adequately capture the dynamic effect of web girders.

Heinvee and Tabri (2015) present a set of analytical expressions for the calculation of damage opening sizes in tanker groundings. The simplified formulae were given for the grounding force, longitudinal structural damage and the opening width in the inner and outer plating of a tanker's double bottom. The simplified formulae are derived based on a set of numerical simulations conducted with tankers of different dimensions, including lengths of 120 m, 190 m and 260 m. Given the formulation for the normalised contact pressure, the actual contact force for a ship is considered to be a product of the average contact pressure and the contact area. To improve the prediction of the onset of the inner bottom failure, a critical relative penetration depth as a function of the ratio of the rock size and the ship breadth was established.

The shape of the sea bottom is an important factor that determines the extent of grounding damage on ships, including the loss of water tightness. Sormunen *et al.* (2016) present a four-step methodology for mathematically analysing sea bottom shapes, where individual peaks are identified and isolated from larger datasets. The objective is to develop mathematical rock models that can be employed in grounding damage analysis. The research by Sormunen *et al.* (2016) was continued by Yu *et al.* (2016b), where a framework for studying, testing and evaluating rock models in terms of resulting grounding damage is presented. The FE method is applied to analyse and compare the grounding damage of rock models of actual rock using otherwise identical grounding scenarios. The results indicate that rock models with a reasonable statistical fit did not always yield similar grounding energy compared with the results using real rock. Differences in energy are especially caused by the rough surface of the real rocks. Knowledge of these relationships can be applied towards estimating grounding damage of ships in future investigations; however, rock surface unevenness should also be evaluated.

Closed-form analytical solutions for the energy released from deforming and crushing structures and the impact impulse during ship collisions were developed and published by Pedersen and Zhang (1998). Zhang *et al.* (2017d) employed these experimental results to analyse the validity and robustness of the closed-form analytical methods and improve the accuracy of some parameters. A total of 60 experimental results have been analysed and compared with the analytical results. This paper presents the outcome and concludes that the results by the analytical methods are consistent with the experimental results. This paper also introduces a simple concept to account for the effective mass of liquids with free surfaces performed onboard a ship and demonstrates how the analytical analysis procedure can be expanded to consider the effect of ship roll on the energy released for crushing.

Faisal *et al.* (2017) presented a rapid method for calculating the hull collapse strength of double hull oil tankers after collisions. The statistical characteristics of hull girder collapse after collision are investigated. Four double hull oil tankers with different sizes are considered: Aframax, Panamax, Suezmax and VLCC. A set of 50 credible collision scenarios was selected by a sampling technique that is associated with collision hazard identification based on a historical ship collision database. Four parameters, namely, vertical collision location, damage penetration, striking ship's bulbous bow height, and striking ship's bulbous bow length, are determined as a consequence of the corresponding collision scenario. An intelligent supersize FE method is utilised to compute the progressive collapse behaviours of hull girder structures with detected collision damages. The residual hull girder strength indices can be determined and formulated with a closed expression that is associated with collision damages and ship length. The developed formulations are useful to quickly calculate the hull collapse strength of double hull oil tankers immediately after collisions.

Corroded tankers may be subjected to significant structural damage if involved in collision accidents. For understanding or preventing collision accidents, various studies are being proposed by researchers to improve the analysis method. In Noh *et al.* (2016), four types of double hull oil tankers (Aframax, Panamax, Suezmax and VLCC) are employed. A probabilistic approach is used to create ship-ship collision scenarios for each target structure and the ultimate longitudinal hull girder strength of the hypothetical oil tanker's hull cross-section. The ALPS/HULL is an intelligent supersize FE method software which is employed for the simulation. A relevant probability density function is introduced using the results from FE simulations of the ship-ship collisions which is commonly used to predict residual strength.

In a study by AbuBakar and Dow (2016), the accidental loads and damage mechanisms incurred on a ship's bow during a ship collision are analysed using nonlinear FE analyses to investigate the capability of the ship's bow to absorb the energy generated during a collision event. The study employed the effect of the rupture due to excessive plasticity of material prior to failure. The study investigates the effect of collision angle and ship speed during an extreme collision event of a ship striking a rigid wall with a full ship model. The correlation between the numerical simulations and available current analytical approaches applied in the EURO-code and other empirical approaches reveal that FE analyses generally produce more conservative results and are capable of capturing the impact force effect due to the ship bow softening effect.

For a design evaluation, a fast, practical and accurate method is needed to determine the absorbed energy and collision damage extent in ship collision analysis. The most well-known simplified empirical approach to collision analysis was created by Minorsky (1959) and its limitation is also well recognised. Zhang and Pedersen (2017) have developed simple expressions for the relation between the absorbed energy and the damaged material volume, which considers the structural arrangements, the material properties and the damage modes. The purpose of the study is to re-examine collision damage analysis in ship design assessments by comprehensive validations with experimental results from the public domain. A total of 20 experimental tests have been selected, analysed and compared with the results calculated using the proposed method. The findings conclude that the proposed method has reasonable accuracy with a mean value of 0.988 and a standard deviation of 0.042.

2.2.2 Fire, explosion and associated secondary loads

Ships and offshore structures are exposed to fire and explosion loadings. These fire and explosion accidents can have grave consequences not only for the ships and offshore platforms but also the safety of personnel.

Fire loads

Parametric uncertainty in choosing the numerical values for the frequency and consequence analysis during a fire risk analysis is a critical issue for determining the design accidental load (DAL). Chu *et al.* (2017) applied the Latin hypercube sampling technique to investigate different fire exceedance curves, in which DAL fire was demonstrated by selecting different sets of representative values. The distribution and confidence interval of the DAL fires revealed an extensive distribution with varying uncertain and critical parameters. The investigation provided quantitative information about inherent uncertainty; this type of additional information enables better decision-makings. Kang *et al.* (2017a) explored a framework for using computational fire simulations during the early phase of ship design, which focused on how to arrange fire control options with minimal changes in existing design procedures. Jin and Jang (2015) and Jin *et al.* (2015) applied a fully quantitative-probabilistic fire risk analysis procedure to evaluate the design temperature distribution and probable failed area of interested objects for a semi-submersible vessel. The failed area of an object is predicted by introducing two different risk analysis tools, namely, cumulative failure frequency and the temperature exceedance curve. Jin *et al.* (2016) introduced an approximation method to reduce the time cost of analysis, which depends on the number of input scenarios in the same fire risk analysis procedure.

Sun *et al.* (2017) discussed the load characteristics in the process modules of offshore platforms under jet fire. Jet fire represents a major fire risk in the process modules of offshore oil and gas platforms. The heat loads generated by jet fire in these areas may cause significant consequences and warrants further investigation. In this research, a Fire Dynamics Simulation (FDS) code is chosen to model different jet fire scenarios. Valuable suggestions for modelling jet fire scenarios in process modules and load characteristics for the prescribed jet fire scenarios are discussed.

When a steel structure is subjected to fire attack, the thermal material degradation of steel members can induce premature material yielding, and the thermal axial expansion and bowing on a steel structure can change its structural geometry. These thermal effects produce the material and geometric nonlinearities of a structure, which defy the accurate behavioural prediction based on general methods of analysis. Iu (2016) proposed an equivalent thermal load procedure to determine the thermal expansion effect prior to a fire analysis. In this procedure, the thermal expansion effect is incorporated into the higher-order element formulation, and the geometric and material nonlinearities are considered by the higher-order elements. The present nonlinear fire analysis can replicate realistic behaviour, including thermal effects, geometric effects and material nonlinear effects of an entire steel structure that complies with a realistic fire scenario in an effective manner using the least number of elements.

High-strength steels are increasingly common in structural engineering applications due to their favourable strength-to-weight ratio, excellent sustainability credentials and attractive physical and mechanical properties. However, at elevated temperatures, the grades that are underused in structures lack reliable information about their structural performance. Varol and Cashell (2017) reviewed high-strength steels in structural applications, including the key design considerations. Their review is focused on the lateral torsional buckling response of laterally unrestrained beams. In this study, an FE model is developed to investigate torsional buckling behaviour at ambient and elevated temperature. Similarly, Reis *et al.* (2016) also reviewed the behaviours of steel plate girders that are subjected to shear buckling at both normal temperatures and elevated temperatures. Sensitivity analyses of the influence of initial imperfections were discussed. Different values for the maximum amplitude of geometric imperfections were considered, and residual stresses were also considered. The effect of the end supports and configuration were also investigated to understand the strength enhancement given by the rigid end support at normal temperatures and confirm if the strength enhancement can be maintained in the case of fire.

Hydrocarbon gas explosions loads

Hydrocarbon gas explosion is a critical hazard that causes a significant environmental impact and loss of valuable assets and lives, as observed from the historical disasters in the oil and gas industry. In response to these events, stronger international rules and regulations have been established to ensure the safety of these structures. Considerable effort has been devoted to quantify accidental design loads for flammable gas based on probabilistic approaches, which requires extensive CFD simulations. The demand for 3D nonlinear dynamic FE structural simulations has significantly increased with rapid progress in computer performance.

Heo (2016) discussed uncertainties in explosion hazard analysis, which cause large variations in probabilistic explosion responses, and compared the gaps between provisions for design load estimation based on probabilistic approaches with current structural design and analysis schemes. Sun *et al.* (2016) applied the Failure Modes and Effect Analysis (FMEA) method to determine which equipment has a high Risk Priority Number (RPN) and discovered that the gas washing pry of an FPSO unit in the operation phase has a high RPN. The leak rate of gas with a specified hole diameter is calculated based on an appropriate leak source model according to the actual operating conditions of the gas washing pry. Then, a CFD simulation was performed to analyse the diffusion behaviour to identify the distribution law of gas and the hazardous area of gas in the leakage conditions. One explosion model is selected for the damaging overpressure of the explosion on each equipment surface and the influence scope of the explosion overpressure to evaluate personnel and equipment risk.

Paris and Dubois (2017) reviewed recent research developments to evaluate global explosion loading on complex systems, such as offshore/onshore process. During the engineering phase, a "Design Explosion Loads Specification" is often developed by the safety discipline to provide the necessary explosion response inputs to other engineering disciplines for each individual item of a safety critical system. This step is an efficient method for managing an explosion in the design for each individual item of a safety critical system. When a combination of items needs to be addressed, this approach may yield an overly conservative design. An alternative methodology based on CFD simulation is presented in this paper to obtain more adequate global blast loads for design verification. The new methodology focuses on the development of dedicated blast load cases for the design to address both internal explosion events and external explosion events that are related to complex items, such as entire onshore/offshore modules.

Secondary loads

Kang *et al.* (2016, 2017b) proposed a numerical model that is based on the time-history of a blast load. In this history, considerable negative phase pressures were observed in the gas explosion analysis results. The idealised model was employed to characterise the dynamic response under the explosion loading. The structural responses of various structural models were thoroughly investigated using the FE method.

A blast load was reviewed by Burgan *et al.* (2016) from the perspective of weight saving of topside. They treated the over-conservativeness in blast wall design to enable a realistic assessment. Three analysis techniques were utilised to compare the effect on the response of the blast wall: (a) Lagrangian, (b) uncoupled Eulerian-Lagrangian (UEL), and (c) coupled Eulerian-Lagrangian (CEL). The paper demonstrates how coupled analysis considers the effect of the interaction between the load and the response of the wall. As the complexity of the analysis increases from Lagrangian to UEL and CEL, the computational demand significantly increases.

Zheng *et al.* (2015) conducted a theoretical analysis to investigate the dynamic response of fully clamped stiffened plates under blast loads. Based on the large deflection theory of plate and the energy conservation theory, an elastic-plastic analytical method for predicting the response of stiffened plates to explosion loading is developed, in which the effect of the elastic deformation of plates is considered. In the paper, dynamic loads of the initial shock wave and quasi-static pressure generated by an inner explosion are substituted by three different types of equivalent loads. The elastic-plastic analytical method and nonlinear FE method are employed to analyse the dynamic responses of six stiffened plates under explosion loading. Compared with the existing experimental data, the results of the elastic-plastic analytical approach proposed in the paper are consistent with the experimental and numerical results.

2.3 Load combinations for application

Load combination is an ongoing area of research, in which the phasing of loads or methodology for combinations can affect the results. A critical aspect is the ability to quantify how loads are combined, specifically utilising measurements to derive the phasing and magnitude. Recent efforts by Schiere *et al.* (2017) have examined the modal response using strain gages but difficulties were encountered when they attempted to identify the magnitude of vertical bending and torsion moments, as the latter has a significantly smaller magnitude. Parunov *et al.* (2017) presented an assessment of the residual ultimate strength of an Aframax-class double hull oil tanker that was damaged in a collision and subjected to combined horizontal and vertical bending moments. Residual strength interaction diagrams are developed with the purpose of rapid residual ultimate longitudinal strength assessment of the damaged oil tanker under combined bending moments. The developed interaction diagrams are compared with previously published research and the Smith-type progressive collapse analysis method for biaxial bending (Dow *et al.* 1981). Although ultimate strength has typically been reliant on the vertical bending moment, Mohammed *et al.* (2016) numerically experimented with the evaluation of this ultimate strength when a torsional moment is coupled. Utilising a progressive collapse approach, the authors numerically evaluated the effects to include torsion and a vertical moment, which were sequentially applied (torsion was applied first in the sequence); the authors outlined the necessity to include this sequencing in future research. These findings align well with those by other researchers, such as research Temarel *et al.* (2016), who determine that a spectral analysis can identify extreme loads for design. However, they note that these various extreme loads do not simultaneously occur. Equivalent design waves have also been employed in direct analysis, in which they are selected based on the dominant load parameters and applied to coupled fluid and structural models. This methodology depends on the process that is utilised to select the dominant load parameters, which highly influences its accuracy. The load combination arena is an ongoing area of research with various methods that are utilised to select the phasing and load combination or to bound the design space.

2.4 Experiments and monitoring

Experiments are critical for providing essential data in a controlled environment and removing some of the stochastic effects of real-life data monitoring. One such investigation is a study of the progressive collapse behaviours and residual strengths of damaged box girders under longitudinal bending moments, as outlined in Cho *et al.* (2016a). The experimental models were box girder structures that consist of stiffened plates. The box girder models and longitudinal bending conditions adopted in this study can represent the situation of a damaged ship hull girder after collisions. Numerical analyses that simulate a bending test were performed through a nonlinear FE analysis solver. For the numerical analyses, the tested box girder models were employed and different levels of damage were induced on the models, with the exception of one model, which remained intact. Numerical modelling and analyses were performed using the Abaqus CAE/FEA software and compared to test data for validation of the FE analyses. The findings indicated that the reduction in ultimate strength is dependent on the extent of damage and its location. The results of this study can serve as a basis for the prediction of the residual strength of an actual ship hull girder that is subjected to accidental collisions. Mooring loads are also an area of experimentation and monitoring. The loadings of quay walls were investigated in Paulauskas (2016), analytical methods were used to investigate mooring loads, coupled with a visual simulator that was calibrated using laser mooring systems, and methods to account for the inertia loads were developed. The author emphasised the effect of passing ships and the wind load on moored vessels and the utility of data that were collected to calibrate the simulators.

2.5 Concluding remarks

The research presented in this chapter outlines some of the current trends in research, from which several conclusions can be formed. Due to the increased availability of numerical methods and their widespread usage across many applications, many researchers have coupled their experimental efforts with numerical methods to correlate their results and develop best practices for utilising numerical codes. This finding is coupled with a trend to develop a comprehensive understanding of loads, in particular, extreme loads such as collisions and groundings, which can cause detrimental damage to structures. This need for a comprehensive understanding and design should be balanced with cost, weight, and operational profiles for vessels. Another area is explosive loads; some authors have focused on quasi-static methods to design a structure to address this topic. Ice loadings and ice operations, in which the operating conditions at high latitudes are changing and vessels that are not initially designed with this purpose are beginning to operate in such environments, comprise another area of research.

3. STRUCTURE MODELLING AND RESPONSE ANALYSIS

Advances in the development of complex mathematical methods for the structural analysis of ships and offshore structures, their implementation within commercially available software and the availability of increased computing performance have enabled the common application of methods, such as FE analysis, in the design process. CFD also follows this development trend, with rules for the implementation of CFD in the detailed design phase for the derivation of loads; these are now available from some Classification societies, such as DNV GL's special hull notation Computational Structural Analysis (CSA) (DNV 2013). Despite of these advances, simple and quick methods are required by designers to undertake iterative structural strength assessments within the time constraints of the design process. In the early stage design process, designs are evolving too quickly or insufficient definitions are available to realise the potential of detailed FE analysis, CFD, or other methods for assessing dynamic response. Therefore, simplifications or alternative methods are required.

Throughout the design process, quasi-static methods are implemented, regardless of whether they relate to the application of load or the structural analysis. For early structural definition, designers may apply rule-based calculation procedures or analytical calculations based on loads that have been dynamically calculated and rationalised to a reduced set of static loads, for example, to account for wave loads or ship motions. In a subsequent design, whole platform stress and fatigue analysis may be undertaken by FE analysis via the application of quasi-static wave loads, which induce a desired peak bending moment and shear force distribution into a structure. For a longitudinal bending strength assessment, a progressive collapse method (e.g., the Smith method) or the Idealised Structural Unit Method (ISUM) may be implemented to assess the ultimate bending strength of a ship's section by iterative incremental application of a bending moment in a quasi-static manner. Quasi-static analysis remains a key approach to structural analysis.

This chapter focuses on the development of structural modelling and response analysis methods that implement or facilitate the implementation of a quasi-static approach to structural analysis, in which a quasi-static load is often considered as the basis of the analysis. The chapter has been divided into numerous sections to address structural modelling and response methods, failure modes and response analysis, new materials and ageing structures. Throughout the sections, simplified or analytical methods, direct calculation methods, experimental analysis, loads and load combinations are considered.

3.1 Structure modelling and analysis methods

Whilst the majority of loading scenarios are dynamic or transient, the reduction of the loading environment to a quasi-static load or series of loads as an individual loading condition or a combination of conditions can significantly reduce the complexity of the subsequent structural analysis. This section concentrates on the development of methods or the implementation of techniques that facilitate quasi-static analysis.

3.1.1 Simplified analysis/first principles

Simplified analysis by first principles or "hand" calculations are well founded in the design and analysis of ship structures, with textbooks such as "Roark's Formula's for Stress and Strain" (Young and Budynas 2011), "Ultimate Limit State Design of Steel-Plated Structures" (Paik and Thayamballi 2003), or "Ship Structural Analysis and Design" (Hughes and Paik 2010), which are often featured in the armoury of the structural naval architect. These approaches form the basis of many design standards and Classification society rules.

Within the reporting period, numerous papers that develop analytical methods or undertake direct analysis to verify previously proposed methods have been published. Papers by Benson *et al.* (2014), Cui *et al.* (2017b), Dekker and Walters (2017), Glassman and Garlock (2016), Khedmati *et al.* (2016), Kitarović *et al.* (2015) and Zhang (2016) are noted. These papers are subsequently discussed in this chapter in relation to the type of analysis. Developments in the rule applications of these approaches are covered in Chapter 5 of this report.

3.1.2 Direct calculations

Direct calculation via the use of FE analysis and methods that facilitate FSI are increasingly becoming standard practice for ships and offshore structural designs. The application of these techniques for dynamic analysis is addressed by the ISSC Technical Committee II.2 Dynamic Response. The focus of this report is the application of techniques to implement quasi-static loading for different analysis requirements.

The main papers within the reporting period that apply FE analysis to the analysis of ships and ship-like structures are papers by Estefen *et al.* (2016), Gannon *et al.* (2016), Tanaka *et al.* (2015) and Zhang *et al.* (2016). These papers are subsequently discussed in this report in relation to the analysis methods, and therefore, are not discussed here to avoid repetition.

Combined FSI analysis continues to develop with a substantial amount of dynamic analysis rather than quasi-static analysis. However, the fluid loading is often transferred from the fluid analysis, for example, CFD as a quasi-static load to a separate FE solver to understand the structural response. Kumar and Wurm (2015) utilised this method and presented a comparative study of bi-directional FSI for large deformations of layered composite propeller blades. Changes in the pressure distribution, stress distribution, thrust, torque and pitch angle of the blade are presented, with quasi-static loading transferred from CFD analysis to FE analysis and the distorted geometry re-meshed and transferred to the CFD in a two-way loop.

3.1.3 Reliability analysis

Structural reliability analysis provides a crucial method for the design of ships and offshore structures, which enables the quantification of uncertainties when designing a safe structure. This quantification may be achieved in the direct design of a structure or the development of rule-based criteria or allowable stresses that suitably account for uncertainties. Reliability analysis requires the assessment of a structure's capability via appropriate modelling. A reliability analysis may require a model to be run 10^6 times, including different combinations of variables to inform about the sensitivity of the structure and subsequent probability of failure during its life. To successfully perform a reliability analysis, the runtime of models should be minimised by simplifications, such as a quasi-static approach. Reliability analysis is considered to be an important methodology; therefore, it is considered in Chapter 4 of this report.

3.1.4 Optimisation-based analysis

An increasing number of studies that employ different optimisation techniques to rationally improve structural design objectives have been identified. The main design objectives include weight, cost and vertical centre of gravity (VCG). Andrić *et al.* (2017b) extend the "standard" scantling optimisation approach for fixed topology to an approach that investigates the influence of different topology variants on optimal structural scantlings. The methodology combines the fast concept exploration of design variants using generic 3D FE models and a two-step decision support procedure that is based on topology and scantling optimisation. How different topological variants can produce different optimal structural scantlings with respect to chosen design objectives (mass and VCG) has been demonstrated.

Temple and Collette (2015) developed a framework to design optimal ship structures considering production and maintenance costs using a multi-objective genetic algorithm. Fatigue and corrosion were considered as damage processes on a yearly basis to estimate the cost of maintenance. A probabilistic service extension metric was employed to account for the uncertainty in the life span. Kim and Paik (2017) optimised a VLCC considering ultimate strength and structural mass as an objective. The coupling of strength assessment with an optimisation algorithm enables a 20% reduction of man-hours by automated computer-assisted design. Andrade *et al.* (2017) demonstrated that FE analysis combined with design of experiments and a response surface method can be a fast approach to generating competitive structural designs.

Ringsberg (2015) presented a study of the performance of car deck structures made of steel and composite materials for a PCTC vessel. Conceptual designs were optimised and evaluated by an FE analysis with respect to stakeholder defined criteria, e.g., strength and the maximum allowed deflection during loading. A weight and cost estimation performed for four different car deck designs was presented. Stone and McNatt (2017) presented a method for the multi-objective optimisation of a ship structure using an integrated hydrodynamic code, 3D FE structural response, limit state evaluation and structural optimisation with Maestro design system software. An example frigate optimisation case demonstrates that the proposed method is very useful for performing ultimate strength-based structural optimisation with multiple objectives, namely, minimisation of the structural weight and VCG, and maximisation of structural safety.

3.2 Failure modes and response analysis

To understand the ultimate limit state of a structure and quantify the reserve between the structural capability and load over the life of a structure, the observed failure modes must be quantified. From a design perspective, quasi-static methods for failure mode assessment are very important, such that the design can be rapidly progressed without a requirement for more complex and time-consuming analysis. This section reviews advances in quasi-static buckling analysis, ultimate strength assessment, fatigue assessment, residual strength assessment and whipping analysis.

3.2.1 Buckling and ultimate strength

Stiffened panels and plates

Gannon *et al.* (2016) numerically investigated the influence of residual stress and distortion due to welding on the behaviour of tee- and angle-stiffened plates under axial compression. The results indicated that the ultimate strength may be reduced by 12.5% due to the presence of welding-induced residual stress. Kim *et al.* (2017a) developed an empirical formula for the ultimate strength of stiffened panels, which is a function of the plate and stiffener slenderness ratio with two correction coefficients obtained by FE analysis. A review of ultimate strength analysis methods for steel plates and stiffened panels in axial compression has been presented by Zhang (2016). Analysis approaches for ultimate strength and their employment in ship designs are reviewed and discussed. The author presents a developed design formula for the ultimate strength of stiffened panels using a comprehensive nonlinear FE analysis. Considering the ultimate strength of stiffened grillages, Benson *et al.* (2015) provide a development of the orthotropic plate approach, which is related to the development of the Smith progressive collapse method, such that the total and inter-frame collapse can be assessed. Considering the bi-axial buckling strength of stiffened panels, Cui *et al.* (2017b) investigated numerous analytical approaches that are suitable for practical design application compared with FE analysis. Their study indicates that the Vlasov assumption in relation to stiffener rigidity may cause an overestimation of the buckling capability, whereas methods that assume the flexibility of stiffeners yield satisfactory results compared with FE analysis. Khedmati *et al.* (2016) present empirical formulae for assessing the ultimate strength of aluminium stiffened panels under combined transverse and lateral pressure; these formulae were developed by regression analysis from FE analyses that include the effect of the heat affected zone.

The ultimate strength of stiffened panels subject to combined in-plane axial and shear loads are investigated by Takami *et al.* (2015) for steel panels and Syrigou *et al.* (2015) for aluminium alloy plating. Jiang and Zhang (2015) performed numerical investigation of the influence of lateral pressure on the nonlinear behaviours of stiffened panels subjected to in-plane stresses. The results indicated that the effect of pressure on the ultimate strength depends on the ratio of longitudinal and transverse stresses and that the collapse loads are more sensitive to pressure when the external loads are dominated by longitudinal stresses. Gordo and Guedes Soares (2015) demonstrated that the form of assumed initial imperfections has greater importance than its maximum amplitude for the ultimate strength of long steel plates. Glassman and Garlock (2016) developed an analytic model for the ultimate post-buckling shear strength of steel plates that is very accurate for an extensive range of material and geometric parameters. Dekker and Walters (2017) developed an analytic model that can predict wrinkling and folding of thin and moderately thick shells. The model does not require calibration, employs a stress-strain curve, and can predict the onset of material failure. The method is consistent with a highly detailed FE model.

Various feasible approaches to enhancement of the plate elastic shear buckling strength are comprehensively investigated in Kitarović *et al.* (2015). Based on derived theoretical envelopes of the considered approaches, stiffening parallel to the longer plate edges is identified as the most effective approach to the considered problem. A simplified analytical formulation, which is convenient for utilisation in structural design of the plated structures, is proposed. The development of a new proof of plate capacity under combined in-plane loads for ship design and classification has been presented by Hayward and Lehmann (2016, 2017). The new proof is based on an improved understanding of plating collapse obtained from an extensive series of nonlinear FE analyses that encompasses the complete range of structural configurations and load combinations relevant to the shipbuilding industry. Compared with existing proofs, the new proof incorporates a physical-based approach towards the tensile stress effect on plate capacity and captures the influence of both plate slenderness and aspect ratio under compressive bi-axial loads.

Structural problems that arise from a larger bilge radius and associated structural arrangement around the bilge shell, which are not sufficiently identified, have been investigated by Okada *et al.* (2016, 2017). The authors developed theoretical formulae, assuming a curved plating connected to a continuous stiffened flat plating with regular stiffener spacing. In these cases, the stipulation in the CSR-H is not always rational, and the authors propose modified structural design methodologies around the unstiffened bilge shell plating. Previous research on buckling and the ultimate strengths of curved plates by Kim *et al.* (2014) has been fulfilled with an experimental study by Lee *et al.* (2016a). The results from the experimental data were applied for fine-tuning and slight modification of the design formula presented in Kim *et al.* (2014) with new correction factors.

Hull girder ultimate strength

Current research in ultimate hull girder strength calculation has developed to include different effects (such as global horizontal bending and torsion moments, and double bottom pressure) in 3D nonlinear FE analyses and the parallel development of new simplified methods that can simulate these effects with acceptable accuracy.

Pei *et al.* (2015) demonstrated radical computational savings when using the ISUM method for predicting the ultimate strength and post-ultimate behaviour of a bulk carrier. The approach was coupled with FE analyses and a load calculation method for the level of a complete ship structural model. Mohammed *et al.* (2016) presented an ultimate strength analysis of a container ship under combined vertical bending and torsional loading using nonlinear FE analyses. The margin of safety between the ultimate capacity and the maximum expected moment were established, which demonstrates that torsion does not significantly alter the capacity of the structure in the study case. In contrast to this research, Darie and Rörup (2017) revealed the importance of oblique seas for the evaluation of the hull girder ultimate strength of container ships. The analysis was completed by coupling FE analysis with 3D hydrodynamic analysis based on Ranking code. This approach evaluated vertical, horizontal and torsional global loads that appears in different wave headings and calculated the hull girder ultimate strength capability around amidship. Tanaka *et al.* (2015) present a simplified method for analysing the ultimate strength of a hull girder under combined bending and torsional loads. The method reduces the section to a series of thin-walled beams and implements the Smith progressive collapse method (Dow *et al.* 1981) to calculate the ultimate strength by accounting for warping and shear stresses. The results are compared with explicit FE analyses and physical tests, which show agreement when the bending moment is dominant. However, as torsion becomes dominant, correlation deteriorates, which indicates that additional development of the method is required.

Fujikubo and Tatsumi (2017) presented an extended Smith method that considers the effect of double bottom pressure on hull girder ultimate strength, which is especially important for container and bulk carrier ships. In addition to the standard Smith discretisation of a hull girder cross-section, the double bottom is idealised as plane grillage extended over a hold length. The results were compared with nonlinear FE analyses, and acceptable accuracy was achieved with vast savings in CPU time. Gordo (2017) investigated the effect of double bottom pressure under alternate hold loading on the ultimate strength of a bulk carrier and revealed that the effect can significantly reduce the hull girder strength in the hogging condition. Applying a quasi-static approach to the loading of a Suezmax tanker, Estefen *et al.* (2016) employed FE analyses to investigate the influence of geometrical imperfections on the ultimate strength of the double bottom. The study reveals that an imperfection mode consistent with the elastic buckling mode will provide the most conservative assessment of ultimate bending strength. Zhang *et al.* (2016) present a method to assess the bending capability of a ship's hull after shakedown. Shakedown is considered to be the initial cyclic loading of a structure, which can cause a progression away from the assumed elastic condition. The paper suggests that the ultimate bending strength may be reduced after shakedown. Fujikubo *et al.* (2015) investigated the effect of shear stresses on the hull girder ultimate strength of a container ship based on different definitions of partial FE models.

Kitarović *et al.* (2016) consider the hull girder ultimate strength of a bulk carrier as determined by an IACS incremental-iterative progressive collapse analysis method. In addition to the original IACS prescribed load-end shortening curves, new curves determined by the non-linear FE analysis have been presented. The results obtained by both sets of curves are compared and discussed on both the local level (structural components load-end shortening curve) and the global (hull girder) level. A similar investigation, which is based on the improved accuracy of load-end shortening curves to be used for hull girder progressive collapse, have been performed by Kvan and Choung (2017). Morshedsoluk and Khedmati (2016) used an extended formulation of the coupled beam theory that considered the effect of a superstructure to calculate the ultimate strength of composite ships.

3.2.2 Fatigue strength

Numerous research studies have been conducted to observe the scenario of fatigue durations. In recent years, designers and Classification societies have worked to prevent another accident, such as MOL Comfort, and ensure the safety for crews and goods. They have improved monitoring systems to promptly obtain information from the hull girder and developed simplified methods for efficiently and accurately predicting fatigue damage.

Since the MOL Comfort accident in 2013, the monitoring of hull displacement has become important in the maritime industry. Storhaug and Aagaard (2016) present the calibration of hull monitoring strain sensors on a deck, which considers both static loadings and dynamic loadings. The calibration provided an accurate calibration procedure and indicated excessive uncertainties in the loading computer, which can be used to reduce the probability of risk, such as in the case of MOL Comfort. Magoga *et al.* (2016) present a comparative study between assumed stress spectra and derived stress spectra from strain measurements, with respect to the fatigue life for three structural details of naval aluminium High-Speed Light Craft (HSLC). The study was performed to obtain the best model of the measured stress range data normalised by the design stress ranges. The results indicated agreement between the linear model and the Weibull model, which estimate the fatigue life based on a Gaussian model correlated with derived spectra and fleet maintenance data.

Due to the recent CSR-H from IACS, the evaluation of fatigue life is greater than 25 years. Liao *et al.* (2015) compared the fatigue life evaluated by the rules with the fatigue life evaluated by advanced hydro-structure coupled analyses and examined the fatigue life of various hot spots located amidship. They demonstrated that the fatigue life predictions obtained by direct spectral analyses significantly deviated from the rules. This finding confirmed that the rules for still water and wave load uncertainties can substantially affect the fatigue prediction.

Micone and Waele (2015) present a comparison of fatigue design codes with a focus on offshore structures. The criteria of fatigue strength for different Classification societies significantly differ, and the fatigue phenomenon is sensitive relative to these codes. The S-N curve for the fatigue design method is simple but may cause conservatism due to the pre-defined load range. The British Standards Institution (BSI) presents the most complete information for applying a fracture mechanics approach, whereas DNV GL offers the most updated and complete information for applying an endurance approach. Current research and rule development activities on the fatigue strength of thick plates are presented by von Selle *et al.* (2016) due to the use of a thicker plate in construction and the trend of optimised structures with higher tensile steel. In the DNV GL fatigue rules, a comparison with former DNV and GL fatigue rules is provided, which confirms the hot-spot area stress and nominal stress concept, especially for the cutting plate edges of thick plates and the welded joint, which are stress concentration points.

Van Lieshout *et al.* (2017) conducted a validation of the corrected Dang Van multi-axial fatigue criterion applied to turret bearings of FPSO offloading buoys. With the three considered cases, they corrected the characteristic parameters (α and β) of the Dang Van curve and confirmed the correction using full-scale and long-duration fatigue tests. The results concluded the application of the Dang Van criterion, which can be efficiently applied to FPSO offloading buoys with a revised locus of hydrostatic stresses.

Horn and Jensen (2016) present a method for reducing the uncertainty of Monte Carlo-estimated fatigue damage using the first-order reliability method (FORM). The objective of the FORM is to minimise the function to determine the design point with a linear approximation. Compared with conventional simulations, the FORM design point should be significantly and properly defined, which will affect the applicability of prediction for fatigue damage. A similar study by Singh and Ahmad (2015) presents a probabilistic analysis and risk assessment of a deep-water composite production riser against the fatigue limit state. The proposed methodology is based on the S-N curve approach and Palmgren-Miner rule with the consideration of 12 sea states and a reliability assessment using a stochastic FE analysis. The FORM and Monte Carlo method are used to calculate the probability of failure; the results confirmed that the FORM is suitable for the reliability assessment of marine structures.

Some study cases represent the trend of the importance of fatigue problems, such as Mao *et al.* (2015), who present a study using a beam theory-based approach for the fatigue assessment of container ship structures. They performed an investigation using experimental records from two container ships and a comparison with the results from direct FE analysis. A new procedure was proposed to obtain relative results from a linear regression analysis with the results from only one sea state FE analysis results considering its efficiency and accuracy. Another example is a case study by Park *et al.* (2017), who performed a fatigue damage evaluation of an LNG tank. This efficient time-domain stress analysis was combined with a modal analysis, which employed quasi-static deformation modes. With the three basic assumptions in this study, the structural response is almost static, and the contact force is independent of friction. An efficient and accurate time-domain fatigue analysis that can be applied to the structural details near the rolling key and chock of an independent type tank is provided.

3.2.3 Residual strength

The global strength assessment of a ship in a seaway is generally undertaken by reducing the problem to a quasi-static scenario of a ship balanced on a wave. In a damage scenario, the same assumption is made. With these assessments, understanding the influence of the damage on the structural response is important. Underwood *et al.* (2015) demonstrated the potential influence of damage on the total failure mode of steel grillages. Subsequently, Underwood *et al.* (2016) demonstrated similar effects within a box girder and proposed that damage analysis should be considered at both the interframe level and compartment level to capture these effects.

Under collision loads, the failure mode of a structure can also change. Considering tubular structures, Bandi *et al.* (2015) introduced a design method for the progressive collapse of thin-walled tubular components under axial and oblique impacts using FE analysis. On a larger scale, Cerik (2015) used FE analyses and experiments to demonstrate how damage can cause sharp catastrophic asymmetric failure of ring-stiffened cylinders, whereas the presence of an additional structure prevents this catastrophic failure but causes failure similar to the undamaged form for orthogonally stiffened cylinders.

Numerous papers investigate the effect of the loss of a column within steel framed structures. Of primary interest to civil structures, the increased open spaces within cruise liners prompt an increased use of pillars. Chen *et al.* (2016a) include a formulation that considers the axial load within a beam as its length increases and structure yields after removal of a central supporting column.

Noting the importance of material data for use in analysis, Calle and Alves (2015) provided a review of material failure modelling in ship collisions. Calle *et al.* (2017), Hosseini *et al.* (2016) and Storheim *et al.* (2015) investigate material failure criteria, fracture estimation and strain-ageing effects of materials, respectively. With a focus on ship-to-ship collisions, Zhang *et al.* (2017d) presented experimental verification of closed-form analytical solutions for the energy released during ship collisions, as previously presented by Pedersen and Zhang (1998). Heinvee and Tabri (2015), Liu and Guedes Soares (2015, 2016), Liu *et al.* (2015) and Sun *et al.* (2015b) present analytical methods in relation to energy absorption in stiffened plates and web girders during collision events. Samuelides (2015) presented procedures that were applied for the assessment of the crashworthiness of marine structures subjected to impact loads and noted the requirement to identify and determine uncertainties. Gao *et al.* (2015) demonstrated an elastic-plastic ice material model for ship-iceberg collision simulations utilising the Tsai-Wu yield surface model and developing new empirical failure criterion. Bin *et al.* (2016) presented an analytical method based on the improved Smith's method to assess the damage and predict the residual strength of a ship in a shoal grounding scenario.

The development of techniques for residual strength assessment continue with a significantly greater focus on dynamic rather than simplified quasi-static approaches. However, evidence exists of some of the advances in dynamic evidence that provide verification and development of closed-form analytical or quasi-static FE approaches.

3.2.4 Whipping

Contributions from impulsive slamming loads and the consequent vibratory response (whipping) to fatigue and extreme loading may be significant for long slender ships with large openings, such as container vessels. Within the reporting period, concern for how it affects the fatigue and ultimate strengths of ships and how it should be included in numerical models and simulations in the design and assessment of a ship's performance continue to be the focus of numerous studies, for example, refer to DNV GL (2015).

An essential input parameter in numerical tools and model tests that affect the vibration level is damping. Storhaug *et al.* (2017) presented a study in which the damping for several container ships and other ship types was determined based on measurement data. Several damping methods were applied to determine the most reliable method. The Random Decrement Technique (RDT) and the spectral method were recommended. The results indicated significant differences in damping among ship types. A target damping of 1.7% for container ships and a target damping of 0.7% for blunt ships were proposed. For container ships, the damping appeared to slightly reduce with vessel size but with moderate confidence. Temarel *et al.* (2016) presented a review study, in which they critically assessed the methods employed for the evaluation of wave-induced loads on ships. Analytical, numerical and experimental approaches were examined. A sensitivity analysis of the response analyses, which is a regular part of a structural reliability study, is performed to identify and estimate uncertainties and reduce these uncertainties to as large an extent as possible.

Storhaug and Andersen (2015) presented a study with the objective of explaining why hogging collapse accidents occurred in moderate to small storms. The method of extrapolation of model test measurements of whipping was used to identify the dimensioning sea states for three container ships. The findings concluded that moderate storms and head or bow quartering seas at realistic speed with voluntary speed reduction are regarded as an acceptable design basis for estimating the total moment, including whipping for container ship design.

During the reporting period, the committee has reviewed numerous papers, which present numerical simulations and analyses that involve whipping. The majority of the studies have been performed using simulation software and methods that fall outside of the mandate of the current committee that refers to quasi-static response analysis. This trend may be attributed to the positive advancement of simulation software and computer capacity, which enables advanced and detailed simulations with reasonable time effort and computational cost. Fukasawa and Hiranuma (2016) presented time-domain nonlinear simulations of three container ships (1,700 TEU, 6,000 TEU and 20,000 TEU) and compared the calculated vertical wave bending moments with the unified IACS (2015a) requirements. Shin *et al.* (2015) investigated the importance of various hydroelastic modelling approaches for the global symmetric and anti-symmetric response of a 16,000 TEU ULCS design. Two- and three-dimensional linear and weakly nonlinear flexible FSI models that respectively combine the Vlasov beam and 3D FE analysis structural dynamics with a B-spline Rankine panel and Green's function hydrodynamics were assessed and compared. Comparisons between rigid body and hydroelastic predictions demonstrated the importance of considering the effect of hull flexibility on the dynamic response and the suitability of different idealisations in preliminary or detailed design stages.

3.3 New metallic materials, composite and sandwich structures

The development of novel materials and structural topologies for the construction of marine structures continues with an accelerating pace. Castegnaro *et al.* (2017) presented the development of a 4.6 m flax-epoxy and balsa wood racing sailboat, from the materials selection to the manufacturing technique. Tensile tests on the flax-epoxy laminates revealed the typical scatter of natural bio-composites. Godani *et al.* (2015) performed experimental and numerical studies that demonstrated the high sensitivity of inter-laminar shear strength of GFRP composites to air inclusions. Different void shapes were modelled using a range of element formulations. Lee *et al.* (2015a) investigated a glass fibre-reinforced polyurethane foam (as used for LNG tank insulation) in cryogenic and room temperatures under compressive loading. A temperature and strain-rate dependent constitutive material model was proposed and implemented in an FE analysis, which demonstrates agreement with the experimental results. Shahbaztabar and Ranji (2016) developed an analytic model for the free vibration analysis of symmetrical cross-ply laminated plates resting on an elastic foundation subjected to uniform in-plane loads and in contact with water on one side; the results correlated well with experiments. Yu *et al.* (2016a) developed a method for the free vibration and buckling of laminated composite plates based on the first-order shear deformation laminate theory and B-spline interpolation functions. The method enables effective modelling of cut outs with complicated shapes and reasonable accuracy. Kotsidis *et al.* (2015) performed static and fatigue tests of hybrid composite-to-steel butt joints that consist of double lap steel-FRP parts and an FRP sandwich. Damage propagation and response of the joint was described. Rahm *et al.* (2017) experimentally investigated the fire resistance of an FRP sandwich bulkhead with thermal insulation and a multiple core FRP sandwich bulkhead without insulation and was able to demonstrate structural fire integrity beyond 60 minutes whilst reducing the structural weight and thickness compared with a reference panel.

Although the marine industry favours steel as a material, lightweight construction can be achieved by seeking new topologies via sandwich construction. Jelovica and Romanoff (2015) and Jelovica *et al.* (2016) investigated buckling and natural frequencies of laser-welded steel sandwich panels. Secondary bending was demonstrated to postpone local instabilities and increase load-carrying capacity while stiffness of the laser welds, joining the faces and the core, have a significant influence on vibrations. Huang *et al.* (2015) and Yan *et al.* (2016a) investigated lightweight steel-concrete-steel composite shells subjected to patch loading, which simulate applications in offshore platforms in ice-covered waters, compared with experiments and developing analytical formulations.

Several studies focused on exploring the benefits of composite materials in replacing steel structures in ships. Ringsberg (2015) presented a study of the performance of a car deck panel fabricated with steel and composite materials to optimise the strength-weight ratio by FE analyses. Stipčević *et al.* (2015) presented an FE analysis study of the bending response of composite panels in the upper decks of a car carrier considering BV Rule compliance. Tawfik *et al.* (2017) presented a study of the use of composite materials for the hatch covers of a bulk carrier; the results conclude that the alternative construction reduces the weight and operating cost of a vessel or provides extra strength of the hatch covers. Developments of novel steels and structural designs for LNG tanks have focused on improved structural performance, reliability and cost-optimisation of joints and insulation systems (Ehlers *et al.* 2017, Lee *et al.* 2015b, Niu *et al.* 2017).

3.4 Ageing structures

Throughout the life of a structure, its ability to continue to resist load will change due to degradation of the structural material, degradation due to the response to cyclic loading, and the impact of accidental loading. This section focuses on quasi-static methods to assess the capability of an aged or ageing structure.

3.4.1 Corrosion

In the design and analysis of ships and offshore structures, allowances are made for corrosion to ensure that the capability of the structure remains sufficient throughout its life. During the term of this committee, numerous papers have been published to investigate the effect of corrosion. Cui *et al.* (2017a) investigated the effect of corrosion on the ultimate bending strength of a ship's hull that was subject to uniform corrosion at varying depths and demonstrated the subsequent degradation in strength. A similar study was presented by Zhang *et al.* (2017f), who represented the corrosion as pitting and developed a strength reduction formulae based on the lost volume. Zhang *et al.* (2017b) presented an experimental study and provided empirical equations to predict the ultimate strengths of corroded stiffened panels. Wang *et al.* (2015c) developed empirical formulations for the ultimate strengths of stiffened steel panels that feature grooving corrosion under axial compression, which revealed correlation with FE analyses at lower column slenderness values. Saad-Eldeen (2015a) presented a study to analyse a severely damaged box girder subjected to the combined action of non-uniform and inter-crystalline corrosion. A series of comparative static nonlinear FE analyses are conducted, and the effect of stiffness reduction on the moment-curvature relationships, failure modes, and ultimate strength, as well as the movement of the neutral axis, were presented and discussed.

3.4.2 Fatigue cracks

Welded structures of all sizes and shapes exhibit fatigue failure primarily in the welded region, rather than in the base material, due to imperfections and flaws that relate to the welding procedure. Therefore, the welded region has received and continues to receive a substantial amount of attention from researchers. Wang *et al.* (2015b) performed a multi-scale investigation of the residual strength of a jacket platform with fatigue crack damage by multi-scale FE analysis. Presently, an efficient method to evaluate the influence of cracks on structural performance is lacking due to the immense scale difference between the meso-scale damage and the macro-scale structure. The results indicate that the proposed multi-scale method can accurately describe fatigue crack damage in a macro-scale structure and be applied to investigate the influence of meso-scale structural damage under extreme loads.

Ao and Wang (2015) investigated the residual ultimate strength characteristics of box girders with variable inclination cracks under torsional loading. A series of FE models are established by changing the crack length and crack angle using FE analyses and verified by comparison with previously developed formulae. Yan *et al.* (2016b) presented a prediction of fatigue crack growth in a ship detail under wave-induced loading. Fatigue life prediction based on fracture mechanics has become the focus of research on the strength of ship structures. However, a general formula for calculating stress intensity factors (SIF) is difficult to summarise, and the application of the fatigue crack propagation theory is limited to simple structures and simple loads. Therefore, the SIF of a crack in a ship detail was calculated by combining FE analysis capabilities, and a method for generating the ship fatigue loading spectrum is demonstrated based on the design wave approach. Lotsberg *et al.* (2016) used probabilistic methods for planning inspections for fatigue cracks in offshore structures. Due to the nature of the fatigue phenomena, small changes in basic assumptions can have a significant influence on the predicted crack growth. The calculated fatigue life based on the S-N approach is sensitive to the input parameters. Fracture mechanics analysis is required for the prediction of crack sizes during the service life to account for the probability of detection after an inspection event. Analysis based on fracture mechanics needs to be calibrated to the analysis of fatigue test data or S-N data. Calculated probabilities of fatigue failure using probabilistic methods are even more sensitive to the analysis methodology and to input parameters in the analyses. Thus, the use of these methods for planning inspection requires considerable knowledge and engineering skill. Therefore, industry has asked for guidelines that can be used to establish reliable inspection results using these methods. During previous years, DNV GL has performed a joint industry project for establishing probabilistic methods for planning in-service inspection for fatigue cracks in offshore structures. The recommendations from this project are included in recommended practice. The essential features of the probabilistic methods developed for this type of inspection planning are described in this paper.

Yue *et al.* (2017) investigated fatigue crack propagation in bulb stiffeners, which are extensively employed in ship structures. The shape of a 3D surface crack in a full-scale bulb stiffener fatigue test was measured and estimated by the Nominalisation Crack Opening Displacement method. Crack propagation in the bulb stiffener was based on the 2D Paris law and linear FE analyses; the predicted fatigue crack propagation was verified by full-scale fatigue tests.

The hammer peening process is a well-known method for improving the fatigue life of welded joints by generating a compressive residual stress field near the weld toe, which is recognised as the fatigue crack initiation site. Morikage *et al.* (2016) investigated the mechanism of fatigue crack propagation in a compressive residual stress field by comparing the results with the experimental results. The results clarified the fact that the morphology of a surface crack, which propagated in the compressive residual stress field, differed from the morphology of a surface crack in a neutral stress field, especially under a low stress intensity factor condition. Tian *et al.* (2017) introduced a structural intensity approach to study the crack detection for offshore platforms. The Line Spring Model of a surface crack is proposed based on the plate crack structure, and thus, the relationship among the additional angle, displacement and crack relative depth is achieved. The expression of appended structural intensity for crack damage is derived. Using the structural intensity approach, cracks are easily detected on the key point. The K-shape welded pipe point is detected using a structural intensity approach, and the crack can be accurately detected.

3.4.3 Dents

Accidental loading often causes localised deformation or dents in a structure, which are attributed to the support of docking, wave impact, contact by quays or floating objects, and dropped objects. The ability to analyse a structure to confirm its residual strength in its dented state is important when assessing whether a structure can remain in service or whether immediate repair is required. Within the reporting period, Saad-Eldeen *et al.* (2015a, 2015b) presented a series of experimental ultimate bending strength analyses of box girders with dents. The results were compared with FE analyses, in which loading was applied in a quasi-static manner to compare the impact on both ultimate strength and flexural rigidity. Additional studies by Saad-Eldeen *et al.* (2014, 2016a, 2016b) investigated the impact of dents on the ultimate strength of steel plates, with or without openings. The analysis was experimental with comparative assessments undertaken by FE analyses. The post-collapse behaviours are discussed, and the inflection plate slenderness with and without dents is observed, for which the behaviour of the plate changed. A certain dent breadth-to-plate breadth ratio, which reveals the different plate response, is established. Subsequently, Saad-Eldeen *et al.* (2014) developed a generalised expression of the ultimate strength reduction factor due to dents.

3.5 Concluding remarks

Structural analysis via the application of quasi-static loading remains an important approach in the design and analysis of ships and offshore structures. Whilst significant research continues in the time domain, this research is important to investigate methods that simplify the analysis process whilst providing suitable accuracy to rapidly develop structural designs, that do not constrain the designer to a limited tool set or require complex and time-consuming analysis early in the design process, when data may not be available to implement these techniques in a useful and meaningful manner.

4. UNCERTAINTY AND RELIABILITY ANALYSIS

Recently, reliability analysis has become more important for the design of ships and offshore structures. Proper evaluation of uncertainties in the target structures and estimation of uncertainties in the responses of the structures are necessary for reasonable reliability analysis. Two main categories of uncertainties exist:

- *Aleatory uncertainty*, i.e., physical uncertainty. Aleatory uncertainty consists of physical uncertainty, which is inherent, and intrinsic uncertainty. Aleatory uncertainty is a natural randomness of a quantity, such as the variability in the strength of materials. This physical uncertainty or natural variability is a type of uncertainty that cannot be reduced.
- *Epistemic uncertainty*, i.e., uncertainty related to imperfect knowledge. Epistemic uncertainty consists of statistical uncertainty, model uncertainty and measurement uncertainty, which are classified as a type of uncertainty associated with limited, insufficient or imprecise knowledge.

This chapter focuses on the recent developments in uncertainty modelling of loads and structures, and recent application of reliability analysis to practical problems. Recent developments of uncertainty analysis methods and risk-based maintenance concepts associated with quasi-static response assessment have been reported.

4.1 Uncertainties in load modelling

4.1.1 Still water and wave loads

Based on the probabilistic model of the configuration of damage to ship structures in IMO's Marine Environment Protection Committee (MEPC), some papers begin to study the probability of the still water bending moment, statistical description of wave-induced loads and the effect of statistical uncertainty due to different time spans of simulations of ship responses for damaged ships. Rodrigues *et al.* (2015) performed a probabilistic analysis of the hull girder still water loads on a shuttle tanker for parametrically distributed collision damage spaces. The collision-induced probabilistic distribution of the damaged boxes was also investigated. Bužančić Primorac *et al.* (2015) investigated the statistical properties of the still water bending moment of a double hull oil tanker that was damaged in a collision or grounding accident. Random damage scenarios were generated by Monte Carlo simulation using IMO probability distributions of damage parameters. This probabilistic model can be applied to the structural reliability assessment of damaged ships.

Regarding the uncertainties in the wave-induced bending moment, Temarel *et al.* (2016) presented a review paper on the uncertainties in predicting wave-induced loads and the probabilistic approaches for the evaluation of long-term response. Gaspar *et al.* (2016) evaluated the effect of the nonlinear vertical wave-induced bending moments on the ship hull girder reliability based on the FORM. Note that the probabilistic modelling for the hull girder strength, still water bending moment and vertical wave-induced bending moment is detailed. Guo *et al.*

(2016) presented a statistical analysis method of ship response in extreme seas, which addressed the statistical description of heave and pitch motions and vertical bending moments by taking an LNG tanker as an example. Iijima *et al.* (2017) examined the effect of ship operation on the hydroelastic behaviours of three large container ships (6,000 TEU, 10,000 TEU and 19,000 TEU). The uncertainty of the wave-induced vibration with respect to ship speed is evaluated.

4.1.2 Wind loads

The retrieval of wind profiles considering statistical uncertainties remains the main topic of recent studies. Achtert *et al.* (2015) presented notable research on the estimation of wind loads that employed the combination of a commercial Doppler LIDAR with a custom-made motion-stabilisation platform. The retrieval of wind profiles in the Arctic atmospheric boundary layer during both cruising and ice-breaking with statistical uncertainties is demonstrated and compared with land-based measurements, which enables the retrieval of vertical winds with a random error less than 0.2 m/s. Xie *et al.* (2016) performed a simulation-based study of wind loads on semi-submerged objects in ocean wave fields. The results indicated that waves can cause significant variations in wind loads; these effects were not adequately recognised and have not been quantified in previous studies. Zhang *et al.* (2017c) examined probabilistic modelling of the drifting trajectory of an object under the effect of wind and currents for maritime search and rescue. An optimal estimation algorithm was proposed to obtain random wind and current velocities based on the spatial correlated fields.

4.1.3 Ice loads

The ISO 19906 standard provides guidance for the calculation of design ice loads using both deterministic approaches and probabilistic approaches (ISO 2010). In determining design loads for different environmental factors, both principal actions and companion actions must be considered. The ISO 19906 enables the designer to calculate the companion wave action as a specified fraction (combination factor) of the Extreme Level (EL) design wave load. Alternatively, the designer can explicitly calculate appropriate companion wave loads. Fuglem *et al.* (2015) presented probabilistic methods to estimate iceberg-wave companion loads. A probabilistic methodology was developed to determine the joint probability distribution of iceberg impact and companion wave forces, and the combined EL and Abnormal Level (AL) values were determined. The effective companion wave loads were significantly less than the effective companion wave loads determined based on the ISO 19906 combined load factors. Xu *et al.* (2015a) performed an experimental study of dynamic conical ice force. A comparison of ice forces from small-scale tests with full-scale measured data from a conical structure has been accomplished. Ranta *et al.* (2015) conducted ice load estimation using combined finite-discrete element simulations and aimed to demonstrate the applicability of these simulations in a statistical study on ice loads and the estimates of their errors. Hansen *et al.* (2015) presented new statistical methods for calculating extreme spatial ice distributions that may be applied in the design process. Statistics for global loads and directional dependency of icing and methods for assessing the expected duration of icing events are described. Heinonen and Rissanen (2017) investigated the coupled-crushing analysis of a sea ice-wind turbine interaction and suggested that the magnitude and time variation of sea ice load depends on various factors, such as the thickness and velocity of ice and the size and shape of a structure.

4.1.4 Sloshing and slamming loads

Model tests remain the main approach in the study of sloshing and slamming loads in recent years and provide a significant amount of information about the uncertainties of these loads. Kim *et al.* (2017b) investigated the scale effect on 3D sloshing flows. A series of model tests were conducted for three differently scaled tanks. The key sloshing load parameters, such as the pressure peak and rise time of sampled sloshing pressures, were systematically analysed by a statistical approach. Ryu *et al.* (2016) investigated sloshing design load prediction of a membrane-type LNG cargo containment system with a two-row tank arrangement in offshore applications. Due to the uncertainties entangled with the scale law that transforms the measured impact pressure to the full-scale impact pressure, a comparative approach was taken to derive the design sloshing load. Swidan *et al.* (2016) presented a series of drop-test experiments to investigate the slamming loads experienced by a generic wave-piercer catamaran hull form during water impacts. The systematic and random uncertainties associated with the drop test results are quantified. Stagonas *et al.* (2016) demonstrated the use of a pressure mapping system for measuring wave impact-induced pressures. The results concluded that the pressure mapping system has the capacity to provide pressure distribution maps with reasonable accuracy by careful calibration and setup.

4.1.5 Impact loads

Impact loads can be considered as transient forces that are generated during accidents and operations and include numerous uncertainties. Jia and Moan (2015) investigated the hydrodynamic effects in ship collision. Their findings reveal that the equivalent added mass for the sway motion depends on not only the duration of collision impact and impact force but also on the collision position, whereas the equivalent added mass for the yaw motion can be assumed to be independent of the collision position. Park *et al.* (2015) presented an accidental limit state-based ship collision analysis approach. Time-variant corrosion wastage was employed in the case of age-related damage. In the case of a collision event, low Arctic temperatures may affect the crashworthiness and delay the ageing effect compared with regular temperatures.

The shape of the sea bottom is an important factor that determines the extent of grounding damage on ships and the loss of water tightness. Sormunen *et al.* (2016) presented a four-step methodology for mathematically estimating sea bottom shapes for grounding damage calculations. A statistical binormal model was suggested to describe the bottom shape, which yielded better goodness-of-fit test results than the results obtained by the cone and polynomial models. Montes-Iturrizaga *et al.* (2016) presented a reliability analysis of mooring lines using copulas to model the statistical dependence of environmental variables. The influence of the statistical dependence between significant wave height and peak period on the reliability assessment of mooring lines is examined. The differences in the estimates of reliability using the Gaussian copula compared with the other copulas can be significantly large. The influence of the uncertainty in significant wave height and the influence of the mean and uncertainty of the breaking strength is also analysed.

4.1.6 Loads combinations

Probabilistic load combination factors of wave and whipping bending moments are investigated by Ćorak *et al.* (2015a, 2015b). The correlation analysis between wave bending moments and whipping bending moments is performed, and a practical method for calculation of the most likely load combination factor among the considered bending moments is presented. By application of the stated method, a significant influence of the random phase angles on the extreme values of the bending moments and load combination factors is confirmed. The von Karman approach with a correction for the pile-up effect is employed for a bow flare slamming load assessment. The procedure is demonstrated using the example of a 9,200 TEU container ship.

Regarding the combination of wave load and wind load, Horn *et al.* (2017) investigated a three-parameter joint probability distribution method. The combined load was a function of not only the environmental parameters, such as the significant wave height, wave peak period and mean wind speed, including their correlation, but also the wave directional offset compared with the mean wind heading (the wind-wave misalignment), as the wind-wave misalignment may excite low-damped vibrational modes and cause changes in the accumulated fatigue damage in the wind turbine foundation compared with collinear wind and waves.

4.2 Uncertainties in structural modelling

4.2.1 Corrosion deterioration

Methods to simulate a random corrosion process have been developed. In the method by Kawamura *et al.* (2015), the corrosion progress from the line coating defect, as observed in the on-board exposure test of the steel plates in a real ship structure, was simulated by generating the corrosion pits on the line defect and expanding the shape of the pits based on some random parameters. Osawa *et al.* (2016b) developed a method to simulate under-film corrosion for epoxy coated steel panels within a ship's water ballast tank environment. The incubation and extension of coating failure is simulated using 2D cellular automaton, and the steel diminution is simulated by IACS CSR-H's three-phase probabilistic model. Analysis parameters are determined using the results of on-board exposure and cyclic corrosion tests. The change in the corroded surface shape is simulated for both conventional steel panels and corrosion resistant steel panels. Osawa *et al.* (2016a) developed a "spattering model" to simulate coating degradation starting from thin film thickness regions (e.g., free edges and weld beads).

Gaspar *et al.* (2015b) evaluated the influence of the aspect ratio of the plate on their ultimate compressive strength reduction due to the effect of the non-uniform corrosion patterns. They considered the random field model to represent the spatial distribution of random corrosion depths (corrosion pattern). The results indicated that the strength reduction due to the effect of the non-uniform corrosion is significant in the longitudinal structures of the ship hull girder. Rahmdel *et al.* (2015) predicted the ultimate strength reduction caused by pitting corrosion of an offshore structure at various ages. The introduced stepwise approach contemplates the non-linearity of pitting corrosion with time by considering the experimental data. Shi *et al.* (2016) investigated the influence of pitting corrosion on the residual ultimate strength of stiffened panels by a series of nonlinear FE analysis. The results indicate that the pits will induce the buckling failure of a stiffened panel.

4.2.2 Fabrication-related imperfections

Fabrication-related imperfections are important to evaluate the uncertainty of the strength of structures. Gul and Altaf (2015) analysed the effects of fabrication-induced imperfections, non-dimensional geometric parameters and material characteristics on the ultimate strength of stiffened plates in a marine structure. Their findings revealed that imperfections have a significant effect on the ultimate buckling strength of a stiffened plate. As the plate flexural slenderness increases, the imperfection effect becomes more dominant and the post-buckling response also becomes sharply unstable. Ghanbari Ghazijahani *et al.* (2015) provided experimental data on the effect of geometrical imperfections on the buckling capacity of locally dented conical shells under axial compression. The results indicate changes in the buckling mode and the capacity for damaged thin specimens as outlined with an average total capacity reduction of 11%.

4.2.3 Impact damage

Ship residual strength in collisions or grounding scenarios can be assessed in terms of the residual strength factor, which is defined as the ratio of time-variant hull girder capacity in damaged conditions to the time-variant hull girder capacity of an intact gross scantling girder. Campanile *et al.* (2015, 2016) investigated the statistical properties of bulk carriers' residual strength. Three damage scenarios (collision scenario, 1st grounding scenario, and 2nd grounding scenario) were analysed according to the current requirements of CSR-H for bulk carriers and oil tankers, assuming as a reference case the bulk carrier section scheme proposed in the last ISSC Report. A collapse probabilistic assessment method under impact loads was proposed by Youssef *et al.* (2016) to assess the risk of ship hull collapse due to collision. A probabilistic approach is applied to establish the relationship between the exceedance probability of collision and the residual ultimate longitudinal strength index. Kim *et al.* (2015b) investigated environmental consequences associated with collisions that involve a double hull oil tanker. Using probabilistic approaches, credible scenarios of ship-ship collision are selected to create a representative sample of the most possible collisions.

Reed and Earls (2015) presented a study of stochastic identification of the structural damage condition of a ship bow section under model uncertainty. A non-contact approach to identify and characterise imperfections within the submerged bow section of a representative ship hull is proposed. A fluid-structure model that predicts the spatio-temporal pressure field and a Bayesian, reversible jump Markov chain Monte Carlo approach is used to generate the imperfection parameter estimates and quantify the uncertainty in these estimates. Gerlach and Fricke (2016) presented an experimental and numerical investigation of the behaviours of ship windows subjected to quasi-static pressure loads and impact loads. A method to calculate the failure probabilities of glass panels under pressure loads is presented. Failure probabilities for the glass panels in the tests are determined and failure mechanisms are clarified.

The deformation behaviours of ship structural members under load depends on uncertainty modelling using material, geometric, and structural considerations, as captured in an appropriate reliability framework. Obisesan *et al.* (2015) presented a new stochastic framework for modelling the performance of ship structures during collisions by assessing the dependency of the deformation behaviours of ship structural members on the uncertainties from the material and geometric properties. Storheim *et al.* (2017) recommended disregarding the strain-rate hardening in simulations of relatively slow accidental actions, such as ship impacts, unless material tests are available and the rate-hardening models can be properly calibrated for the entire strain range. The conclusion is that material model properties and fracture criterion specified in the new DNV-GL RP-C208 are unnecessarily conservative. Based on the experience from the benchmark study, this study concludes that material properties that give a more generous response may have to be employed for these design purposes.

4.2.4 Ultimate strength and buckling

Recently, reliability related to the ultimate strength of a stiffened panel has been investigated by some researchers. Leheta *et al.* (2017) performed reliability analyses using Monte Carlo simulation to compute and compare the time-invariant reliability indices of stiffened panels with either conventional T-stiffeners or novel Y-stiffeners (hat + tee/angle) profiles in a double hull oil tanker's bottom and deck panels under axial compressive loads. The ultimate strength and the applied axial compressive stress formulations in the limit state functions are obtained based on the IACS CSR for Oil Tankers considering the failure modes: unstiffened plate buckling, stiffener beam-column buckling, and stiffener flexural-torsional buckling (tripping). Chen (2017) presented an assessment method for the panel reliability of a ship-shaped FPSO unit. Beam-column buckling and flexural-torsional buckling are regarded as two primary failure modes of stiffened panels. The variability of corrosion wastage and material properties are considered when modelling the panel's time-dependent ultimate strength. The uncertainty of axial compressive loads induced by hull girder bending is evaluated based on the probabilistic characteristics of the still water bending moment and the vertical wave-induced bending moment. The environmental severity factor and the effect of corrosion wastage on the panel reliability are investigated. Sensitivity measures for random variables are applied.

4.2.5 Fatigue damage

Regarding the uncertainty assessment of fatigue damage, Lim *et al.* (2017) discussed a study of the uncertainty in the accumulated fatigue damage in a top-tensioned riser due to vortex-induced vibration. Fatigue damage is estimated by the rainflow cycle counting method and an interesting approach of fatigue damage estimation based on Polynomial Chaos Expansion (PCE). PCE is used to represent the model parameters (a residual of the cylinder maximum amplitude, the natural frequency, and the current velocity) and accumulated fatigue damage (response surface). Yeter *et al.* (2015) presented the fatigue reliability assessment, which accounts for an in-service crack growth on a welded tubular joint of an offshore wind turbine (OWT) support structure. The results of this study underpin risk-based inspection planning for OWT support structures. The uncertainties with respect to the crack growth, stress evaluation and failure assessment diagram were included in the reliability estimates.

4.3 Reliability and uncertainty analysis

Reliability analysis methods are extensively applied in rule-making processes and design procedures. In this section, recent applications and developments of reliability analysis for ships and offshore structures are reported. When we consider uncertainties in structural models and loads, the response of a structure has uncertainties that should be evaluated for rational reliability analysis and the corresponding design process of structures. Recent developments in uncertainty analysis methods by stochastic FE analyses are also reported.

4.3.1 Reliability analysis

New rule formulations and methods of reliability assessment for the ultimate strength of ships by applying Structural Reliability Analysis (SRA) have been controversial research areas in recent years. The FORM and the Monte Carlo Importance Sampling (MCIS) method are extensively applied. Benhamou *et al.* (2017) reported three rule formats: Working Stress Design (WSD), Implicit Working Stress Design (IWSD) and Load and Resistance Factor Design (LRFD). The constant Partial Safety Factor (PSF) formulation and the variable PSF formulation were discussed using these three rule formats. Hørte and Sigurdsson (2017) reported the use of SRA as a tool for code calibration with two examples: "development of the hull girder ultimate capacity criterion for tankers" and "calibration of mooring design code". By applying SRA to wellhead fatigue analysis, the accumulated probability of fatigue failure as a function of time was presented, and possibilities and benefits of applying SRA in structural engineering were demonstrated. Chen (2016) evaluated the uncertainty of the still water bending moment based on the loading conditions from FPSO operational manuals, and a stochastic model of the extreme value of vertical wave-induced bending moment was developed in accordance with extreme value theories. A FORM coupled with a finite difference method was proposed for reliability estimates to address the complicated implicit limit state function for hull girder ultimate strength assessment. Ćorak *et al.* (2017) present a methodology for the assessment of the structural reliability of an oil tanker that was damaged in a hypothetical grounding accident in the Adriatic Sea. The extent of the damage to the ship's hull after a grounding accident depends on several parameters, such as the ship speed, rock size, penetration depth, and longitudinal and transversal location of stranding along the hull. These parameters are assumed to be random variables described by probability density functions in this study. Based on defined statistical properties, random realisations of grounding parameters are simulated by Monte Carlo simulation. Four design equations are adopted to predict the collapse pressure of pipelines with corrosion defects. Regarding the application of SRA to offshore structures, Zhang *et al.* (2017e) described a structural reliability method to analyse the drilling operability envelope of the offshore drilling riser deployment. The uncertainties are primarily derived from wave and current loadings. The efficient structural reliability method Moment Method Based on Entropy Theories and Genetic Algorithm (MEGA) is adopted to obtain the failure probabilities. The reliability method complements the current deterministic approach for new riser design and untested ultra-deep water. Emami Azadi (2017) investigated the reliability analysis method of a three-leg North Sea jack-up platform for various types of ship impact scenarios. The findings of this study indicated that the type of bow or broadside impact and the spudcan-soil modelling may have a considerable effect on the reliability of the jack-up platform during a ship collision.

In recent studies about life assessment of ship structures, structural reliability analysis has an important role. Ibrahim (2016) presented an overview of structural life assessment with reliability analysis. Despite the structural parameter uncertainties, probabilistic analysis requires the use of reliability methods for assessing fatigue life by considering the crack propagation process and assessing the first passage problem, which measures the probability of the exit time from a safe operating regime. The main results reported in the literature pertain to ship structural damage assessments from slamming loads, liquid sloshing impact loads of liquefied natural gas in ship tankers, ship grounding accidents and collision with solid bodies. Under these extreme loadings, structural reliability is the major issue in the design stage of ocean structures. Gaspar and Guedes Soares (2015) reported a system reliability analysis of a ship deck structure for buckling collapse and corrosion limit states. The generalised corrosion of the deck structure is modelled as a random process of correlated uniform thickness reductions described by a nonlinear time-dependent model. The time-variant system failure probabilities are computed using Monte Carlo simulation. The results indicate that the probability of occurrence of a local failure of the ship deck structural system increases significantly over time. The effect of the correlation length of the random process of corrosion on the system failure probability is significant. Bai *et al.* (2016) investigated a time-dependent reliability assessment method of offshore jacket platforms that considers the resistance degradation. For the resistance probability model of the jacket platform, the corrosion effect was considered for the degradation of the resistance. A proper corrosion model was examined. For the load effect probability model, the typhoon load effect, which contains wind, wave and current loads, was employed. Jensen (2015) presented a combination of Monte Carlo simulation and the FORM in fatigue damage estimation in nonlinear systems.

In recent years, some new techniques of reliability analysis have been developed. Gaspar *et al.* (2015a) presented an adaptive response surface approach in the reliability analysis of plate elements under uniaxial compression. A response surface model based on second-order polynomials is combined with the FORM to compute reliability estimates for moderate computational times. Chojaczyk *et al.* (2015) presented a review of the application of Artificial Neural Network (ANN) models in structural reliability analysis by categorising the analysis into five main topics: (1) types of ANNs, (2) ANN-based methods of failure probability computation, (3) ANN training set improvement techniques, (4) comparison of ANN-based reliability methods, and (5) reliability-based structural design and optimisation using ANNs. The findings concluded that ANN-based reliability methodologies are robust and efficient for the analysis of complex structures.

4.3.2 Uncertainty analysis by stochastic finite element method

As shown in the reviewed papers, the estimation of the uncertainty of structural response has become an important issue in recent years. Figure 1 depicts the general idea of uncertainty analysis, in which the inherent randomness (such as material properties, shape, loads, and corrosion) is treated as the input parameters defined by the probability density function of the random variables (θ_1, θ_2) and the probabilistic characterisation of the response (e.g., stress, displacement, strength) should be evaluated by the uncertainty analysis. The "Analysis Method" in the figure is generally a numerical method based on the analysis model, such as the FE method. Recently, the Stochastic Finite Element Method (SFEM) has been developed for the uncertainty analysis of structures. In this section, the recent development of uncertainty analysis by SFEM is reviewed. Stefanou (2009) detailed the development of SFEM prior to 2009. Arregui-Mena *et al.* (2016) reported the recent development and practical application of SFEM in the fields of materials science, biomechanics, and engineering. In the engineering field, the SFEM is used to estimate the reliability and performance of materials and structures, such as soils, bridge structures, components of machines or other structures, assuming that inherent uncertainty exists in the materials and the size and dimension of structures.

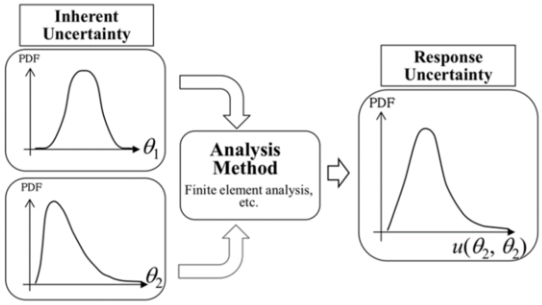

Figure 1: General concept of uncertainty analysis.

Generally, the SFEM can be categorised into two major types: the "non-intrusive method" and the "intrusive method". Representative of the "non-intrusive method", the Monte Carlo simulation method is the most prevalent technique used to evaluate response uncertainty. A large number of simulations of the "Analysis Method" should be performed using numerous different samples of the input parameters (refer to Figure 1). Thus, the required statistics of the response can be estimated from the large number of responses. Due the recent application of a non-intrusive method, Schoefs *et al.* (2016) developed a deterministic analytical formulation of the stress concentration factor from the approximation given by the Regressive eXtended Finite Element Method (RXFEM). In this paper, first, the main computational principle of XFEM is shown for the case of given geometries. Second, the stochastic response is obtained by the XFEM of *N* realisations of different geometries, and by a post-process, the *N* stochastic response solutions are used to evaluate *N* solutions of the stress concentration factor. Last, the approximation of the response surface of the stress concentration factor is derived using the least-squares method.

In the intrusive method, the construction of a stochastic response surface does not require multiple simulations of the "Analysis Method", as the analysis procedure is directly modified to the new analysis procedure for the stochastic analysis. The typical representative methods include the "perturbation methods" and "response surface method with spectral approach".

For the perturbation method, Xu *et al.* (2016) reported a study of the free vibration characteristics of a random functionally graded material (FGM) beam. In this paper, a perturbation method-based stochastic FE method is used to study an FGM beam considering uncertainties in elastic modulus and mass density. Wu *et al.* (2015) reported a modified computational scheme of the Stochastic Perturbation Finite Element Method (SPFEM). Although this modified SPFEM can only handle low-level uncertainties, it can provide second-order estimates of the mean and variance without differentiating the system matrices with respect to the random variables. In this paper, the modified scheme is applied to linear or nonlinear structures with correlated or uncorrelated random variables. A 1D elastic bar with uncertainty in Young's modulus and the eigenvalue problem of a plane steel frame with uncertainty in stiffness are discussed as examples of linear structures. The nonlinear truss with uncertainty in Young's modulus and non-dimensional transient heat conduction with uncertainty in thermal conductivity are reported as nonlinear examples. Da Silva and Cardoso (2017) reported the formulation for stress-based robust topology optimisation of continuum structures considering uncertainties in Young's modulus. In this paper, the first-order perturbation approach is used to quantify the uncertainties. The midpoint method is used to perform random field discretisation. The probability of failure is bounded by the one-sided Chebychev inequality and validated with the use of the Monte Carlo simulation method. The correlation length and the number of standard deviations considered in the formulation have an important role in both the obtained topology and probability of failure. Kamiński and Świta (2015) evaluated the critical pressure of the cylindrical vertical underground steel container with Gaussian uncertainty in its cross-sectional thickness and Young's modulus using the SPFEM. The fourth-order probabilistic characteristics of the structural response are discussed, and the reliability index is calculated by the FORM for the limit-state function defined as the difference between the critical pressure and the maximum pressure.

Recently, the SFEM using the response surface methodology has been developed as the intrusive method, which may originate from the spectral approach by Ghanem and Spanos (2003). Sepahvanda (2016) reported the theory and application of the spectral Stochastic Finite Element Method (sSFEM) of the nonlinear structural dynamics with parametric uncertainty. In this paper, the uncertainty in the damping coefficient is represented by PCE, and the nonlinear stochastic FE is solved using the collocation method. Do *et al.* (2016) reported the structural analysis method with uncertainty in both the Young's modulus and the body force (self-weight) of structures by sSFEM. In this paper, the Young's modulus and body force (self-weight) of structures are modelled by Karhunen-Loeve (KL) expansion. The displacement response is represented using PCE. Chen *et al.* (2016b) reported the SFEM based on a response surface methodology considering the uncertainty in the shape of structures, in which the Hermite PCE is used to represent the uncertainty of shapes and the response surface. The uncertainty of the response of displacement, strain and stress can be effectively estimated by this method, which solves the main stiffness equation only once.

4.3.3 Other probabilistic analysis methods

Experimental uncertainty analysis is commonly utilised in hydrodynamic testing to establish the uncertainty in a result as a function of the input variables. Woodward *et al.* (2016) investigated the uncertainty analysis procedure for a ship inclining experiment. A methodology for calculating a confidence interval for the location of the centre-of-mass of a ship from an inclining experiment and for any load condition is presented. The uncertainty compared with an assumed metacentric height of 0.15 m is provided for four classes of ships.

A modelling approach that employs Bayesian belief networks to model various influencing variables in a seaport system is proposed by John *et al.* (2016) in risk assessment to improve the resilience of a seaport system. The use of Bayesian belief networks allows the influencing variables to be represented in a hierarchical structure for collaborative design and modelling of the system. Fuzzy analytical hierarchy process is utilised to evaluate the relative influence of each influencing variable.

4.4 Risk-based inspection, maintenance and repair

Ageing marine structures may experience structural deterioration, such as corrosion and fatigue, which may cause a reduction of their resistance and subsequent structural failure. Load effects on ship structures contain high levels of uncertainty and may exceed the associated design loads. Inspection and maintenance of ageing structures are needed to ensure satisfactory structural performance during their life cycles. Ordinary Classification society Rules are based on periodic (fixed interval) dry-docking and surveys. In the oil and gas industry, asset integrity management is often based on risk-based methodologies. For ships and floating offshore installations, this approach can serve as an alternative to the traditional periodical classification survey scheme. The increased attention to high-risk structural areas and components and less-intensive inspection of low-risk areas will simultaneously enhance safety and optimise inspection resources. Realising the operational efficiencies and cost savings that can be achieved, the military and defence industry and cargo shipment sector have already shown interest in this new approach (LR 2016a, LR 2016b). In general, the most significant strength deterioration mechanisms associated with ship structures are coating failure, corrosion and fatigue. Using risk-based approaches, the benefit of better coating standards and better structural details can be exploited. Risk-based approaches will also help optimise inspection regimes and prioritise inspection.

Dong and Frangopol (2015) investigated a probabilistic methodology for optimum inspection and maintenance planning of ship structures to mitigate risk of corrosion and fatigue. For the risk assessment, structural reliability analysis associated with ultimate flexural failure of the hull's mid-ship section was considered with evaluation of the consequences (i.e., direct costs) associated with structural failure. Frangopol and Soliman (2016) proposed a probabilistic optimisation approach, in which uncertainties in the damage assessment associated with corrosion and fatigue were considered. A multi-objective optimisation problem that accounts for structural deterioration scenarios and various uncertainties is formulated for the optimum inspection and repair planning of ship structures. Soliman *et al.* (2016) proposed a probabilistic framework for optimising the inspection, monitoring, and maintenance activities during the service life of fatigue critical structures. A probabilistic fatigue crack growth is considered to evaluate time-based performance and probability of failure. Doshi *et al.* (2017) demonstrated reliability-based inspection planning of structural details using a fracture mechanics-based fatigue evaluation for a VLCC. In this study, life is obtained using the Paris equation, and Bayesian methods are utilised for updating the reliability of the structural detail. Then, the reliability of various cases, such as no detection of cracks, and detection of cracks with and without repair, is evaluated at mid-ship locations of the VLCC. This paper demonstrates that reliability-based inspections are a feasible technique for integrity management of ship structural details. Hifi and Barltrop (2015) presented a methodology for calibrating the prediction models of structural defects and degradations. The methodology involves combining data from experience and prediction models to correct structural reliability models, which helps to produce better inspection and maintenance strategies and improve the durability of new and existing ships. Temple and Collette (2015) presented an optimisation framework (Pareto front) to estimate both production costs and maintenance costs for a naval vessel's internal structure and develop trade-spaces between these two objectives to obtain a design that balances both costs. A nominal naval destroyer-type vessel mid-ship section is used as a case study.

Seo *et al.* (2015) considered a risk assessment and inspection planning procedure for corroded subsea pipelines. In the proposed method, the probability of failure is estimated for corrosion damage (pit depth) using a time-variant model derived from measured data in the subsea industry. For the evaluation of the consequence of failure, the burst pressure is considered. These methods can be used to offer a standardised procedure of design and inspection/maintenance planning of pipeline systems.

Decò and Frangopol (2015) developed a method of real-time optimal short-range routing of ships based on a risk assessment with reliability analysis and structural health monitoring (SHM) information. The SHM data are integrated into a risk assessment of ship hulls by Bayesian updating, in which a novel closed-form solution for short-term statistics based on Rayleigh prior distribution is developed. Optimal short-range routing of ships is accomplished by solving two- and three-objective optimisation problems and is illustrated on a joint high-speed sealift.

Sørensen (2017) described reliability analysis of wind turbines with a special focus on structural components. The target reliability level for wind turbine structural components is considered, and reliability-based calibration of partial safety factors for the extreme state and fatigue limit state is presented. A reliability- and risk-based approach, in which a life-cycle approach that considers the total expected costs during the entire lifetime of a structure, is employed.

4.5 Concluding remarks

In this chapter, recent developments in uncertainty assessment and reliability analysis associated with quasi-static response are reported. In relation to load modelling, many studies of the uncertainties of various loads, such as wave loads, wind loads, ice loads, impact loads and load combinations, are performed. An uncertainty evaluation of loading with wave-induced elastic vibration, such as uncertainty caused by slamming, is an important research topic. Uncertainty modelling of structural response and uncertainty of age-related deterioration of structures by corrosion and fatigue are important research subjects. Uncertainty evaluation of the residual strength of damaged ships, such as ships during collisions, is an important research subject in recent years.

Many papers related to structural reliability analysis are reviewed in this chapter. Reliability analysis methods have become a practical and very powerful tool for decision-making in ship design, design code calibration for ships and offshore structures, and maintenance planning during ship operation. Recent development of the stochastic FE method for the evaluation of response uncertainty is also reported. The probabilistic and uncertainty evaluation concepts continue to be important research topics for the rational design of ships and offshore structures.

5. DEVELOPMENT OF RULES AND SOFTWARE SYSTEMS

This chapter contains a description of the latest developments in rules and software systems. Section 5.1 contains a review of the development of international rules and regulations, and Section 5.2 discusses the development of structural design software systems. The review is not exhaustive; only selected class rules and software are reviewed. The selection is based on the competence available in the committee.

5.1 Development of international rules and regulations

5.1.1 IMO Goal-Based Standards

The IMO Goal-Based Standards (GBS) for ships were introduced by IMO in 2002. These standards are broad, over-arching safety and environmental standards that are based on high-level goals and associated functional requirements. These standards currently apply to oil tankers and bulk carriers (IMO 2010). The new SOLAS regulation II-1/3-10 renders the GBS applicable to ships with lengths greater than 150 m and ships for which a building contract was placed on or after July 1, 2016. The 12 IACS Classification societies have submitted rules for oil tankers and bulk carriers to IMO for GBS verification. These rules consist of the IACS CSR and specific member requirements. In May 2016, the IMO's Maritime Safety Committee (MSC) accepted that these rules have been aligned to the goals and functional requirements set by the organisation.

5.1.2 New DNV GL rules

Following the merger of DNV and GL in 2013, the new DNV GL rules for Classification of Ships (DNV GL 2016a) entered into force in January 2016. The new hull structure rules are based on more advanced methods for the prediction of loads and responses, with a clear link to direct analysis. The rules provide an increased safety level and accommodates challenges related to the development of novel and unusual designs.

One of the most significant advances in the new rules is the introduction of Equivalent Design Waves (EDWs) to calculate environmental loads; refer to Heggelund *et al.* (2016). This concept has been previously employed by GL in direct calculations and by CSR (oil tankers and bulk carriers) and has been developed to be applicable for more slender ship types. The EDWs enable a more accurate representation of the load components (e.g., hull girder bending, hull girder torsion, sea pressure and tank pressure) and the phase between them. Consequently, a more precise stress description is obtained, which provide a better basis to optimise the structure. Although the loads in the CSR-H are only applicable to bulk carriers and oil tankers (which have similar characteristics), DNV GL has constructed new EDWs that are applicable for all ship types and sizes via numerous direct wave load and regression analyses.

To verify that the new methodology is consistent with operational experience, extensive consequence assessments of existing designs have been performed.

Buckling is the most important failure mode. Several direct calculation methods can be employed according to the new DNV GL rules: Closed Form Methods (CFM) represented by equations, semi-analytical methods (PULS) or nonlinear FE analysis for single panels and hull girder ultimate strength evaluation. A new class guideline—"CG-0128 Buckling" (DNV GL 2016b)—describes these methods. In the new rules, elastic buckling is allowed. The hull girder ultimate capacity shall be assessed by prescriptive methods, as described in CG-0128.

The fatigue assessment is based on the EDW method. The loads are given for the probability of exceedance 10^{-2} as these loads yield the greatest contribution to fatigue damage. Whipping and springing are recognised as contributing to and increasing the loads for all ships. The class notation whipping-induced vibration supports both advanced numerical analyses and simplified methods based on empirical factors. With the empirical factors, the wave bending moment for ultimate strength and fatigue is expected to increase by 10 to 20% depending on ship size.

5.1.3 Lloyd's Register rule development

Since 2014, the following key changes have been made to the Lloyd's Register (LR) Rules and Regulations for the Classification of Ships (LR 2014):

- Class notations have been amended in relation to the development of the LR ShipRight Structural Design Assessment (SDA), Fatigue Design Assessment (FDA) and Whipping Design Assessment (WDA) procedures from July 2014.
- Direct calculation requirements for container ships have been amended, including changes to permissible stresses from 2015.

Since 2014, the following key changes have been made to the Lloyd's Register Rules and Regulations for the Classification of Naval Ships (LR 2017a):

- Amendments to the requirements for rudder design from January 2015.
- Amendments to Local Design Load calculations from January 2015.
- Sections related to design requirements for rudders from January 2016 have been replaced.
- Anchoring and windlass requirements have been updated from January 2016.

During the reporting period, the following SDA procedures have been published by Lloyd's Register:

- Guidance notes for ShipRight SDA buckling assessment. August 2017.
- Fatigue design assessment: application and notations. June 2017.
- Procedure for semi-submersibles. July 2016.
- SDA procedure for the primary structure of passenger ships. April 2017.

Lloyd's Register continues to develop their goal-based submarine rules, with the current focus of bringing the classification process to submarine design, without publishing specific rules and regulations for the design of submarines.

5.1.4 Materials and extra high strength steels

During the reporting period, an increasing acceptance of the use of extra-high-strength steels was observed. In 2016, Bureau Veritas updated their rules; thus, high-strength grades are mentioned as regular types of steel. IACS UR W31 provides requirements for the use of steel plates with a minimum yield strength 460 MPa (IACS 2015d). This material can be applied to longitudinal structural members in the upper deck region of container carriers (such as hatch side coaming, hatch coaming top and the attached longitudinals). This material can be applied as brittle crack arrest steel required by UR S33 (IACS 2015b). The new DNV GL rules contain requirements for extra-high-strength steels and brittle crack arrest steels. Eight strength levels with a specified minimum yield strength from 420 MPa to 960 MPa are defined. The IACS UR S33 describes the requirements for use of extremely thick steel plates (50-100 mm). A brittle crack arrest design is adopted.

5.1.5 Rules and standards for strength analysis of container ships

In 2015, the IACS Committee on Large Container Ship Safety (CLCSS) issued a report that concludes that the MOL Comfort break-up possibly occurred as the sea loads exceeded the hull girder ultimate strength at the time of the casualty.

In 2015, the IACS General Policy Group approved the new UR S11A "Longitudinal Strength Standard of Containerships" (IACS 2015a). The standard contains a completely revised set of requirements using the principles of IACS CSR. Consequently, the following key elements are considered in the new requirements:

- Net scantling approach, including definitions of corrosion additions.
- New formulations for wave-induced vertical bending moment and shear force based on nonlinear load computations for more than 120 ships.
- Yield check based on stress checks for normal and shear stresses compared with the permissible section modulus and plate thickness.
- Buckling check and hull girder ultimate strength check that follows the CSR approach.
- Hull girder strength assessment considers the effect of whipping (per individual classification society procedure).

The research on the MOL Comfort accident prompted the development of IACS UR S34, which addresses the functional requirements for FE analyses of container ships (IACS 2015c). Global (full ship) and cargo hold analyses are described. The loads are based on the North Atlantic wave environment. The load components and loading conditions to be considered are described. For the global strength, hull girder bending and torsion are analysed.

Whipping and springing are highly relevant for ultra-large container ships. The Lloyd's Register 2014 rules include mandatory requirements for the assessment of whipping and springing on the global hull girder loads (LR 2014). ABS (2017) published new guidance for a springing assessment. DNV GL updated the methods for the assessment of whipping and springing in their new rules; refer to DNV GL (2016c) Section 5.1.2. DNV GL has also developed a method for calculation of slamming and whipping, which accounts for all sea states that a vessel may encounter. This method includes not only extreme sea states at slow sailing speeds but also extreme sea states in moderate seas, when strong slamming impacts can be induced due to high ship speeds. By statistically evaluating AIS data in combination with weather hindcast data, DNV GL confirmed that severe storms are typically avoided by shipmasters via re-routing. These statistical observations, combined with the enhanced use of hull monitoring systems, enable more realistic assumptions about the environmental and operational conditions experienced by a vessel during its service life.

5.1.6 Arctic/Ice

The IMO Polar Code (IMO 2015) entered into force in January 2017. The safety part of the code includes design and requirements related to operation in polar regions, including ice. The requirements for the use of steels in cold temperatures have been extended.

5.1.7 Other updates of class rules

Many IACS members and flag states have developed separate sets of rules to address a sophisticated manner with operations related to wind farms and wind energy. Examples are Bureau Veritas' "Guidance note for certification of offshore access systems" (BV 2016) and "Rule note for classification of offshore handling system" (BV 2014). These new rules are moving towards an offshore approach, in which several types of cases are defined (operational, accidental).

Rules for marine/maritime autonomous vessels have not changed during this period. However, this topic is relevant, and the committee will likely establish new rules for these vessel types during the next period. A review of these rules by the next committee is recommended.

5.2 Development of structural design software systems

5.2.1 Class rule-related software

The trend in hull structure rules is towards more advanced methods for the prediction of loads and structural response. In 2015, the ISSC Technical Committee IV.2 Design Methods (refer to Collette *et al.* 2015) mentioned an increased use of 3D FE analyses, dynamic loading approaches and spectral fatigue analyses. As discussed in the previous sections, this development is incorporated in new class rules. Extensive computational capabilities are required. This recent development has generated updates of existing tools and the development of new tools for structural design based on class rules. The use of simplified methods for load application (such as the methods described in Section 7.1) will be less frequent in the future, whereas methods such as equivalent design waves (EDWs) will become more prevalent.

DNV GL

Both the Poseidon package and Nauticus Hull package have been updated to support the new DNV GL rules for both prescriptive analysis and FE analysis. The updates include better modelling capabilities and automation of calculation tasks, as well as improved result processing and reporting functionalities. The tools for exchanging models with yard design and FE systems have been developed. The toolbox for prescriptive calculations includes rule calculator functionality with an enhanced overview of rule compliance and support for design iterations. The modelling and rule check capability is enhanced with a module for importing 2D drawings. This module contains a rule calculator to enable calculations of plates and stiffeners to be directly provided from the drawing.

The FE analysis module includes improved functionality for the import of FE models from other FE systems (Patran/Nastran, ANSYS) and early design tools (NAPA Steel, AVEVA Marine), as well as the import of hull forms. Hull girder load adjustment is integrated into the module. Screening of the FE model is included to identify critical areas. The module contains improved efficiency for generating local fine mesh FE models of critical details. A new tool for very fine mesh fatigue analysis is integrated into GeniE, and automatic yield, buckling and fatigue check according to the new rules are also included.

Lloyd’s Register and ABS

“Common Structural Rules Software LLC” is a joint venture company formed by Lloyd’s Register and ABS to provide a suite of software tools for CSR. The new software comprises prescriptive analyses and FE analyses and enables the assessment of entire vessel structures according to the IACS CSR-H for bulk carriers and oil tankers. The software consists of two applications: the CSR Prescriptive Analysis (PA) application, which is used to assess hull girder ultimate strength and hull local scantling, and the CSR FE analysis tool, which uses an FE analysis for strength and fatigue assessment.

ClassNK

ClassNK has released similar software: Primeship-HULL (CSR). The data link with NAPA Steel has been updated to include all structural members in the fore and the aft of bulk carriers and oil tankers. This update facilitates the exchange of an entire ship model from NAPA Steel.

Lloyd's Register

The Lloyd's Register (LR) of Shipping RulesCalc software, updated in 2014, is available for rule compliance purposes against the LR Rules and Regulations for the Classification of Ships (LR 2014). Links to 3rd party design software, such as NAPA and Tribon, as well as LR's own ShipRight SDA software, are provided.

Updated in 2017, the LR ShipRight design assessment tool is available to undertake structural and fatigue assessment that provides "end-to-end" assessment of a structure against Lloyd's Register's "direct calculation procedures", including structural design assessment (SDA) and fatigue design assessment (FDA). The software is designed for the assessment of ships and offshore units, specifically FPSOs, FLNGs, container ships, membrane tank LNG ships and ore carriers. Interface capability with Nastran/Patran is also provided.

Bureau Veritas

In 2016, Bureau Veritas (BV) entered into a strategic partnership with Dassault Systèmes to deliver product life cycle management solutions to ships and offshore platforms. BV is using Dassault's 3D-Experience platform for design reviews. This platform interfaces with BV's calculation tools to reduce the approval time for new ship designs, which reduces the modelling time from weeks to days if the 3D CAD model is available. BV also acquired HydrOcean in 2015 to gain CFD capabilities. BV is also using the 3D-Experience platform to automatically generate FE models of ships, which are assessed using its VeriStar Hull software.

5.2.2 Automatic mesh generation

Automatic generation of global models in an early stage design can be turned around quickly using programs such as Maestro or other tools. However, when more detailed local assessments and detailed verification of the accuracy is needed, the time to develop these models substantially increases. Creating a detailed global FE model of a complex marine structure is typically a very time-consuming task. Therefore, the first FE analysis is typically performed rather late in the design process and serves as a validation of the design. To save time, this analysis is typically performed as few times as possible.

The marine industry has already suggested the significant potential to reduce the modelling time if the FE models can be directly created from 3D CAD models. This potential would enable detailed analyses to be performed early in the design process and reduce the risk of major design modifications in subsequent stages. This approach would also be helpful as a part of an (automatic) optimisation process; refer to Figure 2.

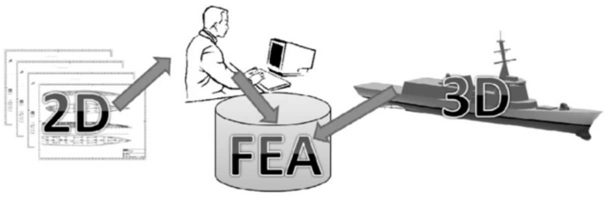

Figure 2: Approaches for the creation of models for FE analysis (Holmberg and Hunter 2011).

The idea of using a single tool for the entire process, starting with the creation of a 3D model at early design stages, has been profusely required in naval shipbuilding. This tool should be capable of generating an adequate and valid calculation mesh (i.e., FE mesh) for submittal to an FE solver based on geometry, scantlings and material properties from the 3D CAD model. The tool should be part of an integrated system that encompasses all stages in the design process (refer to Figure 3).

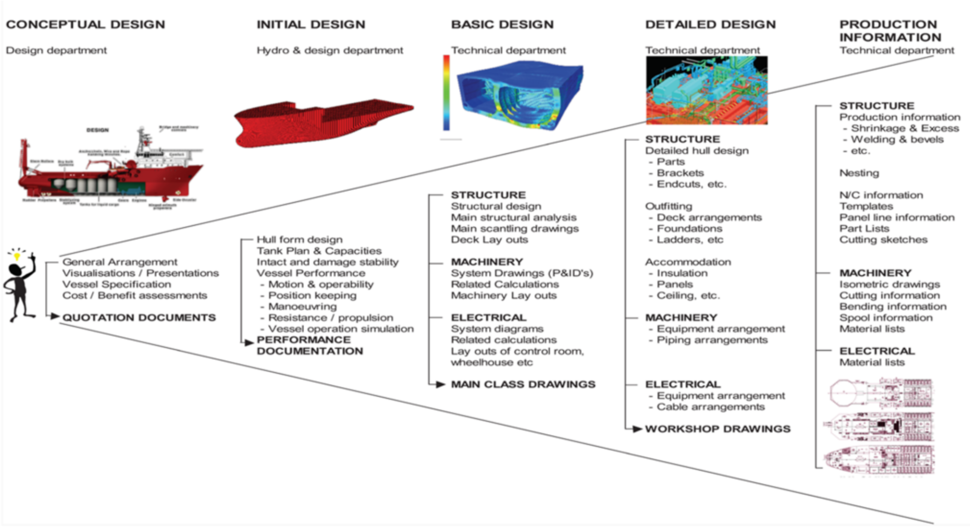

Figure 3: Design stages in the ship design process (Pérez 2015).

Many FE tools include standard formats for direct import of 3D CAD models. Due to the complexity of marine structures, these tools tend to fail. A significant amount of time is frequently used to mitigate the errors produced by the automatic mesh generation process (e.g., eliminating bad nodes, elements, and connections) which are preventing a successful analysis. Another challenge is that a marine structure contains an enormous number of structural details that must be idealised in a proper manner in the model. Therefore, an automatic mesh generator must be guided to ensure that the mesh is based on best-practice modelling techniques. To compensate for this finding, tools especially made for complex marine structures have been constructed.

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The current development of class rule-related software includes improved functionality for import/generation of FE models from early design tools. Note the following recent studies and attempts in this area:

- NAPA Designer/NAPA Steel includes a new CAD-style 3D modelling tool—NAPA Designer. This tool claims to streamline the shipbuilder's working process with automatically created classification drawings and global FE models from NAPA Steel. The software has direct interfaces to several Classification society software and claims to significantly reduce the modelling time.
- The AVEVA Marine software has the capability of enabling direct export to ANSYS FE software in the form of the ANSYS Parametric Design Language (APDL).
- Zeitz *et al.* (2014) presented a structural optimisation of a container vessel mid-ship section realised by coupling the GL structural design tool POSEIDON with the

CAESES/FRIENDSHIP-Framework as an example of rational structural design in the early design stage.

- Pérez (2015) proposed to use a single tool for the entire design process starting with the creation of a 3D CAD model in the early design stages. The main challenges of this approach are related to the integration at all stages and disciplines into a single CAD tool.
- Acin and Kostson (2015) presented some of the relevant modelling tools available in Strand7 and discussed how routine and repetitive tasks can be automated and customised using the Application Programming Interface (API).
- Son *et al.* (2016) developed interfaces between design software to enhance productiveness in modelling, even in the environment of CSR-H.
- Andrić *et al.* (2016) presented the development of the structural design support system OCTOPUS-CSR for concept and preliminary design phases. This system can contribute to reduced production cost and increased profit and durability of a bulk carrier.

In contrast to the integration of different tools, Stilhammer *et al.* (2015) claim to cover the entire structural design process within the environment HyperWorks. However, a substantial amount of detail, especially with respect to the implementation of loads and evaluation criteria, has to be developed and added before this tool can be efficiently applied in daily practice.

An important aspect of these tools is the creation of an FE mesh on a set of complex surfaces. The ISSC Technical Committee IV.2 Design Methods (refer to Collette *et al.* 2015) commented on continued dissatisfaction with the industry standard NURBS for modelling hull surfaces. This discontent is attributed to complications that range from handling complex geometry to mathematical limitations in the NURBS formulations that hinder automatic data processing. To improve the efficiency of integrated design tools, the algorithms for creating an FE mesh on complex surfaces have been investigated.

Lin *et al.* (2015) described enhanced algorithms for data transfer from 2D AutoCAD drawings to 3D FE models. This study comprised feature recognition rules and algorithms for automatic mesh generation. Wang *et al.* (2015a) explored algorithms for intersections between ship hull surfaces and its frames. Different methods and algorithms were combined to provide higher mesh quality and close approximation to an actual ship hull structure. Petrolo and Carrera (2016) presented a novel structural modelling strategy that claimed to be promising in a CAD/FE method coupling scenario.

5.3 Concluding remarks

The development towards the use of direct calculation methods in ship design continues and is reflected in both the rules and the calculation tools from the Classification societies, including an increased use of 3D FE analyses, dynamic loading approaches and spectral fatigue analyses. A thorough review was performed for the new DNV GL Rules and the latest development of LR Rules based on available competence in the committee. The rules demonstrated progress towards more advanced methods for both wave load and response calculations. After the MOL Comfort accident, new methods for the assessment of whipping and springing have been published by several Classification societies, e.g., ABS, DNV GL and LR. The development of rules for marine/maritime autonomous vessels has not occurred during the reporting period. New rules for these vessel types will likely emerge during the next period. A review of these rules is recommended for the next committee.

Despite efforts to develop structural design software systems, a tool that is widespread in use and significantly reduces the time required to establish the required FE models (from weeks to days) is needed. The efforts mentioned in this study are based on the assumption that a 3D CAD model is available at the time the FE model is needed. This assumption may not be consistent with the work process required by the yard/designer, especially if FE analyses are to be used as a design tool rather than a design verification tool. As noted by Pérez (2015), the challenge is to integrate all stages and disciplines into a single tool. Although this challenge exists, smaller improvements (such as the use of APIs in Strand7 or NAPA Steel macros) are more efficient and can significantly reduce modelling time (from months to weeks).

6. OFFSHORE AND OTHER SPECIFIC MARINE STRUCTURES

The environmental loads on offshore structures are more specific than the environmental loads for a ship travelling worldwide and depend on the structural type and operation site. Thus, the extent of the dependency on the classification rules in terms of the design load calculations for offshore structures is substantially smaller than that for the design load calculations for a conventional ship. Instead, direct analysis methods based on sophisticated theories and procedures have been developed to reflect the unique characteristics of each structure. This approach differs from the approach for ships, and the review of the trend is helpful to achieve an in-depth understanding of the design load procedures provided by the class rules.

Within the reporting period, research efforts on the prediction of extreme design loads have been continuously driven towards improvements in the analysis accuracy via nonlinear time-domain analysis, sophisticated soil-structure interaction, and coupled hydrodynamics analysis. Fatigue strength in offshore structures is more critical to scantling design than ships, and considerable research has addressed the nonlinearity of environmental loads to overcome the limitation of spectral analysis. Probabilistic and reliability methods are adopted to reasonably treat various uncertain factors, especially factors embedded in soil properties, fire and explosion simulation, and crack propagation. Special purposed marine structures, such as RoRo vessels, car carriers and livestock carriers, warrant investigation of the strength assessment procedure, which has been established considering its particular structural characteristic. The structural aspects of livestock carriers are briefly introduced.

6.1 Fixed offshore structures

6.1.1 Uncertainty, reliability for soil property and wave loads

The reliability of fixed offshore structures and systems depends on many factors, such as the reliability of soil. The types of mechanical damage caused by seabed and soil, which is commonly observed on some members of offshore platforms, include denting, out-of-straightness, corrosion and fatigue cracks. The structural behaviour of an offshore structure or system shall be evaluated by modelling the structure, seabed and relevant artificial supports and performing static and dynamic analyses.

The definitions of the characteristic soil properties in numerical codes require analysis by a geotechnical engineer in defining the design soil profile, i.e., they are qualitative and descriptive. Nadim (2015) presented an overview of the uncertainty and variability of mechanical soil properties in offshore site investigation, and proposed some ideas for utilising the reliability tools in an optimal manner. First, the paper addressed how to extract the maximum amount of information from geotechnical site investigation; second, the paper discussed how to establish characteristic or representative soil properties for design while considering the uncertainties caused by the natural variability of soil properties.

In a marine environment, a series of soil layers deposited beneath the foundations has particular importance in the response of seabed and seabed-structure systems considering the constant effect of incoming cyclic waves. The response variations are presented in terms of pore water pressure and shear stress distributions within the layers. Ülker (2014) modelled a dynamic response of saturated and layered soils under harmonic waves using the FE method and verified the results by corresponding analytical solutions. In addition, a 3D integrated numerical model—FSSI-CAS 3D—for fluid-structure-seabed-interaction was developed by Ye *et al.* (2013). The data exchange is implemented at the interface between the fluid domain and the seabed/marine structures domain adopting the coupling algorithm. The developed 3D numerical model is validated by an analytical solution and a laboratory wave flume test.

6.1.2 Load, extreme response due to nonlinearity of Morison's force

Since the 1950s, numerous studies have focused on the approximation and simplification of dynamic analysis to obtain extreme quasi-static responses of fixed offshore structures. One of these studies explores how to efficiently treat nonlinear terms of Morison's equation in strength and fatigue strength assessments. Reza *et al.* (2017) investigated response spectra of fixed offshore structures impacted by extreme waves based on the higher-order components of the nonlinear drag force. A steel jacket platform is simplified as a mass attached to a light cantilever cylinder; their corresponding deformation response spectra are estimated by utilising a generalised single degree of freedom system. The effect of the higher-order components of the drag force is compared to the linearised state for different sea surface levels. When the fundamental period of the offshore structure is approximately one-third of the main period of wave loading, the linearised drag term is not capable of achieving a reliable deformation response spectrum. Abu Husain *et al.* (2016) provide a method for predicting the extreme response for fixed offshore structures by the Monte Carlo time simulation technique. The method predicted the probability distribution of the extreme values of response during operation with the consideration of safety and efficiency. Considering the nonlinearity of the drag component of Morison's wave loading, the probabilistic analysis of the response is investigated with the effect of the sampling variability.

One of the methods employed in the derivation of the drag and inertia coefficients in Morison's equation is the conventional method of moments. However, the coefficients obtained from this method show considerable scatter due to the large sampling variability. Mohd Zaki *et al.* (2016) compared the sampling variability of the drag and inertia coefficients from the conventional method of moments with the sampling variability derived from two alternative forms of the method, i.e., method of linear moments and method of low-order moments. Simulated data have been applied to compare the efficiency of the three methods of moments.

6.1.3 Fatigue

In the fatigue assessment of jacket platforms, the small-scale leg diameter, which is often the drag-dominated and wave-induced force in these structures, can be addressed using either a linear form or a nonlinear form of the spectral Morison equation. However, incorporating a nonlinear form of the Morison equation to acquire the spectral density of the wave force, which is an important step in fatigue estimation, is complicated. Ding and Pang (2016) presented fatigue assessments that contain a nonlinear effect for a fixed offshore structure. The linear and nonlinear form of wave-induced force spectral densities are calculated in the frequency domain, and the fatigue life of the jacket platform is assessed in the time domain.

The results obtained from a computationally excessive full-scale time-domain analysis of an offshore jacket structure quantifies the errors from the assumptions and simplifications made in a spectral fatigue analysis. These findings also indicate that the simplifications involved cause not only well-known inaccuracy but also a lower fatigue resistance. Mohammadi *et al.* (2016) indicated the main causes of the inaccuracies of the spectral fatigue analysis and quantified these causes. In addition, the paper verified the efficiency of an approximation method developed in a previous study that drastically reduces the computational burden. Häfele *et al.* (2017) conducted interesting research on reducing the number of load cases for fatigue analysis on jacket structures. They performed a fatigue study with 2,048 design load cases and incrementally reduced the number of design load cases. The level of uncertainty in fatigue damage evaluation and the efficient selection of design load cases were addressed to reduce the computational effort for sophisticated jacket design procedures.

6.2 Floating offshore structures

6.2.1 Uncertainty and reliability analyses

Chatzi *et al.* (2016) provided an overview of 12 papers that address the subjects "uncertainty and reliability" in various fields. They discussed modelling, discretisation, and boundary conditions, as well as tools and methods. An increase in functional requirements for explosion protection and international design standards for offshore topside structures is observed. These standards require assessment of the structural robustness. Probabilistic models are necessary for deriving explosion properties, installation properties and environmental uncertainties. Czujko and Paik (2015) suggested reliability-based methods for accidental limit states to assess the robustness. The blast wall reliability requires two models: the first model is a probabilistic model for the explosion loads, and the second model is a deterministic nonlinear model of the blast walls. If both models are combined in a Monte Carlo simulation, then the exceedance curves can be derived from the results. The results of this new method show that the safety margins of blast wall structures are very small and indicate the need for new procedures for the assessment of safety against explosions.

6.2.2 Loads: nonlinear hydrodynamic loads and coupled loads

The significant variation of responses for floating offshore structures are wave, wind and current loading, especially of coupled loads and hydrodynamic loads. Recent studies have discussed the response of a mooring system and the effect on FPSO structures. Loukogeorgaki *et al.* (2015) presented a 3D experimental investigation of performance for a pontoon-type floating structure compared with the numerical simulation results. This study focused on the reaction of the structure under perpendicular and oblique regular waves, checked the tensions of a mooring system under pretension conditions, and attempted to determine the new equilibrium position for a mooring system under the effect from wave and current loading with three different incident wave angles. Sen (2015) analysed the motion response of a moored floating structure with large amplitudes and steep incident wave fields in a 3D numerical wave tank by a coupled time-domain solution scheme. The findings concluded that the motions of floating structures need to consider the nonlinearities not only in the hydrodynamics and hydrostatics but also in the modelling of the line stiffness. Roy *et al.* (2017) introduced nonlinear simulations to investigate the interaction between mooring lines and spar structures of an offshore spar platform. In this coupled time-domain analysis, the dynamic combination of drag, inertia, and bending coefficients of mooring systems were considered.

The large deformation under waves should be considered for computing the body motion of Very Large Floating Structures (VLFS); hydroelasticity theory has been developed to study the response of VLFS. To increase the computational efficiency, a multi-segment beam model is proposed by Sun *et al.* (2015a) to study a VLFS, which is a multi-module connected by hinge connectors. The results concluded that rigid body motion is dominant under long waves but elastic deformation dominates under short waves. The hydroelastic response is sensitive to the wave heading but the largest elastic deformation always occurred when the projection of the length of the VLFS on the wave heading direction is close to the wave length. Similarly, Zhang *et al.* (2015) utilised the multi-module models for calculating the dynamic characteristics of a floating airport.

The springing effect becomes another main issue not only for large-scale commercial ships but also for offshore structures. Kim and Kim (2015) provided a simple method for predicting the extreme loads for the tension force on a tension-leg platform considering the springing effect. The research presented a statistical observation of springing, including the second-order wave loads from sum-frequency wave forces.

6.2.3 Fatigue and fracture: coupled loads, safety margin

Repeated loads caused by waves, winds, and currents cause fatigue damage to offshore structures. Offshore structures include many members with complex geometries, such as stiffened plates and tubular joints under various loads. Therefore, substantial efforts have been made to propose a fatigue analysis procedure that is suitable for a structural member. Gam *et al.* (2017) proposed a fatigue analysis procedure for a vertical caisson on an FPSO unit subjected to a nonlinear wave loading. In the case of a sea water caisson, local stress due to the nonlinear Morison force and global stress due to hull girder loads simultaneously act. When performing fatigue analysis, the nonlinearity of the drag term in the Morison equation should be considered. The proposed method linearises the Morison force by introducing the linearisation coefficients and considers both loads in the frequency domain. Park *et al.* (2017) developed a procedure of stress analysis of the structural details near the rolling chock using the time-domain modal analysis technique, in which both the contact behaviour and friction behaviour can be accurately simulated. To perform the time-domain analysis focused on the contact and friction, the interaction between the hull and the tank was modelled via Coulomb friction.

The fatigue damage in the spectral method can be calculated from the standard deviation and the up-crossing rate of the stress amplitude spectrum. Cho *et al.* (2016b) introduced two practical approaches that can be applied when statistical data of the local loading are not available. In the first approach, the maximum stress range is assumed to always occur during the total cycles. Then, the local fatigue damage is very conservatively estimated, and the total fatigue damage is obtained by summation of the global and local fatigue damages. In the second approach, the local fatigue damage is estimated based on the assumption of the Weibull fitted local loading. The use of the cube root summation is proposed between the global fatigue damage and the local fatigue damage. Han *et al.* (2016) proposed two formulae to combine fatigue damage for offshore structures subjected to low-frequency and high-frequency Gaussian components. Extensive numerical simulations on bimodal spectra are performed to verify the accuracy of the two formulae; the results calculated by the two new formulae are satisfactory.

Fatigue assessment in the time domain is regarded as the most accurate method but is less adopted in practice as it is time-consuming. To improve the efficiency of the time-domain method, an innovative block partition and equivalence method of the wave scatter diagram is developed by Song *et al.* (2016b). After the wave scatter diagram is partitioned into several blocks, the equivalent wave height, wave period and occurrence probability of the representative sea states are determined based on a modified energy equivalent principle. The equivalent wave period of the representative sea state is calculated via the spectral moment formula. Combined with the determined wave period, the equivalent significant wave height can be determined by reversing the wave spectrum integral formula, in which the equivalent wave energy of a divided block of the wave scatter diagram is modified by introducing a factor to compensate for the effects of low- and high-amplitude cycles of fatigue damage.

A hybrid frequency-time domain method, which can be considered to be a hybrid of the spectral method and the time-domain analysis method, is proposed by Du *et al.* (2015). In the newly developed method, the spectral density function of structural stress is obtained in the frequency domain and then converted into a stress time history using an improved signal conversion approach. With this methodology, the fatigue damage of structures can be easily assessed with the rainflow counting method and the Palmgren-Miner rule. The newly developed damage assessment method can also avoid the complicated coupled dynamic analysis in the time-domain method, which significantly reduces the computation time.

For an FPSO unit converted from large oil tankers, predicting and extending their service life is critical. Yu *et al.* (2017) investigated the fatigue damage calculation procedure for an FPSO unit. The remaining fatigue life of the FPSO unit was evaluated by the method of spectral analysis to determine the fatigue damage of the oil tanker during the operation period and the FPSO working period. Zhang *et al.* (2017a) highlighted the difficulties in evaluating the remaining fatigue life of offshore structures. The fatigue health monitoring system, which records the stress data of hot spots, was discussed in the paper. The location of monitoring was initially determined according to guidelines for the fatigue strength of a ship structure.

6.3 Other specific marine structures

6.3.1 RoRo vessels and car carriers

The vertical bending moments induced by abnormal waves on a bulk carrier and RoRo vessels are explored by Vásquez *et al.* (2016). The study focused on the influence of the hull geometry on the vertical bending moment in extreme sea conditions. The experimental data were used as benchmarks to validate the predictions by a partially nonlinear time-domain seakeeping numerical model. Clauss and Klein (2016) performed an experimental study to determine the vertical bending moment due to freak waves on three different types of ships, including a RoRo vessel. They revealed that critical loads and motions depend on combinations of wave height, wave group sequences, crest steepness, encountering speed and a ship's target position. The influence of the bow geometry was investigated in terms of block coefficient, bow flare angle and freeboard height. Stipčević *et al.* (2015) presented a feasibility study using lightweight, cost-effective sandwich panels in the upper decks of a car carrier. Sandwich panels are intended to carry vehicle loads and are supported with hull girder grillage. The study was performed in collaboration with a shipyard, and BV rules were considered.

6.3.2 Livestock carriers

Livestock carriers are ships that exclusively specialise in the transportation of large numbers of live animals (e.g., sheep, cattle). Two types of livestock carriers exist from a general/structural point of view:

- *Closed livestock carriers*, in which the majority all of animal pens are located within the closed holds and internal decks of a ship. From a structural point of view, closed type livestock carriers are similar to pure car carriers, car-truck carriers or similar closed box ship types, and their structural response is well documented and known.
- *Open livestock carriers*, in which the majority of animal pens are installed on superstructure open decks. This arrangement provides continuous natural ventilation of the pen areas while minimising the reliance on the supplementary mechanical ventilation system. These open-type livestock carriers can generate very complex structural responses, which are relatively poorly documented in the literature due to the small number of vessels.

The open livestock carrier can be classified as a ship with a strong hull-superstructure interaction due to an extensive superstructure that is characterised with large side shell openings and the absence of transverse/longitudinal bulkheads in the superstructure part (refer to Figure 4). The height of the superstructure is approximately equal to the height of the lower part of the hull, and its influence on the longitudinal strength of the ship is very important. The most suitable and accepted method for the final checking of the structural adequacy of ships with large superstructures is the 3D FE coarse mesh model of a complete ship (ISSC 1997). A direct strength calculation guideline for livestock carrier ships does not exist; thus, an existing guideline for a similar type of ships, such as RoRo or passenger ships, can be utilised (e.g., LR 2012, LR 2017b). The most important aspects and main challenges in the rational structural design of a large open-type livestock carrier for all structural design processes (concept, preliminary and detail) have been reported by Andrić *et al.* (2011, 2017a).

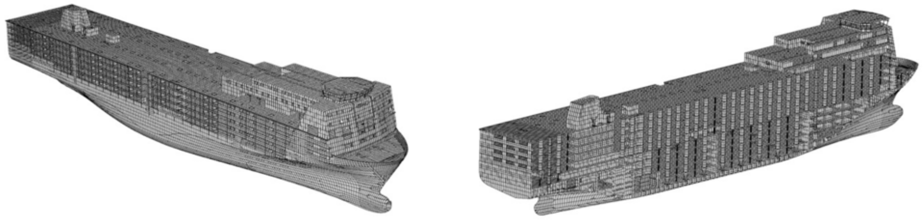

Figure 4: Full ship FE model of a livestock carrier (Andrić *et al.* 2017a).

A livestock carrier with a maximum length of 200 m that is constructed of mild steel is usually sufficient to satisfy the longitudinal strength requirements, and higher tensile steel is used to solve areas with stress concentration problems. Livestock carriers are loaded with relatively low deck loadings compared with multi-deck cargo ships (RoRo, car carriers) and are similar to cruise/passenger ships. Deck plating typically ranges between 5 to 8 mm and is covered with a special 2 to 3 mm lining for maintenance reasons, which reduce the need for corrosion addition. Some characteristics of livestock carriers are relatively fine hull lines and continuous distribution of lightweight loads, which implies that the ship is always in a hogging condition in still water, such as cruise ships. The combination of rule hogging waves and maximum still water bending moments produces maximal longitudinal and shear stresses, whereas the combination of rule sagging waves and minimum hogging still water bending moments can cause potential buckling problems in superstructure decks. The effective superstructure design is very important due to a regulation of weights and the vertical position of gravity due to stability requirements. Superstructure deck effectiveness according to the well-known Caldwell formulae (Caldwell 1957) can be expected to fall between 60 and 75% (Andrić *et al.* 2017). Large ventilation steel tubes and engine casings as large box-type structures have a significant influence on the primary stress distribution, and the higher bending stiffness of these structural parts cause an increase in the superstructure effectiveness. The transverse strength has been primarily carried by transverse bulkheads connected to large web frames. This type of ship has several watertight transverse bulkheads from double bottom to freeboard deck to satisfy the stability requirements in the damage condition. Several highly stressed areas can be identified on all examined transverse bulkheads, primarily in connection with ventilation tubes, partial casing bulkheads and strong web frames. Large ventilation tubes are other important load-carrying structural parts that can absorb part of a racking moment.

6.4 Concluding remarks

Research on offshore structures has been continuously driven towards the consideration of the load nonlinearity in the prediction of extreme loads and the fatigue analysis. The former has been addressed by the time-domain analysis for critical sea states in a wave scatter diagram; thus, the effort has been concentrated on the development of sophisticated hydrodynamic codes. Research on the latter has focused on obtaining an efficient and simplified method as performing an FE analysis for all sea states in a wave scatter diagram is not feasible. However, the fatigue analysis in time-domain analysis is gaining popularity due to the requirement of the estimation of the remaining fatigue life in life extension projects and structural health monitoring systems.

7. BENCHMARK STUDIES

The committee has performed two benchmark studies during the reporting period. The first study is an investigation of the discretisation of wave loads and its impact on the longitudinal structural behaviour in direct calculations using global ship models. The topic was selected due to the increased use of direct calculation procedures during the early stages in ship design, in particular concept and initial design, when the rules software cannot be employed due to the large amount of input data and detailed information that are required. In the design stage, time is one of the main drivers; therefore, linear static analysis is common practice and considerable simplification in modelling is needed to maintain time efforts within the required targets. The objective of the study is to highlight the importance of identifying the lower limit in the simplification of physical phenomena to minimise mistakes in direct calculation analyses, design and procedures for verification of ship structures.

The second study is an analysis of FSI models performed on a stiffened plate with two different software. The objective is to evaluate the maximum impact pressure and maximum permanent deflection and calculate an equivalent uniform pressure for different rising velocities. The results are compared with the results of quasi-static models proposed by the Classification society.

7.1 Ship structural response from different wave load schematisation

This study investigates the longitudinal structural response of two ship structures using various wave load discretisation methods for wave load modelling. The study only focused on the structural behaviour due to vertical bending moment, and therefore, horizontal bending and torsion moments were neglected. The analysis was performed using linear static FE analysis on global ship models. Rules from the Classification society Lloyd's Register were selected as the reference for the calculation and evaluation of wave loads; however, the use of similar rules of another Classification society can achieve similar results. The following rules are employed in the study:

- Lloyd's Register Structural Design Assessment for Primary Structure of Passenger Ships (LR 2004), which is hereafter referred to as LR-SDA.
- Lloyd's Register Rules (LR 2014), which is hereafter referred to as LR-Rules.

Four wave load schemes referred to as load cases were compared for two ships with different mid-ship section structural geometries. Global displacements and stress responses were analysed and compared in two typical transverse sections to identify the differences between the load cases and the structures' responses. The study aims to provide guidance for designers, engineers, and analysts and highlight that different methods for representing the same wave load in an FE model can, in some cases, cause incorrect structural responses.

7.1.1 Description of the ship structures, models, loads and loading conditions

Two simplified ship structures were selected for the analysis, and FE global models were developed. The transverse sections of the ships are described in Figure 5, in which the main dimensions and scantlings are shown. The first model, which is shown in Figure 6a, has a typical transverse cross-section of a cargo ship box girder with a single bottom, single skin side shell, one strength deck and a transverse primary structure. The second model, which is shown in Figure 6b, has a typical structure for a passenger ship, a more complex topology than the topology of the cargo ship, a double bottom, a single skin side shell with openings, and a multiple deck superstructure with external bulkhead fitted with openings and one internal longitudinal bulkhead. The primary structure supporting the decks and double bottom consists of transverses/floors and girders, and pillar lines are fitted every two web frames according to the girders.

The ship data, loads and analysis results are presented with respect to the right-hand coordinate system defined in Figure 7:

- The origin is located at the intersection between the longitudinal plane of symmetry of the ship, the aft end of the ship's length (L) and the baseline.
- The x-axis is the longitudinal axis, positive forwards.
- The y-axis is the transverse axis, positive towards port.
- The z-axis is the vertical axis, positive upwards.

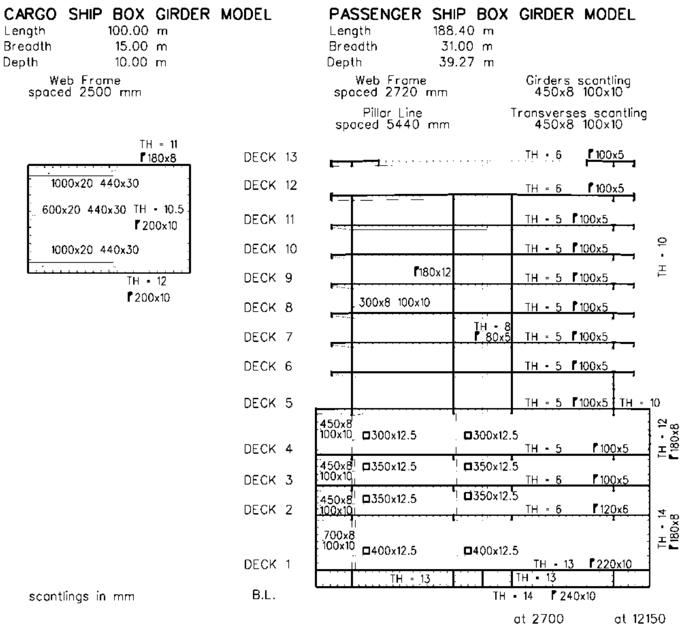

Figure 5: Cargo ship and passenger ship box girder: main dimensions and scantlings.

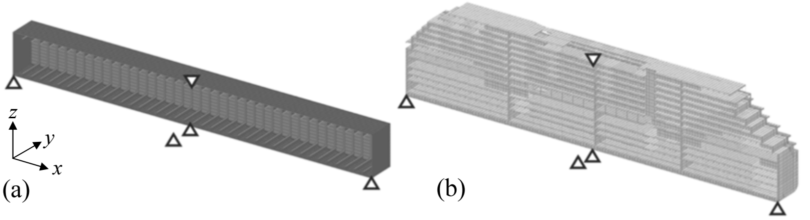

Figure 6: (a) Cargo ship box girder and (b) passenger ship box girder FE models with boundary conditions (only half-breadth model presented).

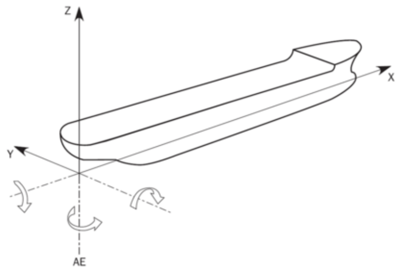

Figure 7: Reference coordinate system.

Two full-breadth box girder FE models of the two ships were developed with a coarse mesh size to represent the correct behaviour versus the longitudinal loads. Due to the different dimensions of the ships, the element size for the cargo ship model was approximately 150 mm, whereas the element size in the passenger ship model was approximately 1,400 mm. All primary structural elements were modelled with four-node 2D shell elements, whereas secondary elements such as stiffeners were represented by two-node 1D beam elements. The FE analyses were performed with the FE software MSC Patran as pre- and post-processor and MSC

Nastran as the solver. All presented stress results have been calculated in the elements' centroid and the mid-plane of the element thickness.

To prevent rigid body motions, as suggested in the LR-SDA, Pt. A, Ch. 1, Sec. 5.1, a set of six constraints was applied to both FE models (refer to the markers in Figure 6):

- $\delta_x = 0$: has been imposed to a point on the bottom, in the intersection between the transverse mid-ship section and the bottom.
- $\delta_y = 0$: has been imposed to a point on the bottom and the deck, in the intersection between the transverse mid-ship section and the longitudinal centre plane.
- $\delta_z = 0$: has been imposed to a point on the bottom, at the intersection between the stern and the bow transverse section with the longitudinal centre plane.

To assess the longitudinal strength of the ship FE models, the hogging design wave formulation for passenger ships, extracted from LR-Rules, Pt. 4, Ch. 2, Sec. 2, was selected for both of the ships. The longitudinal distribution of the vertical shear force and the vertical bending moment were calculated for the two ships. This distribution of loads represents an envelope of wave loading conditions. Thus, for the purpose of approximating these loads to a single loading condition, the formulation presented in LR-SDA, Pt. A, Ch. 1, Sec. 4.6 was applied; refer to Figure 8.

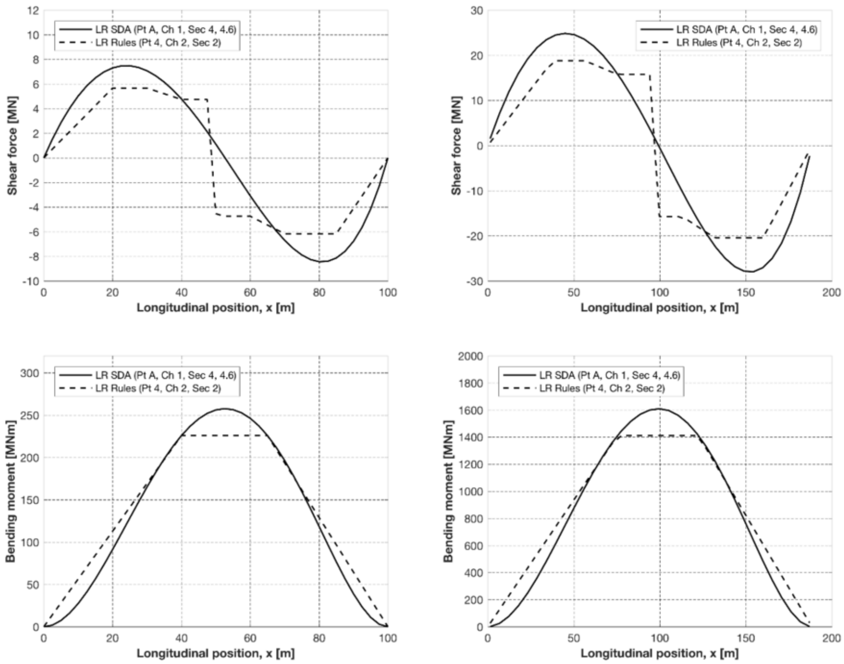

Figure 8: Shear force and bending moment longitudinal distributions for the cargo ship (left) and the passenger ship (right) box girders.

These approximate loads, which comprise a set of balanced loads, were applied to the FE models as nodal forces. To study the difference in the longitudinal strength response due to the load discretisation, four schemes referred to as load cases to apply these loading conditions were proposed, each with a different representation of nodal forces on the transverse sections. Figure 9 illustrates the four load cases for the cargo ship FE model:

- Load case (a): forces applied on the nodes at the centreline of all bottom transverses.
- Load case (b): forces applied on the side nodes of all bottom transverses.

- Load case (c): forces applied on all nodes of all bottom transverses.
- Load case (d): forces applied on all bottom nodes.

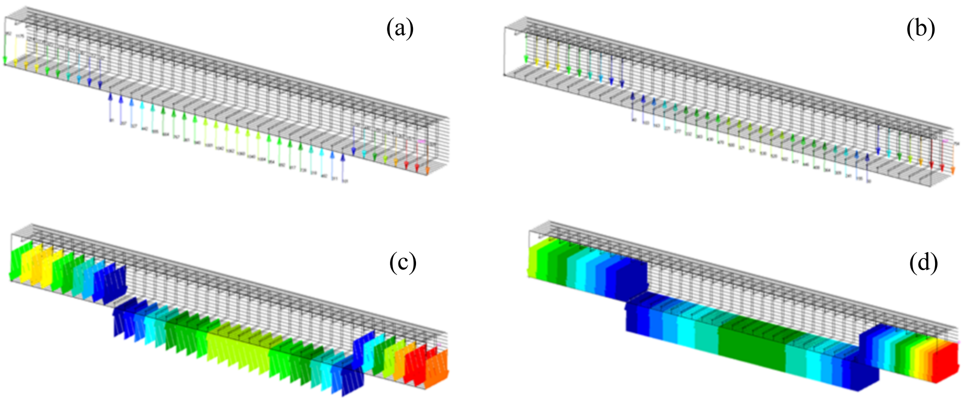

Figure 9: Example of distribution of nodal forces applied to the ship models, illustrated here for the cargo ship box girder FE model; (a) to (d) refer to the load cases.

7.1.2 Results

The first comparison of results was made on the deflection of the hull girder in two points, as shown in Figure 10. The two points were selected with the aim of monitoring the bending of the bottom structures due to the different applied local loads:

- Point 1: located at the intersection between the bottom, the transverse section at half-length and the longitudinal centre plane.
- Point 2: located at the intersection between the bottom, the transverse section at half-length and the side shell plane.

The stress responses of the models were compared in two reference sections, as shown in Figure 10, for the most significant stress tensor components:

- Section 1: located at 0.5×L, where σ_{xx} is presented at the bottom and the side shell.
- Section 2: located near 0.75×L, where τ_{xz} and σ_{zz} are presented at the side shell and the internal longitudinal bulkhead.

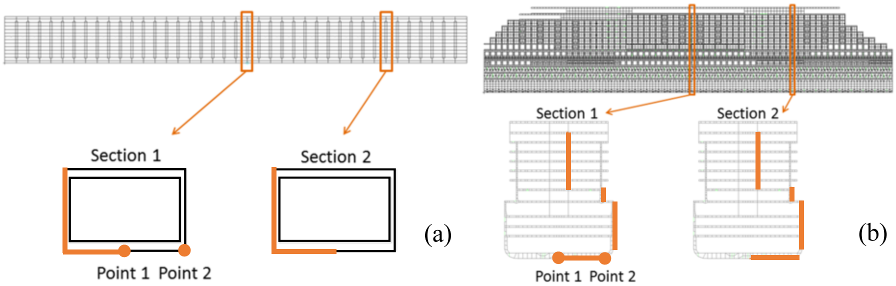

Figure 10: Location of the reference points and the sections for the (a) cargo ship and (b) the passenger ship.

The vertical displacements for the four load cases (a) to (d) are presented in Table 1. The results for the cargo ship in Point 2 show that the variation in the global vertical displacement due to the different load cases is approximately 1%, which can be considered negligible on the global bending response. The load cases in Point 1 are slightly larger than the load cases in Point 2 but remain very low. The corresponding stress responses are presented in Figure 11. The responses confirm that no substantial differences in responses are observed between Point 1 and Point 2, with the exception of σ_{xx} at the bottom, where the secondary bending due to local loads has a larger influence. The global behaviour and responses of this simple but typical cargo ship box girder model is not very sensitive to the discretisation of the applied wave loads.

Table 1: Displacements in the *z*-direction.

	Cargo ship box girder, *z* [mm]		Passenger ship box girder, *z* [mm]	
Load case	Point 1	Point 2	Point 1	Point 2
(a)	132.1	108.2	110.6	103.3
(b)	105.4	107.7	98.8	102.8
(c)	119.9	106.9	104.4	102.3
(d)	119.1	106.3	104.8	102.1

For the passenger ship, the vertical displacements in Point 2, which are representative of global bending, reveal a small spread of approximately 1%. The difference in the values in Point 1 highlights the local bending on transverse structures, as shown in Table 1. The results for the longitudinal stress in Section 1 are presented in Figure 12. The results show a nonlinear distribution for the side shell and the internal bulkhead, which is typical for this type of transverse section. This distribution is caused by the presence of two longitudinal load-carrying structures connected by a deck. In this case, the stress values indicate a considerable difference in magnitude among the four load cases—approximately 5 to 10%. This difference is evident in the different slopes in the linear stress distribution on the side shell and the superstructure bulkhead.

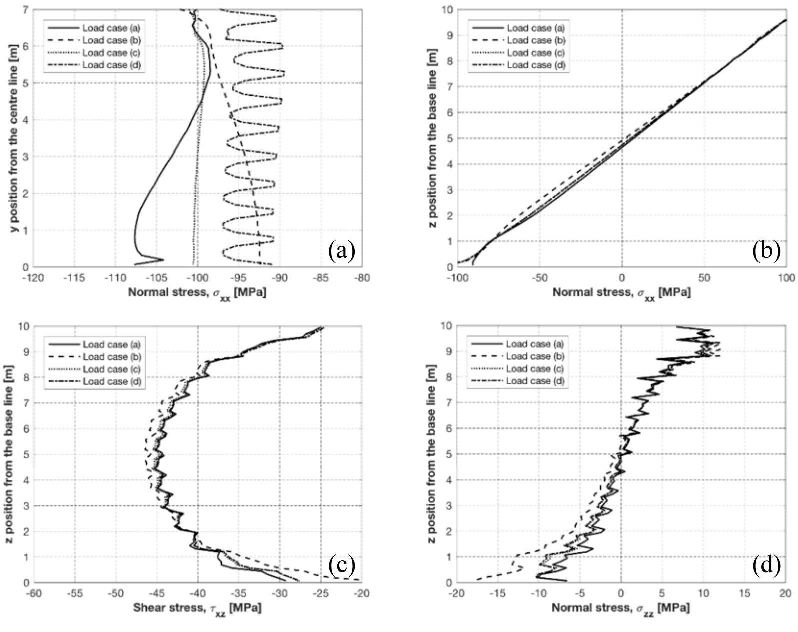

Figure 11: Cargo ship box girder model: stress components for Section 1 (a: bottom; b: shell) and Section 2 (c, d: shell).

If the passenger ship hull girder is considered as two connected beams—a beam that represents the hull and a beam that represents the superstructure—the two beams share the total load with a different percentage for each of the four load cases. This effect is visible in the shear stress in Section 2 in Figure 12. The stress values exhibit a spread of approximately 15% among the different load cases. Table 2 presents the calculated ratio of the section shear force performed by the hull and the superstructure girder. For this type of ship, the stress response and the load carrying ratio between two different longitudinal structural members depend on the method used in the wave load modelling by load (nodal force) discretisation.

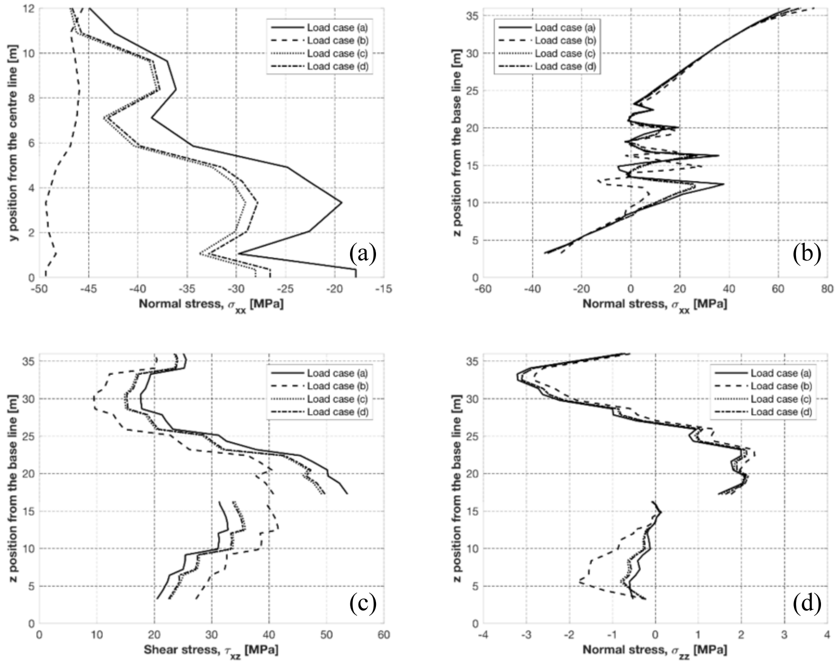

Figure 12: Passenger ship box girder model: stress components for Section 1 (a: bottom; b: shell and bulkhead) and Section 2 (c, d: shell and bulkhead).

Table 2: Shear load ratio between the hull and the superstructure girders.

Load case	Superstructure girder	Hull girder
(a)	0.45	0.55
(b)	0.32	0.68
(c)	0.40	0.60
(d)	0.41	0.59

7.1.3 Concluding remarks

In recent years, the use of the direct calculation method in the early stage of design of ships has become common practice. Due to short timelines, this phase of the structural design requires the use of quasi-static analysis and extensive simplification in modelling. The current benchmark study indicates the relevance of a proper representation of the loads in the direct analysis approach, especially in the study of the longitudinal behaviours of ship structures. Simplification in the schematisation of loads on a 3D model can cause an incorrect analysis of ship structure global response and incorrect structural design, scantling or verification of structural elements.

The study reveals that general conclusions about the lower limit in the simplification of loads cannot be obtained, as it depends on the ship structure topology; thus, a dedicated study of ship types is needed to achieve this goal. The results of the study indicate that the force must be transversely distributed on the bottom shell nodes in the schematisation of wave loads. Regardless of the ship type, the lower limit in the simplification of loads is represented by load case (c). The force representation similar to load cases (a) and (b) will produce an incorrect structural response from the analysis for some ship types. To design novel or unusual ship structures and establish new direct calculation procedures and rules, designers and engineers must pay attention to the load discretisation method. In direct calculations, the closer the representation is to the physics of the phenomenon, the more realistic the behaviour of the ship FE model and more suitable the analysis.

7.2 FSI analysis of a stiffened plate subjected to slamming loads

Most slamming-related studies address the wedge impact and its water pile-up. In offshore structures, wave-induced slamming loads occur on flat structures, such as the upper deck box of semi-submersible drilling rigs or the topside platform of spar structures. Because the deadrise angle is zero, the effect of air trapped between the water and the flat structure should be considered. The effect from the FSI becomes more pronounced, and determining the slamming pressure acting on the structure becomes more complicated. The objective of this study is to compare two FSI analyses of a stiffened plate, in which two different commercial software packages have been employed: LS-Dyna and Star-CCM+/Abaqus multi-physics co-simulation (hereafter referred to as Star-CCM+/Abaqus). Both software packages are recognised software used for FSI simulation purposes in various fields.

The results of the two analyses are compared with respect to the maximum impact pressure and maximum permanent deflection. Equivalent uniform pressures that produce the same permanent deflections are presented. The results are also compared with the analytical models proposed by a Classification society for the calculation of the slamming pressure; this calculation is a function of the rising velocity. Generally, this velocity can be calculated from an air-gap analysis, which is part of the hydrodynamic analysis. The slamming pressure can be employed for strength assessment of the structure subjected to the slamming load.

7.2.1 Model description

The simulation model and its dimensions and boundary conditions are shown in Figure 13. Figure 13a shows the x-symmetric and the y-symmetric boundary conditions on the stiffened plate applied along the central vertical line and the central horizontal line, respectively. The upper and right sides are restrained in the z-direction. Thus, the model represents 1/4 of a stiffened plate surrounded by vertical deep girders or bulkheads.

The slamming load was represented by a moving block of water, as shown in Figure 13b. The dimensions of the slamming load in the x-y plane (length and width) were slightly smaller than the dimensions in the same plane of the stiffened plate because, if the water block would have had the same or larger dimensions as the stiffened plate, the water would pass through the stiffener and the plate would experience the impact force from the water and an additional drag force. The difference in sizes between the water block and the stiffened panel structure was adjusted to a sufficiently small size to have a negligible influence on the structural response of the stiffened plate. Other model details were defined as follows:

- Plate thickness: 15 mm.
- Stiffener size (web height×thickness + flange width×thickness): 300×10+120×10 mm.
- Stiffener spacing: 800 mm.
- Young’s modulus: 210 GPa.

- Poisson's ratio: 0.3.
- Density of steel: 7,830 kg/m^3.
- Yield stress: 235 MPa.
- Material model: elastic-perfectly plastic (the strain-rate hardening effect is neglected).
- Vertical velocity of water at impact: 4, 5, 6, and 7 m/s.

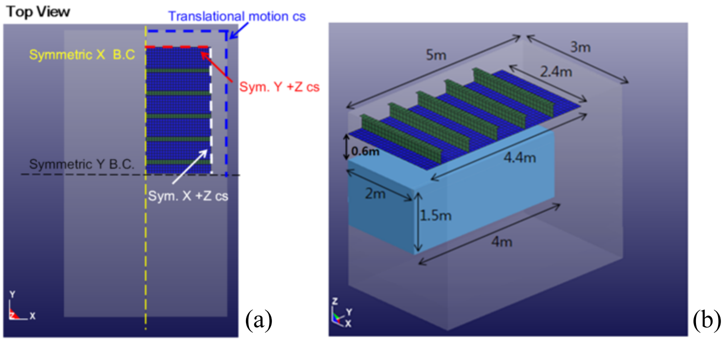

Figure 13: (a) Top view of the 1/4 model with boundary conditions (BC: boundary condition, sym: symmetric, and cs: constrained), and (b) 1/4 of the full simulation model.

7.2.2 *Description of the simulation software packages and analyses*

Two of the members in the committee had access to the FSI software packages LS-Dyna and Star-CCM+/Abaqus. This section gives a brief description of the specific modelling details required for each of the FSI analyses; see Table 3 for a brief summary.

Table 3: Brief summary of the two FSI software packages and models.

	LS-Dyna	Star-CCM+/Abaqus
Fluid model	Incompressible and inviscid	Compressible and viscous
Interaction effect	Penalty coupling method and multi-material method	Multi-physics co-simulation
Solver	Explicit	Implicit: both fluid and structure solvers
Model definition	One integrated model	Two separate models
Time step	1.0×10^{-5} s	1.0×10^{-3} s, 2nd order for fluid
Structural mesh size	100×100 mm	100×100 mm
Fluid mesh size close to structure	100×100×100 mm	100×100×5 mm
Gravity effect	Included	Included

LS-Dyna (Seoul National University)

LS-Dyna is a general-purpose FE software package that is often used to simulate FSI problems based on the assumption of incompressible and inviscid fluid. A Lagrangian mesh is used for the structure, and a Eulerian mesh is used for the fluid, such as water and air. In the Augmented Lagrangian Eulerian (ALE) method, the fluid calculation starts with the Lagrangian method. The material is deformed as in the Lagrangian formulation. The relative motion between the mesh and the material is computed, and an advection step is taken wherein element-state data are transferred back to the new configuration. In each time step, calculations are performed through two stages, resulting in a longer computational time. Through the ALE interface, the fluid and the structure interact with each other. The structure deforms under hydrodynamic pressure, and the fluid pressure is affected by the structural response. A multi-material ALE formulation enables the modelling of a free water surface by allowing both air and water to be represented in the same element.

The simulation model in this study consists of four parts: air, water, plate and the stiffeners. The water and air components are modelled using 3D solid elements, and the stiffened plate is modelled using 2D shell elements, as depicted in Figures 14a and 14b. The 3D fluid elements are divided into three parts, where the mesh size in the z-direction of the 3D solid elements is different in each part while remaining uniform in the x- and y-directions. The fluid component close to the plate (the upper part), where the coupling between the fluid and the structure occurs, is modelled with fine high-density mesh with an element size of 100×100×100 mm. The shell element dimensions of the stiffened plate are the same as those for the fluid, i.e., 100×100×100 mm. The mesh size in the z-direction in the middle part of the fluid is doubled and is linearly increasing in the lower part, as shown in Figure 14c.

The plate and its stiffeners are modelled by shell Belytschko-Tsay formulation. The water and the air are modelled by the solid ALE multi-material formulation in LS-Dyna; see Table 4 for the properties of air and water. For water and air, a linear polynomial equation of state is used: $P = C_0 + C_1\mu + C_2\mu^2 + C_3\mu^3 + (C_4 + C_5\mu + C_6\mu^2)\times e$ where $\mu = (\rho/\rho_0) - 1$. For air, the gamma law is used by setting $C_0=C_1=C_2=C_3=C_6=0$, which is expressed as $P = (\gamma - 1)\times\rho\times e$, where γ is the ratio of specific heats, ρ is a defined reference air density and e is a specific internal energy. The gravitational effect is considered; however, to prevent initial deformation, it is not applied to the structure.

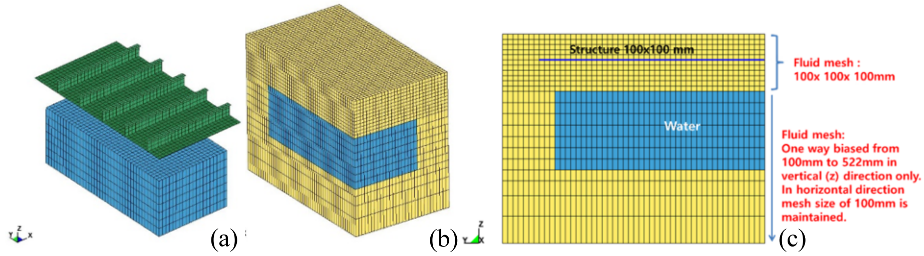

Figure 14: LS-Dyna models: (a) FE model of the stiffened plate and the water block, (b) geometry and mesh for the fluid domain, and (c) mesh configuration of the fluid domain.

Table 4: Water and air properties of EOS.

Parameter	Water	Air
ρ [kg/m³]	1,000	1.285
C_0; C_1	0.0; 2.06×10^9	0.0; 0.0
C_2; C_3	8.432×10^9; 8.014×10^9	0.0; 0.0
C_4; C_5; C_6	0.4394; 1.3937; 0.0	0.4; 0.4; 0.0
E_0; υ_0	0.0; 0.0	0.0; 0.0

LS-Dyna uses a penalty coupling method that tracks the relative displacement between the fluid and the structure. Structural damping is not considered; hence, the coupling force can be considered proportional to the penetration depth and the penalty factor. The penalty factor is a multiplier of the contact stiffness between the materials in contact. A previous parametric study by Cheong *et al.* (2016) showed that the difference in calculated pressures for the penalty factors 0.01, 0.05, 0.1, 0.5 and 1.0 was minor. Thus, a penalty factor of 0.1 is considered reasonable and is used in this study. A time step of 1.0×10^{-5} s is automatically determined by the explicit solver in LS-Dyna.

Star-CCM+/Abaqus (Chalmers University of Technology)

A link between the two software packages Star-CCM+ and Abaqus is already available in the co-simulation tool. The FSI formulation in Star-CCM+/Abaqus is referred to as a multi-physics co-simulation problem. Both air and water must be included in the fluid model, and the short time scales and high pressures included in the slamming event calls for a time-accurate analysis using compressible fluids. Viscous effects are also included to capture as much physics as possible. This forms an unsteady, compressible, two-phase and viscous problem.

The definition of the simulation model is quite similar to the model defined in LS-Dyna; however, some differences are found. The FE model for the plate and the stiffeners is shown in Figure 15a. The model is located between the upper and the lower plate surfaces in the fluid model of Figure 15b. Two volumes are created representing the main part of the domain and the plate. The 15-mm thick plate is subtracted from the main part to generate the internal boundaries of the plate, as depicted in Figure 15b. It is assumed that geometrical details of the upper (air) side of the fluid domain have a very small influence on the computed pressure on the lower (water) side. The geometry of the plate stiffeners is therefore not included in the fluid model. The mesh size in the main part of the fluid domain is 100×100×100 mm, and the shell element mesh size of the plate is taken as 100×100 mm. A local refinement (100×100×5 mm) is introduced close to the plate to resolve the fractions of water and air.

The RANS equations are solved using a k-ε turbulence model to represent the influence of viscosity. Both the upper and the lower sides of the plate in the fluid model are connected to the plate in the structural model. At each time step, the computed pressure distribution on the lower side of the plate of the fluid model is applied as a load on the structural model. The displacement distribution is then transferred to the fluid model and the deflection of the plate is updated. The volume mesh distribution is updated according to the deflection of the plate through a mesh morphing approach.

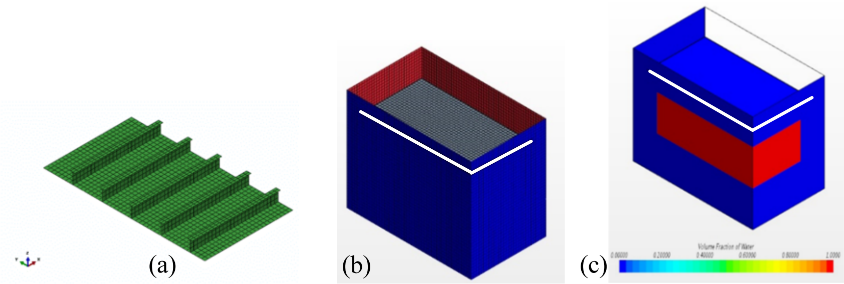

Figure 15: Model view: (a) FE model of the plate and the stiffeners, (b) geometry and mesh for the fluid domain, and (c) initial conditions of the volume fraction for water.

A second-order time stepping is used in the computations. The volume of fluid approach is used for the two-phase problem. The fraction of air and water is then computed for each finite volume. The compressibility for air is represented by the gas law in the computations. The compressibility for water is introduced via a user-defined field function of density through the Tait's equation as $\rho = \rho_0 \times ([p+B]/[p_0+B])^{1/A}$, where ρ_0 is a reference density, p is the computed total pressure, p_0 is a reference atmospheric pressure, A = 7.15 and B = 3.047×10^8.

The initial conditions for the two-phase problem are introduced via user-defined field functions for the volume fractions of air and water. The volume fraction of water is shown in Figure 15c for the block of water. The effect of gravity is included, and the initial velocity is set to give the block of water the velocities 4, 5, 6 and 7 m/s when reaching the plate, taking gravity effects into account. At the inlet boundary (from below in Figure 15c) the volume fraction of air is 1.0, and the volume fraction for water is 0.0. The velocity for the incoming flow is set to a small positive value. A constant pressure condition is used at the outlet.

7.2.3 Results

The time histories from the two analyses of the total vertical force on the plate are plotted in Figure 16a, and those for the deflection at the centre of the plate are plotted in Figure 16b. The time history of total force for LS-Dyna is fluctuating, whereas that for Star-CCM+/Abaqus is smooth. The ALE method adopted by LS-Dyna uses the penalty coupling method, which uses a contact stiffness between fluid and structure. No use of damping in the coupling method results in the noisy pressure history. The method allows for a certain level of water penetration into the structure and a gap between the water and the structure. If the time history of the total vertical force for LS-Dyna is averaged over 0.01 s, it becomes more smooth and similar to that of Star-CCM+/Abaqus, as shown in Figure 16a. Even if the pressure levels of two simulations are similar, the pressure peak shapes are different. Star-CCM+/Abaqus shows two distinct peaks, whereas LS-Dyna shows two small peaks. This difference could be related to how to realise the complicated interactions among the fluid, structure and entrapped air between the two software packages. Further refinement of the fluid mesh along the vertical direction in the vicinity of the structure in Star-CCM+/Abaqus leads to more smooth and realistic interactions.

Another difference is that Star-CCM+/Abaqus shows negative pressure when the rising water rebounds from the stiffened plate, whereas LS-Dyna does not. In the case of LS-Dyna, negative pressure occurs in the vicinity of the plate centre, but the total force is positive when summed up over the plate. Moreover, the time history of deflection for LS-Dyna shows a smoother shape than that of the total vertical forces, as shown in Figure 16b, and the maximum values show a good agreement. The distribution of deflection over the plate at the moment of maximum deflection is presented in Figure 17.

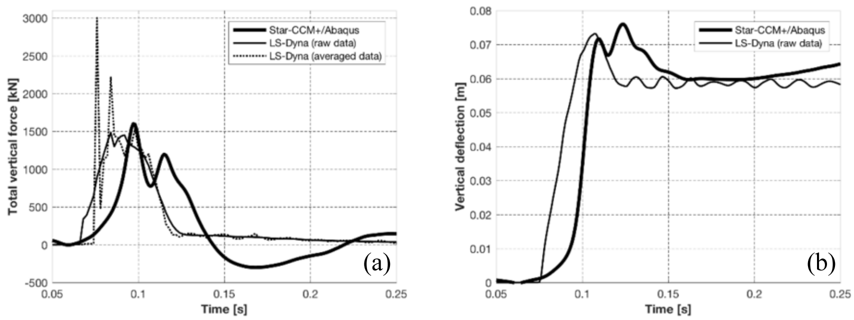

Figure 16: Results of two cases for 6 m/s of water speed: (a) time history of the total vertical force, and (b) time history of the deflection at the plate centre.

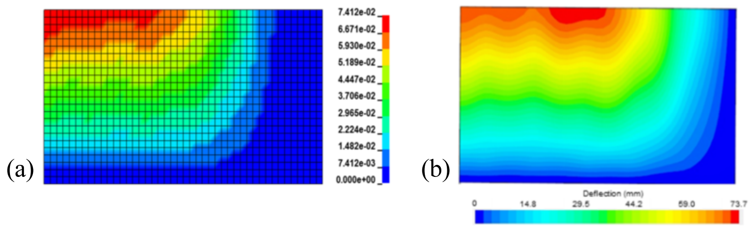

Figure 17: Distribution of deflections at the moment of maximum deflection, Δ_{max} (unit: mm): (a) LS-Dyna (Δ_{max} = 74 mm), and (b) Star-CCM+/Abaqus (Δ_{max} = 76 mm).

Table 5 summarises the maximum and permanent deflections from the FSI analyses at a node near the plate centre x = 0.1 m and y = 0.1. The results show good agreement between the LS-Dyna and Star-CCM+/Abaqus analyses.

Table 5: Comparison of maximum and permanent deflections.

	Maximum deflection, Δ_{max} [mm]		Permanent deflection, $\Delta_{residual}$ [mm]	
Velocity [m/s]	LS-Dyna	Star-CCM+/Abaqus	LS-Dyna	Star-CCM+/Abaqus
4	25	26	14	15
5	46	44	34	34
6	74	76	59	62
7	103	112	87	95

FSI analysis is quite time consuming, especially for complex structure configurations. Simplified formulations are used to be efficient in assessments in the early stages of a design, and they must also be reliable. One of the objectives of the study is to find the corresponding equivalent static and uniform pressure that results in the same permanent deformation as the FSI analysis. Table 6 presents the results from this study, listing the equivalent static slamming pressure coefficients that are comparable with those provided by DNV-RP-C205 (DNV 2010). The coefficients take into account the FSI effect, which becomes more pronounced as the deadrise angle decreases in the current case. According to DNV (2010), the space average slamming pressure can be calculated as $p_s = 0.5\rho C_P v^2$, where C_P should not be less than 2π ($\approx$ 6.28) for flat bottom slamming with a deadrise angle of less than 4 degrees, considering air cushioning and 3D effects. As identified in Table 6, the obtained values of C_P depend on the water velocity and are much greater than 2π.

Table 6: Calculated equivalent static slamming pressure coefficients from the FSI analyses.

Velocity, v [m/s]	LS-Dyna		Star-CCM+/Abaqus	
	Pressure, p_s [kPa]	C_P	Pressure, p_s [kPa]	C_P
4	173.5	21.7	177.0	22.1
5	186.0	14.9	192.0	15.4
6	207.0	11.5	227.0	12.6
7	250.0	10.2	287.0	11.7
	Average:	14.6	Average:	15.5

7.2.4 Concluding remarks

LS-Dyna and Star-CCM+/Abaqus use different FSI techniques and different fluid models. Thus, the resultant time histories of impact pressure show some differences, i.e., LS-Dyna shows more fluctuations in the results than Star-CCM+/Abaqus. The difference in fluctuations is caused by the use of a more refined fluid mesh in the vicinity of the structure in Star-CCM+/Abaqus and the different interaction methods used among fluid, structure and the entrapped air. Nonetheless, the two software packages show good agreement in the maximum total vertical force and plate deflection for all water impact velocities. Because slamming is not accompanied with water breaking or turbulent flow at the moment of water impact, the ideal fluid model in LS-Dyna shows nearly the same results as the results of Star-CCM+/Abaqus. From the study on the equivalent static pressure, the pressure coefficient C_P is not constant over different water velocities; it tends to decrease when the velocity of water increases.

In the simulation with Star-CCM+/Abaqus, a further local grid refinement of the fluid domain around the structure was found to be necessary to resolve the volume distribution of water and air close to the surface of the plate. Although the refined fluid models require a high time resolution, it is expected to give a better prediction of the pressure peak and the effect of air cushion. The same local refinement would have a similar effect on the LS-Dyna results.

8. CONCLUSIONS AND RECOMMENDATIONS

The committee reviewed recent studies as defined by the committee mandate. The report presents a summary of current publications relevant to quasi-static analysis methods applied to ships and offshore structures. The summary consists of a general introduction to strength assessment approaches and a review of load modelling, structure modelling and response analysis, uncertainty and reliability analysis. Recent developments of rules and software systems are described. A review related to offshore and other specific marine structures is also included. Two benchmark studies—the first study investigates two ship structures and the second study explores an offshore structure—are described. The following paragraphs highlight conclusions and observations from the literature review and the benchmark studies.

Conclusions

The review of load modelling revealed that advancements in numerical simulations provide additional basic knowledge about complex events, such as sloshing, grounding, slamming, and extreme events. The research conducted during the reporting period indicates that a significant amount of research targets these areas. Collision and grounding are other areas of ongoing interest. Investigations of quasi-static approaches have been conducted to address these complex problems. The coupling of loads, in which fluid/air/structural models are being evaluated to address their impact, and the coupling of primary loads of structures, such as torsion and vertical bending, are additional areas of interest. This coupling manifests in several areas, such as the development of methodologies to evaluate the progressive collapse of structures and the development of analytical methods to understand this behaviour.

The chapter on structure modelling and response analyses highlighted the importance of structural assessment using quasi-static methods and its relevance to the modern structural design of ship and offshore structures. The committee considers the presented research to be similar to the ISSC Committee II.1 report in 2015. An area that has continued to develop during the reporting period comprises strength assessments of damaged structures. The implementation of quasi-static approaches in direct calculation software, particularly FE analyses, continues to receive significant attention from researchers. Local and global assessments focus on specific failure modes by application of a single load or multiple load combinations. FE analysis is continuing to replace experimental analysis primarily due to the increasing capability of commercially available software and hardware, which can run larger and more complex simulations than in the past, and due to the expense of undertaking physical experiments. However, the committee urges researchers to consider the use of appropriate experimental work to verify simulations. The boundaries of current understanding are always being pushed and may surpass the current verification of direct calculation tools. Therefore, verification is required to ensure that conclusions are drawn based on simulations that correctly reflect the physical world rather than an erroneous numerical phenomenon.

The topics of uncertainty and reliability analysis are important for the quasi-static response of ships and offshore structures because this type of analysis is related to uncertainties in quasi-static calculation models. Reliability analysis has become a practical and very powerful tool for decision making in ship design, design code calibration for ships and offshore structures, and maintenance planning during ship operation. The literature review discussed recent knowledge of uncertainties of various loads and structures, which affect the implementation of reasonable and practical reliability analyses. The most recent development in the use of a stochastic FE method for evaluating response uncertainty was reviewed, and it has the potential to become a powerful tool for future rational uncertainty analysis.

In the chapter on the development of rules and software systems, the development towards the use of direct calculation methods in ship design continues as reflected in the rules and calculation tools from the Classification societies, including increased use of 3D FE analyses, dynamic loading approaches and spectral fatigue analyses. The development of programs for the fast generation of global strength models continues. However, a breakthrough development of an efficient and prevalent tool has not occurred. Small improvements, such as the use of macros, seem to be more efficient.

The literature review of offshore fixed platforms revealed many studies of the prediction of extreme quasi-static response considering the nonlinearity of Morison's force and the statistical characteristics of environmental loads. The use of reliability analysis for the uncertainty of soil properties is another unique feature of fixed platforms; some interesting studies have been presented during the reporting period. In the area of floating offshore structures, numerous efforts have been made to develop nonlinear and coupled hydrodynamic codes to predict extreme loads on not only the hull structure but also the mooring chains and risers by considering the nonlinear effects of second-order wave loads. Accidental loads, such as fire and explosion loads, which need to be determined in a probabilistic manner in the structural design of topside structures, have received considerable attention. Examples of specific marine structures that exhibit a unique structural design or arrangement specific to their functionality, e.g., livestock carrier vessels, were presented. Their strength assessment primarily depends on a direct FE analysis due to the lack of supporting classification rules.

In Chapter 7, the first benchmark study of ship structural response from different wave load schematisations included cargo ship and passenger ship box girder models. In recent years, the use of direct calculation methods in the early stage of the design of ships has become common practice. Due to short timelines, this phase of the structural design requires the use of quasi-static analysis and simplifications in modelling. The current benchmark study reveals the relevance of a proper representation of the loads in the direct analysis approach, especially in the study of the longitudinal behaviours of ship structures. Simplification in the schematisation of loads in a 3D model can cause an incorrect analysis of the global response of a ship structure and incorrect structural design, scantling design or verification of structural elements. The second benchmark study comprised an FSI analysis of a stiffened plate subjected to slamming loads. Despite differences between the simulation models and the underlying theory in the two software packages that were employed, the FSI results showed agreement. The resultant permanent deformation exhibits better agreement with actual values than the impact force, which is sensitive to the interaction mechanisms between the fluid and the structure. The software package LS-Dyna, which is developed based on the assumption of an ideal fluid, provides results similar to the CFD results. The spatially averaged slamming pressure according to DNV-RP-C205 (DNV 2010) was used to calculate the C_P value, which depends on the water velocity. The values of C_P varied among the applied software, and recommendations for future studies and model refinements were suggested for the case study of a stiffened panel structure and its loading conditions.

<u>Recommendations</u>

General recommendations for future research topics and specific recommendations that refer to Chapters 2 to 6 in this report are listed as follows:

- Advanced methods for mesh generation of FE models and new FE techniques.
- Improve methods to account for corrosion and fatigue in assessing structural strength.
- Uncertainties of internal loads and load effects on structural strength.
- Reliability-based lifecycle design.
- Risk-based inspection, maintenance and repair.
- Development of new rules and regulations by regulatory bodies.
- Structural aspects of specialised ships and offshore structures.

Chapter 2: Future efforts should focus on certain critical areas, such as a non-ice strengthened hulls that operate at high latitudes and the loading conditions that should be utilised to quasi-statically evaluate these vessels. Another area of interest is how the quasi-static response methods begin to interact with other methodologies, such as structural health monitoring approaches, and special operations, in which a holistic view is being explored to provide the operator and designer with critical information while fusing data from various sources to make informed decisions. Quasi-static approaches for load modelling can be employed in algorithms to develop real-time feedback. With an increased use of numerical modelling via research efforts, numerical methods are addressing the analysis of alternatives and early-stage evaluations of ship designs, in which numerous alternatives can be optimised to achieve a higher relevance to quasi-static methods and ensure that numerical simulations provide reasonable solutions.

Chapter 3: To enable design iterations and rapidly implement a cost-effective design process in the detailed design phases, the committee recommends that researchers consider the development of design curves or equations that can be implemented to enable designers to assess the failure modes of structures under more complex loadings than current possible loadings. This assessment will ensure that structures are appropriately and efficiently designed and consider that individual load applications may be less efficient to ensure that a suitable reserve is provided between capacity and demand. As the applications of FE analysis, CFD and combined FSI approaches become more advanced, these methods can provide an understanding that is not possible or practical to achieve via experimentation, and the use of these methods to improve or develop existing formulations or provide new formulations should be considered. Detailed complex analysis is part of the design process, usually as the design detail increases. To avoid design constraints due to early decisions based on analytical methods that may not fully capture the structural arrangement or loading scenario in question, development of broader early-design tools should avoid unnecessary rework or conservative parameters in the design, which may increase key factors, such as cost and weight.

Chapter 4: The concepts of reliability and uncertainty analysis continue to be important research topics for the rational design of ships and offshore structures. Reliability analysis will continue to be applied to the practical decision-making procedure in ship design and the design code calibration procedure to enable the reliability method to become a standard. The evaluation of uncertainties that refer to wave loads considering elastic vibration and corresponding fatigue strength are important future research topics.

Chapter 5: The next committee should continue to focus on the development of new rules and regulations by regulatory bodies. The next committee should promote the advancement of "autonomous vessels" because research in this area may contribute to changes in rules and regulations, which may influence how ships are designed. A review of different methods for load application (e.g., simplified and equivalent design waves), applications in quasi-static response analysis and the associated impact on the structural design (benchmark study presented in Section 7.1) are also recommended.

Chapter 6: The impacts of nonlinear environmental loads are often determined based on short-term analysis, in which a time-domain nonlinear analysis is performed for some critical sea states selected from a wave scatter diagram using an environmental contour, i.e., H_s-T_p contour. This methodology may not be equivalent to a long-term extreme value that can occur once during the design lifetime of offshore structures. This issue has been recently identified as a potential future research topic. Regarding the fatigue of offshore and specific structures, nonlinear analysis is often required, but the computational effort is significant because a time-domain nonlinear analysis needs to be performed for all sea states in the wave scatter diagram. Although several simplified methods have been proposed, improvements are needed to facilitate the general and extensive use of these methods. Considering the practical use of a reliability analysis with many uncertain factors, its application to real projects remains unacceptable. The computational burden and lack of statistical information about many uncertain factors are the main reasons for these limitations. These issues must be improved, even if some deterioration in accuracy is inevitable.

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