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

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COMMITTEE II.1

QUASI-STATIC RESPONSE

COMMITTEE MANDATE

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

COMMITTEE MEMBERS

Chairman: Seref Aksu
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KEYWORDS

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

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1 INTRODUCTION

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

The present committee report is organised in the following manner:

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

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

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

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

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

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

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

The conclusions drawn from the study formed Section 8.

2 STRENGTH ASSESSMENT APPROACHES

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

2.1 Quasi-Static Modelling of a Dynamic Problem

2.1.1 Loads

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

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

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

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

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2.1.2 Response

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

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

2.2 Linearization / Simplification of Nonlinearities

2.2.1 Ice Loads

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

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

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

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

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

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

2.2.2 Slam Loads on High Speed Catamarans

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

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

2.2.3 Accidental Loads Arising from Collisions and Grounding

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

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

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

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

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

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

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

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

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

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

3 CALCULATION PROCEDURES

3.1 Load Application Methods

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

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

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

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

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

3.2 Global Wave Loads

3.2.1 Intact Ship

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

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

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

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

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

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

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

3.2.2 Damaged Ship

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

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

3.3 Fluid-Structure Interaction

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

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

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

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

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

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

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

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

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

3.4 Modelling

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

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

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

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

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

3.5 Response Calculations

3.5.1 Buckling and Ultimate Strength

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

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

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

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

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

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

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

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

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

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

3.5.2 Combined Global and Local Loads and Responses

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

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

3.5.3 Fatigue Strength

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

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

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

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

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

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

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

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

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

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

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

3.5.4 Welding Distortions

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

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

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

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

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

3.5.5 Service Life Assessments

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

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

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

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

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

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

3.6 Finite Element Modelling and Analysis

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

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

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

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

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

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

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

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

Ship hull deformation influences the propulsion shafting alignment significantly.

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

4 UNCERTAINTIES ASSOCIATED WITH RELIABILITY BASED QUASI-STATIC RESPONSE ASSESSMENT

4.1 Uncertainties Associated with Loads

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

4.1.1 Uncertainties Associated with Still Water Loads

4.1.1.1 Intact Ship

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

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

4.1.1.2 Damaged Ship

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

$$M_{SD} = K_{us} M_{SI} \quad (1)$$

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

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

4.1.2 Uncertainties Associated with Wave Loads

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

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

4.1.3 Combination Factors

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

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

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4.2 Uncertainties Associated with Capacity

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

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

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

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

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

4.3 Reliability Based Structural Assessment

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

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

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

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

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

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

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

4.4 Reliability Based Inspection, Maintenance and Repair

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

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

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

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

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

5 SANDWICH PANELS AND DEFORMATION LIMITS

5.1 Recent Studies on Steel Sandwich Panels

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

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

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

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

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

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

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

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

5.2 FRP-GRP Composites

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

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

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

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

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

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

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

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

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

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

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

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

In the area of ship crashworthiness and impact protection, metallic foams are increasingly utilised as energy absorbers and weight savers. Metallic foams constitute the core of some sandwich structures. Zhu *et al.* (2009) investigated impulse loading of sandwich panels with aluminium foam core. An analytical method to predict the deflection of the panel was used to measure energy absorption during plastic deformation. The deformation process was divided into three phases; impulse at the front face, compression of the core, and deformation of the back face.

Pandit *et al.* (2009) investigated variations in material properties of sandwich plates on transverse deflections. In demonstrating the performance of a stochastic laminated sandwich model, the authors investigated the effects of boundary conditions and lay-ups on the deflections of square sandwich plates with scatter in material property.

6 SHIP STRUCTURES

6.1 Design Trends, Developments and Challenges

Stronger, safer and more durable structures are now recognised due to increased awareness by the authorities and the society in general in relation to safety of passenger and crew, environmental protection. At the same time, the increased competition demands for the increased productivity and the reduced costs in the ship building industry.

In this section, the recent developments in areas of green shipping, energy efficient designs, cleaner alternative propulsion, safer ships, Northern Sea route and Panama Canal expansion are discussed in relation to their potential impact to design and operation of ships.

6.1.1 Green Shipping

Ships are continuously travelling in world's oceans and have close interaction with the sea environment and atmosphere. Ships are the most energy efficient transport media in terms of transportation of goods per tonne-mile. Ships have been, and will continue to be used in global logistics. In recent years there have been pressures for energy efficiency and reduced emissions from the regulatory authorities as well as from society in general due mainly to the depletion of fossil fuels and global warming. Based on an article published in New Scientist (2011), if all the international shipping fleet were a single country, shipping would be the 7th largest emissions contributor in the world. This is larger than the whole aviation industry (see Figure 1). As with other modes of transportation, ships are required to be more energy efficient as well as compliant with global environmental protection. Therefore, it is very important for ship designers to design environmentally friendly ships, not just for regulatory compliance, but mainly for their performance and competitiveness.

A number of technologies are considered as green ship technologies for near future and long-term. Improvements in the area of hull hydrodynamic efficiency of ships, weather

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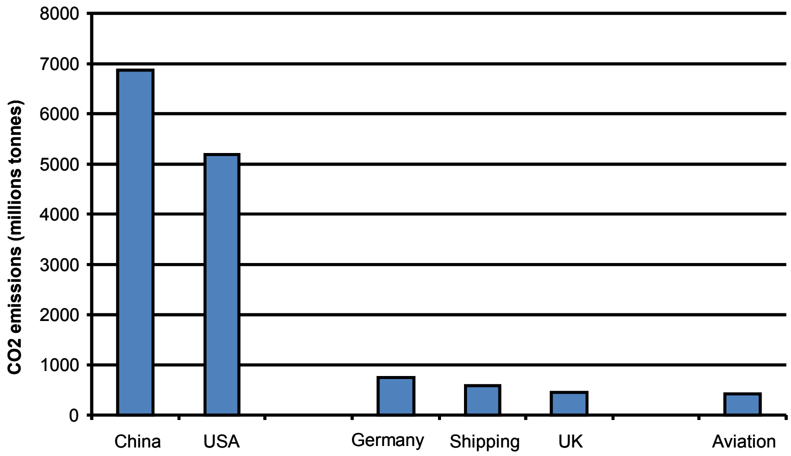

Figure 1: CO_2 emissions from any fossil fuels burned for energy generation, transportation, heating and other uses. All large shipping and aviation are considered as individual groups. (Figure adapted from New Scientist, 15/12/2011)

routing, and using LNG as fuel onboard are considered as the near future green ship technologies. For the longer term, future green ship technologies, hydrogen and fuel cell ships, renewable energy ships - using solar, wind and wave power, and nuclear powered ships are considered. In this section, the recent developments in these green technology areas are reviewed.

Energy efficiency and minimisation of emissions have recently become important topics to reduce global warming. A wide range of research topics on ship powering have been conducted to minimise resistance for this purpose. Ship hull form optimisation has been utilised commonly to reduce the wave resistance component of a ship. Air lubrication is one promising method to reduce the viscous resistance of a ship. It can be established by the utilisation of techniques such as air cavity, micro-bubbles, and air film formation. Insel *et al.* (2009) describes efforts to reduce the resistance for a tanker form by means of air lubrication, the work was carried out at Istanbul Technical University. The results indicate that resistance reduction can be obtained by using this technique even at low speeds. Mizokami *et al.* (2011), also developed frictional resistance reduction technology by means of air lubrication, carried out confirmation of the air blow condition with a mock-up examination and the numerical computation. It was stated that for a large shallow water ship, the air lubrication method provided an energy saving of 12 %.

Reduction of fuel consumption as a result of slow steaming or route optimisation has also received increased attention recently by the ship operators as a countermeasure to reduce green house gas (GHG) emissions. Selecting a proper route for a ship will not only reduce fuel consumption but also provide safe navigation. Habu *et al.* (2010) presented a study on the route optimisation in stormy weather. In this study, the selection of optimum route for ships running in stormy weather is established based on improved efficiency and navigation safety. For the calculation of navigation cost, an efficiency criterion function is used, which consists of the navigation time and fuel consumption. The navigation safety was evaluated by considering limiting values for wave height, wind speed and roll angle.

In order to increase ship performance in actual navigation conditions, a definitive

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evaluation method of the performance needs to be established. Tsujimoto *et al.* (2010) developed the 10 mode "Index for Ships". The index consists of ship speed in ten kinds of weather conditions as well as ship speed in calm seas. Verifications were carried out by numerical simulation, model tests, and full scale measurement and it is concluded that the hybrid calculation is robust to evaluate ship speed in actual scenarios.

Nelson (2010) discussed the increasing efforts made by LNG shipowners in employing enhanced operational techniques and new technologies to reduce the impact on the environment and, in some cases, also reducing the vessel's operating costs. The operational techniques and new technologies such as hull form, propeller design and interaction with the hull, main propulsion system design, underwater coating technologies, reliquefaction plants, and emissions control systems are considered and/or implemented by the LNG shipowners to meet the current and proposed future national/regional and international environmental regulations.

6.1.2 Energy Efficiency Design Index, Energy Efficiency Operation Index (SA)

In July of 2011, the IMO established two instruments to reduce marine CO_2 emissions. These instruments, the Energy Efficiency Design Index (EEDI) and the Ship Energy Efficiency Management Plan (SEEMP), will be mandatory and will come into force on January 1st, 2013.

The IMO adopted the Energy Efficiency Design Index (EEDI) as a newbuilding standard, assuring that ship designs achieve a minimum level of efficiency and decreased carbon emissions. Although EEDI certification will not be mandatory for newbuildings until the 1st of January 2013 (contract date), owners and managers at the vanguard of sustainable shipping are already voluntarily looking to the EEDI as a means of demonstrating the efficiency of their new ship designs.

While measures such as the EEDI focus on a ship's design, and thus on newbuildings, the SEEMP concentrates on energy savings potential during the operational life of a vessel. Every ship shall have an SEEMP, preferably tied into a company-wide energy management program. The SEEMP fosters structured and codified management processes to increase a vessel's energy efficiency - IMO specifically mentions the EEOI (Energy Efficiency Operational Indicator) as a well-established and industry-specific tool to quantify and monitor results, although other methods may be used as well.

From 2013 onward, the SEEMP will be mandatory for all vessel segments. The presence of an SEEMP on board each vessel will be checked at the intermediate or renewal survey (whichever comes first after Jan 1st, 2013) but so far there is no requirement for the SEEMP to be approved by the flag state or by a Recognized Organization (RO).

Devanney (2011) discussed the impact of the energy efficiency design index on very large crude carrier design and CO_2 emissions. The author argued that, over a market cycle, imposition of EEDI will result in a slight increase in VLCC CO_2 emissions, relative to no regulation at all. The following specific concerns were raised. First, for VLCCs, EEDI effectively limits installed power, which requires owners to use smaller bore, higher revolutions-per-minute engines resulting in higher specific fuel consumption and, more importantly, require a smaller and less efficient propeller. This means the EEDI-compliant VLCC consumes more fuel when the market is not in boom, which is 90 % of the time. Further, the author suggested that a \$ 50 per tonne of CO_2 bunker tax might be more efficient and will reduce VLCC CO_2 emissions by more than 6 %.

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6.1.3 Cleaner Alternative Propulsion

Nishizawa *et al.* (2010) presented a feasibility study on an electric propulsion tanker without ballast water. The hull shape was developed to minimize the frictional resistance and the viscous pressure resistance for a tanker with 100,000 DWT. Because of a buttock-flow stern hull shape, the new tanker was designed as an electric propulsion ship with podded-propulsors. Based on the results of the present feasibility study, the authors concluded that the high initial cost for building can be balanced by lower operational costs achieved by reduced fuel, lubricant and maintenance costs, and by increased income as a result of increased deadweight capacity.

Using LNG as fuel is an efficient way to cut emissions. All SO_x emissions are eliminated and the NO_x and CO_2 emissions are reduced by about 80 % and 20 % respectively (Levander *et al.*, 2006). It is argued that natural gas is one of the largest sources of energy worldwide and at today's rate of consumption it is expected to last about 150 years. There are currently approximately 25 ships that are operating with LNG fuel in world waters. Viking line is building the world's first large LNG passenger ferry (Horizons, 2011). However, there are some storage, safety and operational concerns using LNG.

- The main problem with using LNG in ships is the large amount of space required for the LNG tanks. Compared with marine diesel oil (MDO), an equal energy content of LNG requires about 1.8 times more volume than MDO. After adding the tank insulation, which results in a maximum filling ratio of 95 %, the required volume is increased to about 2.3 times. The practical space required in the ship may become even larger if a cylindrical LNG tank and the surrounding space lost around is considered.
- Natural gas is perceived to be highly explosive and dangerous when used as a ship fuel. However, this is not necessarily true and it can be used safely as fuel if the right precautions are taken. In a liquid state, natural gas is not explosive, nor is it corrosive or toxic. However, there are material issues with low temperatures. On the other hand, the marine industry has significant experience in dealing with this problem by the operation of LNG vessels. In gaseous state, natural gas is lighter than air, which means that in case of leakage the gas will disperse upwards and not build up in the ship's bilge. The ignition temperature of natural gas is relatively high (600° C) compared with diesel oil (250° C) (Levander *et al.*, 2006).
- Availability of propulsion engines. Previously, a number of LNG ships had gas turbines as main propulsors. Although less fuel efficient compared with diesel engines, LNG operators were able to burn the boil-off gas with these. Recently, major engine manufacturers (Wärtsilä, MAN) introduced hybrid dual-fuel (H-DF) engines that can burn liquid or gas fuel at the same time. These engines use LNG as primary fuel and marine diesel oil as pilot and back-up fuel (Levander *et al.*, 2006).

Bernatik *et al.* (2011) discussed the safety and security aspects of storing of LNG as a potential alternative fuel. The contribution deals with possible scenarios of accidents associated with LNG storage facilities and with a methodology for the assessment of vulnerability of such facilities. The study presents the results of determination of hazardous zones around LNG facilities in the event of various sorts of release.

Although Brown (2011) agrees with very clear considerable local benefits in using LNG as a marine fuel, he cautions that LNG is just another fossil fuel and draws attention to concerns and claims that LNG does not reduce CO_2 emissions on a like-for-like

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basis with other fossil fuels when carbon foot print from well to flue emissions is considered. Much of the excitement around LNG's prospects devolves from the prospect of abundant, cheap, gas as a result of gas from new reserves of 'unconventional' gas exploited through technologies such as fracking of shale gas. However, a study by Howarth *et al.* (2011) raises concerns on methane escape to the atmosphere. Natural gas is composed largely of methane and the authors claimed that 3.6 % to 7.9 % of the methane from shale-gas production escapes to the atmosphere in venting and leaks over the lifetime of a well. Methane contributes substantially to the greenhouse gas footprint of shale gas on shorter time scales, dominating it on a 20-year time horizon. The footprint for shale gas is greater than that for conventional gas or oil when viewed on any time horizon, but particularly so over 20 years.

Utilizing the ocean wind power is considered as an option to reduce the fuel oil consumption of a large merchant vessel. Ouchi and Uzawa (2010) proposed a new eco-ship concept of "Motor Assisted Sailing Ship" to contribute to a low carbon society. The ship is fitted with huge hard sails (height: $50\,m$, Bredth: $20\,m$, Area: $1{,}000\,m^2$) made by CFRP composite having a high lift performance wing shape section and also having a vertically telescopic reefing mechanism. The nine pieces of hard sails (total sail area $9{,}000\,m^2$) generate enough forward thrust to drive $180{,}000\,DWT$ Bulk Carrier at $14\,kn$, in the case of wind velocity of $13\,m/s$ from a beam. A case study using real sea conditions was carried out and more than 50 % of propulsion energy is acquired from the ocean wind power on average.

6.1.4 Safer Ships

Onboard decision support systems (DSS) are used to increase the operational safety of ships. Ideally, DSS can estimate future ship responses within a time scale of the order of 1–3 hours taking into account speed and course changes, assuming stationary sea states. A paper by Nielsen *et al.* (2009) suggested a procedure which is based on parallel system analysis, to incorporate random variables and associated uncertainties in the calculations of the out-crossing rates that are the basis for risk-based DSS. Bitner-Gregersen and Skjong (2009) presented a concept for a risk based decision support system for navigation of ships that encounter deteriorating weather conditions and dangers of damages to a ship and its cargo. The authors advocated that it is possible to develop a system that is systematically built on risk assessment approaches with the intention of being applicable for a specific ship with a specific loading situation in a real-time environment. Bitner-Gregersen and Skjong (2009) based their concept on modern reliability methodology, state-of-the-art hydrodynamics software and information sources relating to the environment.

Tamura and Shinoda (2010) presented a paper on the application of FSA (Formal Safety Assessment) to collision accidents between fishing vessels and cargo vessels. Most marine accidents related to vessels are caused by human errors, such as misdetection, misjudgement and misoperation. The study claims that collision accidents between fishing and cargo vessels with consequences of loss of life occur frequently in the sea off Japan. In this context, the safety assessment for these types of marine accidents is carried out through the steps of Identification of hazards by Variation Tree Analysis, Construction of Marine Casualty Database, Collision Course Analysis, Risk Assessment by Event Tree Analysis, Estimation of probabilities of collision accidents based on ship traffic data and Evaluation of Risk Control Options using Contingent Valuation Method, which is in accordance with Formal Safety Assessment (FSA) approved by IMO in 2002.

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Yuzui *et al.* (2011) proposed Inclusive Impact Index by the IMPACT Research Committee in the Japanese Society of Naval Architects and Ocean Engineers. Inclusive Impact Index is defined and calculated based on the ecological footprint, ecological risk, human risk, cost, and benefit. Applicability of the index to the environmental risk assessment problems in the maritime field such as evaluating the risk of an oil tanker is discussed.

Det Norske Veritas in Australia have reported weaknesses in the applicability of the International Maritime Organisation (IMO) High Speed Craft (HSC) code to passenger and cargo craft used in crew transfer, patrol and service. In response to industry requirements to standardise certification and safety rules of craft operating in different countries and offshore installations, DNV have published new rules. The 'Tentative Rules for Domestic Service Craft' cover structures and equipment (Det Norske Veritas, 2011). The notation for hull structural design states that the bow and fendering system, intended to be pushed against hard foundations, must be strengthened to withstand the applied loads.

6.1.5 Northern Sea Route, Panama Canal Expansion

As intentions for use of large-size commercial ships as a part of arctic transportation systems are becoming reality, however it appears that these decisions are mostly based on the results of cost-effectiveness calculations. Pavlenko and Glukhareva (2010) discussed the issues connected with the usage of the Northern Sea Route and Northwest Passage. The authors suggested possible solutions that can be used for the development of international marine shipping infrastructure, safe navigation support and systems of response to emergency situations in Arctic Ocean. Somanathan *et al.* (2009) modelled shipping through the Northwest Passage in northern Canada and compared the economics of this route relative to the Panama Canal. Container shipping between Yokohama ad New York and St. Johns, Newfoundland, is simulated for the two routes using bluewater ships for the Panama Canal and identically sized Canadian Arctic Class 3 (CAC3) ships for the Northwest Passage. The required freight rate (RFR) to recover all costs including capital recovery is found to be similar for the two routes. Sazanov (2011) reviewed some main challenges related to large-size ships manoeuvrability and performance in ice as well as interaction of ships with icebreakers. From the limited review carried out here, it appears that not much research was conducted on the structural/design changes required for the commercial ships to operate in Northern Sea route.

An article in Oil and Gas journal (Oil and Gas, 2010) argued that Panama Canal expansion will permit more than 80 % of the global LNG fleet to move through the canal, compared with only 6 % of the fleet currently. However, no LNG vessels now traverse the waterway because that 6 % of the fleet is too small to engage in large, long-haul trade. Panama Canal expansion may have a significant effect on the LNG cargo movements. For example, producers such as Trinidad and Tobago, Algeria, Nigeria, and Angola will be able to move their cargoes to Asia. Similarly, Asian cargoes will be able to access Atlantic Basin markets. As the trade expands, there may be need for more LNG vessels.

6.2 Types of Analysis for Various Ship Types

6.2.1 Passenger Ships

On passenger ships, the committee considered two main aspects related to quasi-static response; the modelling of structural details such as openings and joints and the principles of assessing the global response of the hull girder.

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Mobasher-Amini *et al.* (2009a; 2009b) presented a domain decomposition method for passenger ship structures where structural heterogeneities exist for example due to window or balcony openings. The method utilizes linear elastic Finite Element Method. It also addresses the problems of subdomain interfaces arising from the presence of elastic joints or stiffeners. Bäckström and Kivimaa (2009) worked in detail on the topic of large openings in longitudinal bulkheads and simulate the crack propagation due to shear-induced deformation. Biot and Moro (2011) carried out similar analyses using both linear-elastic and elasto-plastic notch stress analyses. Andric and Zanic (2010) made detailed investigation how the openings should be modelled to achieve reasonable accuracy in the global finite element analyses. They concluded that with orthotropic equivalent plate elements reasonable accuracy can be obtained when stiffness is concerned. Romanoff *et al.* (2010) claimed that when using novel deck structures, such as steel sandwich panels, special attention needs to be paid on the interaction between the sandwich decks with non-symmetrical joints and the global hull girder analysis.

Remes *et al.* (2009) presented a new conceptual structural design platform, ConStruct, especially designed for passenger ships. It is based on the Coupled Beams theory presented by Naar *et al.* (2004). The work was continued in Remes *et al.* (2011) where they investigated the hull-superstructure interaction of optimised passenger ships. They concluded that for ship with equal volumes on the hull and superstructure, the global bending moment is carried out equally between the hull and the superstructure in weight optimal design. When vertical centre of gravity is set as design objective the superstructure starts to carry more of the bending moment due to the shift of neutral axis. It is also seen that the neutral axis varies across the length of the ship and therefore the entire length of the ship needs to be modelled; this happens even in case of prismatic ship. Andric and Zanic (2010) concluded that prismatic FE-model can be used to calculate the normal stresses at the midship and the deflections along the length of the ship. Thus, these two investigations propose that beam methods where deck efficiencies are assumed to correct the effects of non-linear normal strain distribution along the height direction of the ship are not sufficient for structural analysis other than at the midship location. In Caprece *et al.* (2010), the ship has been split into three representative short beam sections where the bending moment and the shear forces are applied. The paper, however, does not present a comparison of normal stresses to conclude how well the approach works. Having these aspects in mind, a proposal would be to complete a benchmarking study where different methods to assess passenger ship response would be compared. Davidson *et al.* (2011) considered the load cases and structural design of a multihull ferry. The authors conducted research to determine the most efficient roof-to-hull structure, where various roof-to-hull structures in terms of resistance to deflection and cargo and passenger carrying capability are considered.

The cruise ship, Costa Concordia, ran aground off the coast of the Isola del Giglio island on the night of 13th January 2012. She suffered serious damage on 3–4 watertight compartments, lost its stability and capsized. The 4,200 people aboard are evacuated to the nearby Isola del Giglio island (Associated Press). At the time of last update of this report, 17 people are known to have died and 15 people are still unaccounted for (BBC, 28th Jan 2012).

From the initial investigations, it appears that human factors caused navigational misconduct which then resulted in the grounding accident. The captain of the cruise vessel has been arrested for misconduct and man slaughter. It is too early to speculate, with certainty, either the account of events that led to the capsizing of the vessel or

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what possible implications that the accident will have on the design of passenger vessels. However, the committee is certain that the accident will have an influence on passenger vessel design.

6.2.2 Container Ships

In recent years container ships have seen dramatic change with respect to their size and it is an ongoing trend. In 2011, the first container ships carrying 18,000 TEU were ordered. The capacity of these vessels, at 400 m length and 59 m wide, were designed to capitalise the size effect. A larger ship will be more efficient in terms of fuel consumption per TEU transported; however, it presents challenges operationally and from a naval architectural point of view. The extreme size of the hull and its inherent flexibility may be limiting design factors. Extensive research is required to ensure an adequate structural capacity over the ships lifetime.

With more bow flare, more flexible hulls and higher speeds, larger vessels are more exposed to whipping. Storhaug *et al.* (2010) investigated the effect of springing and whipping on a 360 m ultra large twin island container ship design. Model tests with a new flexible design have been carried out to investigate how the wave-induced vibration affects the fatigue and extreme loading at different cross sections. The focus is given to the consequence of extreme loading with whipping based on long duration tests in realistic extreme weather, but also the effect of whipping (and springing) on fatigue is investigated. The tests are carried out in head seas, and all parameters are realistic such as loading condition, vibration modes, vibration frequencies, damping, wave spectra and speed.

To assess high-frequency ship response for rule development purposes of large modern container ships, Rathje *et al.* (2011) compared numerical predictions with experimental data. The numerical results were based on a technique that relied on superimposing rigid body motions on elastic hull girder deformations, whereby a finite element Timoshenko beam idealizing the hull was two-way coupled to a RANS solver for the fluid-structure interaction problem. The experimental data were obtained from model tests of a segmented 10,000 TEU container ship equipped with load cells, accelerometers, and pressure sensors. A long-term measurement campaign onboard a 4,600 TEU panamax container ship yielded full-scale measurements. For the investigated cases, data analysis confirmed that predictions accounting for high frequency response yielded higher section loads than those based on rigid body assumptions.

Senjanovic *et al.* (2011) pointed out that natural frequencies of Ultra Large Container Ships (ULCS) can fall into the range of encounter frequencies in an ordinary sea spectrum. Present Classification Rules for ship design and construction do not cover such conditions completely and hydroelastic analysis of ULCS seems to be the appropriate solution for analysis of their response in waves. Within the paper the importance of the hydroelastic approach and methodology of hydroelastic analysis are elaborated. Furthermore, structural model based on advanced beam theory is described in detail. The improvements include taking into account shear influence on torsion, contribution of bulkheads to hull stiffness as well as determination of effective stiffness of engine room structure. Hydrodynamic and hydrostatic models are presented in a condensed form.

Two aspects relevant for operation and structural design of wide-bodied container ships were addressed by Rathje *et al.* (2010). First, speed loss in waves was investigated to demonstrate the effect of waves on comparable calm water speeds. Second, wave-induced global hull girder torsional loads were determined to assess effects of the

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increased breadth on hull girder torsion, generally considered the most critical load component. An extended Reynolds-averaged Navier-Stokes equations solver simulated the ship advancing in calm water as well as in selected regular head and bow waves. Spectral techniques obtained long-term predictions of torsional moments, based on nonlinearly corrected transfer functions of ship response computed with a boundary element method. To assess the reliability of these torsional moments, additional simulations were carried out of this ship in two equivalent regular design waves that represent wave conditions considered critical for structural design.

Tanaka *et al.* (2009) presents the results of an experimental study to evaluate the effect of torsional moment on the ultimate strength of container ships in longitudinal bending. The progressive collapse tests are conducted using 1/13-scale three-hold models referring to a Post-Panamax container ship. The models are fixed to the rigid wall at the aft end (cantilever beam) and loads are applied to the fore end so as to generate both torsional and vertical bending moments. Several loading conditions which vary the ratio of torsional and bending moments are adopted for the progressive collapse tests and the nonlinear finite element analyses using LS-DYNA. From the results of collapse tests and numerical simulations, the progressive collapse behaviour including the warping-strain distribution and the ultimate strength interaction relationship is examined.

Along with the rapid increase in the size of container ships over the last few decades, it has become necessary to use thicker plates in way of the hatch coaming. The use of higher tensile steel with yield strength $460\,N/mm^2$ is also inevitable to avoid using excessively thick plates. The main area of application for the new higher tensile steel is the upper hull girder area. To investigate the effect of plate thickness and tensile strength on fatigue strength for the weld joints, Kwon *et al.* (2011) conducted a series of fatigue tests with specimens of butt weld joint and longitudinal fillet weld joint with the different plate thickness and tensile strength steel. From the test results of each series of specimens which were taking into account recent developments concerning material and welding techniques, the effect of plate thickness and material was investigated. Using the fatigue test data, fatigue strength was calculated on butt weld joints and longitudinal fillet weld joints in way of hatch coaming top plate for a large container ship.

The characteristic high tensile loads in this area in combination with large plate thicknesses and high strength steel raise the possibility of brittle fracture. In order to address these concerns, research has been carried out on brittle crack arrest ability from a number of different perspectives, including the use of both numerous large-scale crack arrest tests and numerical calculations. According to Yamaguchi *et al.* (2010) a back-up brittle crack arresting function has been included in the ship's construction in order to ensure structural reliability and hull integrity. The effect of joint design on crack arrestability of thick steel plate using shipbuilding steel without block joint shift was investigated by An *et al.* (2011). Several crack arrest tests were conducted by varying joint designs to prevent a catastrophic failure along the block joint of hatch side coaming structure. A brittle crack arrest technique was developed using an arrest weld, which located in end of hatch side coaming weld line. Steel plates with $80\,mm$ thickness were used and two welding processes, which are flux cored arc welding (FCAW) process only and combined welding process (EGW+FCAW).

Kaneko *et al.* (2010) developed thick YP460 N/mm^2 class steel plates for the application of large heat-input welding. This report describes the development concept of YP460 MPa class steel plates and the material characteristics of the base metal and

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welded joints. A brittle fracture test (ESSO) was performed to determine the stress intensity factor K_{ca} as an index of arresting characteristics.

For the new material class with $460\,N/mm^2$ minimum yield strength Doerk and Rörup (2009) describe the development of a safety concept based on a brittle fracture prevention strategy using fracture mechanics methods. The safety concept results in toughness and quality requirements, which are practically applicable in shipbuilding industry. Effects of different influence parameters such as design temperature, fracture toughness, initial defect size, and shape of load spectra are discussed. Furthermore, prospective inspection and assessment strategies are presented.

Shin *et al.* (2011) established an alternative for the prevention of the unstable fracture of ultra-large container ships during design life of 20 years. In order to do it, primary and secondary stress levels and fatigue crack growth rate for the weldment were evaluated in accordance with classification rules and relevant test methods. From the test results, it was found that the fatigue crack growth rate increased with an increase in welding heat input. With those results, the allowable embedded defect size and crack tip opening displacement (CTOD) requirement for the weldment to prevent the unstable fracture at the hatch coaming were established by using a comprehensive fracture assessment.

Toyoda *et al.* (2008) conducted full scale measurement of deflections of a Post-Panamax container ship. Interferences between fittings such as hatch covers, lashing bridges and other container securing instruments need to be addressed when new size of ships is explored. The three components of the deflections were measured, i.e. torsional deflection, cross deck fore-aft deflection due to container inertia force, and longitudinal deflection due to hull girder bending moment. A method was proposed for combining the deflection from these three components by using correlation analysis.

The bow flare impact characteristics and structural response of container ships are studied by Chen and Xiao (2010). Occurrence probability, significant and extreme value of impact pressure is predicted for the ship sailing with different speeds and within different sea states. The pressure distribution on the bow side region is analysed including the effect of speed and sea states. These impact pressures were applied to FE models to determine the stresses in the structure.

Mortola *et al.* (2011) studied a two dimensional nonlinear strip theory for the sea keeping analysis under large amplitude waves. The nonlinear system of equations of motion is numerically solved via a fourth order Runge-Kutta method. The proposed method is applied to the S-175 Container ship and the results are compared with the predictions for small amplitude waves obtained from the results published by other researchers.

Drummen *et al.* (2009a) presented an experimental and numerical study of container ship responses in severe head seas. Experimental results were obtained using a flexible model of a new container ship design. The experiments showed that, taking hull flexibility into account, the fourth and sixth harmonic of the vertical bending moments had a maximum value of between 25 % and 50 % of the first harmonic. The authors also demonstrated that hull flexibility can increase the vertical bending moment by up to 35 % in sea states relevant for design. Miyake *et al.* (2008) conducted experimental studies on the hydroelastic response, including the effects of whipping and springing, and hull structural strength of mega-container ships using a modified Wigley model with the elastic backbone having the rigidity equal to that of a 12,000 TEU container ship in regular waves. During tank tests, the authors observed the occurrence of the

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superharmonic springing resonance. Experimental results were used to validate a 3-D Rankine source method capable of analysing springing.

The coefficient of contribution method, in which the extreme response is determined by considering only the few most important sea states, is an efficient way to estimate nonlinear long-term load analyses. To efficiently find the nonlinear short-term probability distributions of the vessel responses in these sea states, response conditioned wave methods can be used. Drummen *et al.* (2009b) investigated the accuracy by comparing the short-term probability distributions obtained from random irregular waves with those from response conditioned waves. The authors also discussed how response conditioned wave methods can be integrated into a long-term response analysis. The focus was on the probability distributions of the midship vertical hogging bending moments in the sea states contributing most to the hogging moments with a mean return period of 20 years and 10,000 years. The authors concluded that the response conditioned wave methods can be used to accurately determine the nonlinear short-term probability distributions for rigid hulls, but either accuracy or efficiency is to a large effect lost for flexible hulls, when slamming induced whipping responses are accounted for.

7 OFFSHORE STRUCTURES

The offshore oil and gas technology is moving to deep and ultra deep water. The demand for FPSOs has increased significantly in recent years. For FPSO conversions rather than new builds, which offer significant economic benefits for operations in benign environments, determining the remaining fatigue life of the structure is an important consideration. Similarly, for drilling and exploitation in deep water, the semi-submersible drilling platforms show a series of advantages in performance and as such they are dominating offshore installations for oil and gas exploitation in deep water. Among these kinds of units, the early 21st century design, sixth-generation semi-submersible drilling platforms, capable of operating in deep waters up to 3,000 m, is becoming dominant in the industry. Also, fatigue has been the determining design factor for tubular joints commonly used in fixed offshore platforms. Thus, there is a significant body of research in the area of fatigue available in the literature. Finally, recent studies in the area of uncertainty in risk and reliability assessment of offshore structures are reviewed.

7.1 Design Trends, Developments and Challenges

Quasi-static push-over analysis is used to evaluate the maximum quasi-static load that a fixed offshore structure can withstand. The quasi-static approach idealises the dynamic nature of wave forces acting on the structure. Memarpour *et al.* (2009) compared quasi-static and dynamic methods in measuring the ability of an offshore structure to resist loads that exceed design values. Wind, wave and current loads were applied quasi-statically by gradually increasing the magnitude of the loads until collapse of the structure. In the dynamic analysis, cyclic wave loads and monotonic wind and current loads were applied in phases to represent a storm. For the offshore platform studied by the authors, the quasi-static analysis resulted in a higher ultimate strength than the dynamic analysis.

Jacket platforms in the Bohai Gulf are often victims of random ice induced vibrations. Liu *et al.* (2009) presented a study where two different approaches, namely: the failure probability-based approach and the expected loss-based approach, were considered to determine the short-term dynamic ice cases for dynamic analysis of ice-resistant

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jacket platform in the Bohai Gulf. Considering the variation in the ice environments and the variability of ice-resistant structure's properties, the random ice spectrum and the pseudo-excitation method (PEM) are employed to improve the efficiency of the procedure. Pushover analysis was also adopted for the study of jackup platform seismic behaviour under earthquake loads for different working conditions (Jin and Liu, 2010). Comparison between structural capacity spectra obtained from dynamic time history analysis method and pushover analysis method verified the validity of the pushover analysis method.

Research on strength analysis of a semi-submersible platform was presented by Li *et al.* (2011a). The authors demonstrated that a beam model to carry global strength analysis of semi-submersible platform yields the same result using combined shell/beam model. Thus, they argued that beam model to the estimation of the strength of the whole structure at basic design stage for rapid and efficient solution can be adopted.

Kumar *et al.* (2010) presented a review study on the installation engineering of topside modules on ship shaped offshore floating structures. The study covers the investigation of governing technical parameters for heavy lifting, followed by installation phase and hull integration covering necessary structural modifications to deck structure. The interrelationships amongst a number of key parameters/aspects of installation process of a topside module such as weight control, heavy lifting and rigging, local FEM analysis of lifting points and members, installation tolerance and design of fine guides, are studied.

Elshafey *et al.* (2009) presented a study where the response of a scale model of a jacket offshore structure was investigated both theoretically and experimentally. The effects of varying the structure's weight, and the characteristics of the wave loading were investigated. Excellent agreement between the experimental and theoretical results was obtained. Elshafey *et al.* (2010) investigated the damage detection in offshore jacket platforms subjected to random loads using a combined method of random decrement signature and neural networks. The random decrement technique is used to extract the free decay of the structure from its online response while in service. The free decay and its time derivative are used as input for a neural network. The output of the neural network is used as an index for damage detection. Early damage detection can be achieved by observing changes taking place in the signature, thus, preventing the occurrence of unpredicted structural damage. The authors used only the random decrement corresponding to the fundamental natural frequency as the method is most effective in identifying damage occurring in members which most influence the fundamental natural frequency of the structure. It was suggested that the methodology introduced can be used in conjunction with traditional inspection techniques to reduce the overall inspection costs.

The module stool is a key structure to link the module and the deck in floating production, storage and off-loading (FPSO). The welded joints of the module stool should be guaranteed to possess enough toughness against cracking and rupture. A paper by Miao *et al.* (2010) describes the testing and approval of welding procedure for a low temperature (-18° C) crack tip opening displacement (CTOD) test on the weld centre and the fusion line of the module stool of a large FPSO, to be used in the Bohai offshore oil field.

Before a jack-up can operate at a given location, a site-specific assessment of its ability to withstand a design storm during operation must be performed. During this

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assessment, the complex state of stress and strain under a spudcan is usually simplified to a value of foundation stiffness that is integrated as a boundary condition into the structural analysis. Soil stiffness is a critical parameter affecting the foundation and structural load distribution and displacements, and hence determining the jack-up natural period and dynamic response. The level of spudcan stiffness is an area of intense interest and debate. Cassidy *et al.* (2010) investigated appropriate stiffness levels for numerical simulation. Utilising results from a detailed "pushover" experiment of a three-legged model jack-up on dense sand, the authors compared the experimental pushover loads and displacements on the jack-up and spudcans to numerical simulations using different assumptions of spudcan stiffness. Constant stiffness levels are shown to be inadequate in simulating the experimental pushover test.

Baarholm *et al.* (2010) presented a study for predicting design response of offshore platforms by combining contours of significant wave height and peak period together with platform response distributions. To aid their research, the authors carried out model tests on Troll A platform with increased topside weight at Marintek. A comprehensive analysis program, including model test and numerical calculations, were carried out by the authors in order to establish a reliable set of design loads for the modified platform. The study revealed a need for verification of the applied percentile level for the design loads and suggested the necessary steps for the verification process.

Alati *et al.* (2011) focused on the comparative fatigue analysis pursued on typical tripod and jacket support structures for offshore wind turbines located in Mediterranean area. The theoretical basis has led to simplified methods. The method demonstrating how to compute the separate wind and wave responses while still accounting for the inherent, mutual interaction between aerodynamic loading and hydrodynamic response.

Shao (2010) investigated the fatigue life of welded tubular joints in offshore platforms by the magnitude and distribution of the hot spot stress. The number of fatigue loading cycles for a tubular joint sustained before failure is determined by the magnitude of the hot spot stress whereas the initiation position and the propagation direction of the surface crack are determined by the location of the hot spot stress. The hot spot stress distribution along the weld toe for a tubular X-joint subjected to axial loads is analysed using finite element method. The effect of geometrical parameters on the magnitude and the distribution of the hot spot stress were investigated through consideration of 112 X-joint models.

Notaro *et al.* (2011) focused on bow impact scenarios when the OSV hits and penetrates into the FPSO side shell. The variation of energy absorption and damage extent has been studied as a function of different physical parameters. The detailed model of the midship area of FPSO has been created in ABAQUS and was impacted by OSV which was considered as a rigid body. The study showed that likely collision scenarios for OSV's operating close to a FPSO may lead to penetration and rupture of the side shell. This may be critical for single skin vessels with respect to environmental consequences.

7.2 Uncertainty, Risk and Reliability in Offshore Structural Analysis

Connecting advanced structural and reliability analyses can improve the structural design process which results in the development of efficient systems. Reid (2009) illustrated aspects of 'realistic' reliability assessments for bridges that are applicable to offshore structures. The differences and implications of using 'notional', 'realistic' and 'actuarial' failure probabilities were discussed. Notional probabilities are ascertained from a reference set of modelling assumptions and are used to calibrate codes

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to accepted standards, but are not necessarily accurate for failure probability. In comparison, the modelling assumptions used to form realistic probabilities align with realistic assessments of actual structural behaviour. However, Reid (2009) advises that risk-based optimisation should be based on actuarial probabilities, which are based on probabilistic models validated with failure observations of a group of structures.

Karadeniz *et al.* (2010) presented a calculation system of integrated algorithms for the reliability based optimisation of the offshore jacket structure. The methodology is composed of a structural analysis package (SAPOS), a reliability analysis program based on the first-order reliability method and an optimisation program based on sequential quadratic programming using the International Mathematics and Statistics Library.

Reliability assessment on mooring system of deepwater platform in catastrophic ocean environment was presented by Chen *et al.* (2010). A probabilistic model of breaking strength is developed for a mooring chain.

8 CONCLUSIONS AND RECOMMENDATIONS

The committee reviewed recent works concerning topics identified by the committee mandate. A summary of current publications relevant to quasi-static analysis methods applied to ship structures was presented. The summary included strength assessment approaches, calculation procedures, composites, ship structures, and offshore structures.

From the review of the recently published literature, the committee members' observation was that nowadays whenever a problem or question arises that involves dynamics, the standard procedure is to either seek an answer from existing quasi-static references such as papers published by Paik and other readily available sources or to use any one of the many available finite element programs that have full dynamics capabilities, thereby avoiding the approximations and uncertainties that arise when modelling a dynamic problem quasi-statically. This is viewed as a very positive situation by the Committee. Researchers have developed the methods and tools needed to deal with dynamic problems over many years, and they are now readily available to anyone needing them. However, this does not mean that there are no further questions to resolve about quasi-static modelling; there are many.

The review included quasi-static modelling of a dynamic problem with reference to loads and response. In particular, references were made to ice loads and collision loads and the linearisation/simplification approaches to determine the corresponding responses.

Recent studies on calculation procedures for wave loads, fluid-structure interaction, and modelling were discussed. An attempt to approximate a dynamic wave load case as quasi-static was identified. Consideration of structures as coupled to the surrounding flow has led to theoretical and computation modelling of flexible panels and SPH methods. Approaches to model non-linear stiffened structures and composite behaviour were also reviewed in the literature.

Recent research studies on advance structural modelling and analysis techniques for evaluation of yielding, buckling fatigue and ultimate strength capacity of the structures are discussed. Current research on compressive buckling strength is focused on determination of ultimate strength behaviour of unstiffened and stiffened panels under axial compression, lateral pressures and plate bending. Ultimate strength behaviour of plates with large openings is discussed. Fatigue and ultimate strength assessments

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of deteriorated (corroded) structures are found to be the focus areas of the current research.

Finite element modelling has been used to simulate the structural response of a range of ship structures, from single sandwich panels through to partial or full ship models. Maritime applications of FE analysis included failure prediction (buckling, fatigue, ultimate and residual strength) of steel, aluminium and composite structures, comparison of computational analysis to test and full scale trial data. FE analysis was often utilised as a tool in a systematic procedure, such as for determining material or damage behaviour for use in another analysis.

In the realm of ship structures, issues related to design, maintenance and monitoring, and classification society rules have been presented in the literature. The requirement for safer and more durable naval structures has been increasingly recognised. Within design development, particular areas of research included designing fatigue optimised shapes, the effect of high waves from large ships on nearby structures, and the choice of hull-forms and materials for naval operations as well as for passenger ferries. The uncertainties associated with the reliability based quasi-static assessment of ship structures are discussed for intact and damaged ships. Of concern to ship maintenance and realisation of efficient systems, corrosion modelling, structural health monitoring, and reliability assessments have been identified as important themes.

Recent works on steel sandwich panels covering aspects such as bending and shear characteristics of laser-welded sandwich panels, structural optimisation, and ultimate strength have been reviewed. The modelling issues related to the interaction between the sandwich panels and the girder system, are also reviewed. In recent years, there has been a significant emphasis placed on understanding the behaviour of composites used in the maritime industry. The fire structural response of polymer composites and crashworthiness of sandwich structures have received particular attention. The review included response analysis of various applications such as composite propellers, composite patches on naval steel vessels, composite panels with holes, etc.

The current developments in areas of Green Shipping, Energy Efficiency Design Index, Cleaner Alternative propulsion, safer ships, Northern Sea Route and Panama Canal Expansion are reviewed. As the effects of global warming are becoming more recognised by the industrial nations combined with the depletion of fossil fuels, the efforts to reduce green house gas emissions are increased. LNG as fuel onboard is a promising technology amongst the near term green shipping technologies. However, there are some storage, safety and operational concerns using LNG as fuel which will impact on ship design. Also, it appears that the industry has some concerns that LNG does not reduce CO_2 emissions on a like-for-like basis with other fossil fuels when carbon foot print from well to flue emissions is considered due to release of methane from shale-gas production.

A comprehensive review of passenger vessels and container vessels in relation to quasi-static response evaluation has been provided. The experience database collected by the maritime industry is challenged by larger ships and new trades. The size of container vessels and passenger vessels increased dramatically and the committee focused on and reviewed recent works concerning strength and analysis methods.

Review on the offshore structures included analysis of fixed offshore structures under ice loads and design storm loads, and the push-over analysis, analysis of topside modules securing arrangements to deck on FPSOs, fatigue analysis of support structures for offshore wind farms, etc. Review of the offshore structures reliability analyses is

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also included. The quasi-static push-over analysis of offshore structures resulted in a higher ultimate strength than the dynamic analysis. The study on the collision analysis between offshore support vessel (OSV) and FPSO indicated that the collision may lead to rupture of the side shell of FPSO which may be critical for single skin FPSO in relation to environmental consequences.

Future recommendations of topics for review are:

- Interconnectivity and model exchange bi-directionally between 3-D product models and FE models
- Advance methods for mesh generation of FE models
- New FE techniques
- Advance methods to account for corrosion and fatigue in assessing structural strength
- Reliability based inspection and maintenance and life-cycle design concepts
- Development of new rules and regulations by regulatory bodies
- Impact of technologies to reduce greenhouse gas emissions on structural design
- Structural aspects of specialised ships
- Structural aspects of offshore structures

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