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Volume 1

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 quantification of quasi-static load and response analysis approaches, and their limitations, including exact and approximate methods for derivation of different acceptance criteria.

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KEYWORDS

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CONTENTS

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1. INTRODUCTION

In the design of ship and offshore structures, Naval Architects and Structural Engineers require access to a wide range of analysis methods to successfully progress from concept brief through to a production ready design, that will safely operate for the duration of its service life.

Significant development in computational analysis techniques have occurred over the preceding decades, coupled with increased availability of high-performance computing; however, computationally intensive methods regularly do not fit the requirements of a design team, particularly in the early design phases. Whilst some quasi-static methods may have arisen at times of lesser computational capabilities, quasi-static analysis methods remain relevant, providing an appropriate balance between accuracy and speed, often having an ability to provide a quick result based on minimal input data, facilitating rapid design iteration.

In ship and offshore structures, the loading, whether local or global, is predominantly caused by a dynamic motion that is cyclic or oscillating, for example the wave loading of a ship hull girder in a seaway, the sloshing loading due to the motions of fluid in a tank, the loading on a deck or equipment foundation, etc. True dynamic analysis of such scenarios is complex and time consuming to undertake, and often can't be successfully completed until the structural design details are in a progressed state. Therefore, quasi-static methods implementing a simplified approach that resembles the scenario, whether through a defined loading or to induce a seemingly equivalent structural response, have been developed. Not all loading scenarios can be suitably represented by quasi-static methods, particularly where loading is complex or structural response of the individual parts of the system may interact. However, where a quasi-static method can be implemented to develop a structure with sufficient reserve to facilitate safe operation, the benefits to the design process can be significant.

In structural response analysis, a method may be considered to be quasi-static where the effects of structural dynamics (structural inertia and damping) may be neglected. In this regards the time component, or time derivatives, may be neglected. To adopt a quasi-static method, the true time dependant loading must be sufficiently slow in relation to the structural response not to coincide with resonant response frequencies. Due to this 'slow' progression, during analysis the system may be considered to be in static equilibrium at all time instances.

These points are true for many quasi-static analyses, where loading may be through incremental application of force or displacement to a structure, and static equilibrium of the system is achieved before the next increment is applied. Therefore, time associated with the loading is only implied and not explicitly included in the assessment. In other words, the structural responses at any time instant will be only determined by the loads at that time instant, and the structural responses have no memory effect.

Whilst the applied loading may be incremental, it need not be entirely linear, and in the same regard the structural response also need not be linear. For example, the loading and response could be coupled, such that as the structure deforms the load is iterated to reflect the new state of the system. However, in the application of quasi-static methods, the relative accuracy and therefore suitability of the method should always be considered.

Quasi-static analysis covers a broad spectrum of methods from hand calculations to finite element analysis (FEA) and may even combine methods such as computational fluid dynamics (CFD). The methods may be used directly for structural assessment, or as part of broader method, such as the input to a reliability analysis or optimisation routine, or to derive a peak stress or stress sequence for fatigue assessment. For this reason, there may be perceived overlap between this and other ISSC committees. However, this committee has specifically focussed the presented report around methods that are quasi-static in nature, including where the topics, such as fatigue, ultimate and accidental limit states, that are covered in depth from a different perspective by other ISSC Technical Committees.

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1.1 Committee mandate

The mandate for committee II-1 has remained largely unchanged for several terms (for example ISSC 2015a & ISSC 2018a). However, for this term minor changes have been made. The revised mandate has removed the specific reference to "stress" as the acceptance criteria to not limit consideration of other serviceability limit states. "Load" was introduced to recognise that the application of loading in quasi-static methods was specifically covered by previous reports of the committee, because quasi-static methods may relate to the principle of loading, structural response, or both. Finally, specific reference to reliability methods was removed to not limit the focus of the mandate and consider other methods where a quasi-static approach may form part of the approach, for example in optimisation.

1.2 Committee report overview

ISSC Technical Committee II.1 has presented reviews of various strength assessment approaches with a focus on topics covering simplified analysis and direct calculation methods, as well as methods utilising quasi-static approaches within their process, such as within optimisation or reliability methods. The previous report by ISSC Technical Committee II.1 (ISSC 2018a) presented a comprehensive review of the use of quasi-static methods within reliability analysis. Subsequently this committee presents further consideration in relation to the influence of uncertainties within the quasi-static method and its suitability or influence resulting from use within methods such as reliability analysis.

Chapters 2 to 4 are the core chapters of the report with reference to the committee's mandate. Chapter 2 presents load modelling, considering anticipated operational, or design, loads as well as accidental loads. Chapter 3 and Chapter 4 present assessment of the structural response, divided between deterministic, partial safety factor or load and resistance factor design (LRFD) approaches in Chapter 3 and limit state assessment in Chapter 4.

In conjunction with the committee's mandate, Chapter 5 presents a review of developments in quasi-static approaches by Classification Societies.

Recognising the broad use of quasi-static methods, whether directly in design assessments or as the basis of methods such as reliability assessments, optimisation studies, etc. the committee undertook a review of uncertainties within quasi-static methods to provide context to the suitability of their use. This review is presented in Chapter 6.

The report is concluded in Chapter 7 with notes on the developments seen within the reporting period.

Throughout the report the recommendations and views presented by the previous committee (ISSC 2018a) and the Official Discusser (ISSC 2018b) have been considered as discussed throughout the report.

2. LOAD MODELLING

Quasi-static load modelling is an important basis for the design of ships and offshore structures. Evaluation of the loads during life-time operations is critical for the structural safety assessment. This chapter outlines the advancing of quasi-static methods for load characterising and modelling techniques. Environmental loads due to wind, waves and current are often stochastic and have many frequency components. In that sense, load in nature is time varying, but can be equivalent to load values without time dimension i.e., quasi-static. That means, if the load frequency is much smaller than the lowest natural frequency of the system responses (motions or vibrations), such load will not induce a dynamic effect on the system's responses; therefore, it can be considered as quasi-static load. In general, quasi-static loads can be divided into two major categories of operational loads and accidental loads. Operational, or design, loads are typically loads that are derived from the intended routine operations of a structure, including lifetime considerations for the occurrence of loads based on the expected operational scenario. Accidental loads are attributed to accidents such as collision/grounding and fire/explosion. This

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chapter also outlines research on items such as load combinations and load measurement from full scale and model scale tests.

2.1 Operational/design loads

This section summarises the various types of operational, or design, loads and the research efforts conducted since the committee's last ISSC report (ISSC 2018a). Operational/design loads can be defined as the loads that a structure is typically expected to encounter in routine operations during its lifetime, considering the statistical methodologies for factoring the occurrence of each load component and providing safety mechanisms via probabilities of non-exceedance and appropriate reserve factors.

2.1.1 Wave loads and extreme wave loads

Single body wave load

Recent research about wave loads on ships under single-body assumptions for hydrodynamics are focused on nonlinear hydroelastic and nonlinear wave load models. The growth in size of hull is a tendency for economic profits that may result in serious whipping and springing phenomenon that can increase both the ultimate load and fatigue load on the hull structure. The hydroelastic motion and load of a large flexible ship sailing in irregular seaways are predicted and the hull girder ultimate strength is subsequently evaluated by Jiao et al. (2019a) with a three-dimensional time-domain nonlinear hydroelasticity theory where the included nonlinearities are those arising from incident wave force, hydrostatic restoring force and slamming loads. A numerical wave load prediction method is validated by small-scale model test and large-scale model sea trial and the difference between ship motions and loads in long-crested and short-crested irregular extreme waves is experimentally identified (Jiao et al 2019b). The evaluation of extreme events in waves (such as slamming, green water, air-gap exceedance) still requires a combination of experiments and different levels of numerical tools (Jiao et al 2019c). Essen et al. (2020) have worked to improve experimental and numerical wave modelling and especially their combination to be able to reproduce any wave condition from a basin or from sea in numerical tools and vice versa, including a sound treatment of basin effects, numerical effects and statistical variability. A number of extreme waves are generated by changing their wave height to simulate an extreme ocean wave and the relationship between structural response and wave height is analysed. Acanfora and Rizzuto (2019) have predicted inertial loads in time domain on a drifting ship in irregular beam waves. It is found that the inertial loads can be considered as a stationary process by using linear modelling and is dominated by synchronous roll resonance phenomena. On the contrary, the non-stationary property of the roll phenomena is revealed by non-linear models due to the effect of non-linearity.

Multiple bodies wave loads

Efficient estimation of wave interactions between multiple floating bodies (diffraction forces and radiation coefficients) is of importance to many applications. Xie and Iglesias (2019) have conducted an experimental study of wave loads on a small vehicle in close proximity to a large vessel. It is found that the effect of the hydrodynamic interaction on the wave loads on the lifeboat model is substantial and the load responses show a strong non-linearity. In head waves, the effect of the hydrodynamic interaction on the wave loads is greater in the transverse modes than in the longitudinal modes. Ning et al. (2019) have studied on wave response at the gap between two barges of different draught with experimental and numerical method. It is found that the equivalent viscous effect is determined not only by the relative barge draughts but also by the propagating direction of incident waves. To address the computational complexity dramatically increasing with large number of bodies in the wave, Zhang, J. et al. (2020c) have developed a data-driven surrogate modelling implementation that is an innovative application of the many-body expansion principle, based on combinatorial techniques such as the principle of inclusion and exclusion, to overcome the curse of dimensionality for the surrogate model development. Instead of using a single surrogate model to predict the hydrodynamic

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characteristics, multiple surrogate models corresponding to clusters with fewer bodies are employed. These lower-order surrogate models can be developed at a substantially smaller computational cost, especially for the first terms of the many-body expansion that contribute dominantly to the total hydrodynamic characteristics. Chen et al. (2019b) have investigated the responses of a high-speed trimaran. A three-dimensional hydroelastic method in oblique irregular waves is developed, in which the nonlinear hydrostatic restoring force caused by instantaneous wetted surface and slamming force are considered. In contrast to monohull ships, the load responses at transverse sections near the stern are significantly larger because of the arrangement of side hulls at stern. Nguyen et al. (2018) have investigated the hydrodynamic force acting on ship hull and rudder in various wave directions by experiment. It is found that the lift force in various wave directions changed dramatically when the rudder turned to different angles.

Extreme wave load

Extreme wave load is predicted with the machine learning method and an artificial neural network has been developed by Ahn et al. (2021) to mine a database of the sloshing model tests for various cargo holds, vessels, environmental conditions, operational conditions, and experimental conditions. The database was organized, cleaned, and analysed and was used for the machine learning to predict the model test results from the test conditions. Many different types of parameters were scaled and transformed as the input attributes followed by the optimisation of the hyperparameters and the architecture. The prediction results were validated according to the changes in the environmental conditions, operational conditions, and model dimensions and the accuracy was acceptable to be applicable to the designing perspective. Xu et al. (2020) have used FAST code, an aero-hydro-servo-elasto dynamic modelling tool, to analyse offshore wind turbine internal bending moments due to environmental hydrodynamic wave loads, acting on a specific floating offshore wind turbine (FOWT) under actual local sea conditions. A computationally efficient Monte Carlo based methodology for estimating extreme load or response statistics, based on simulations or measurements and an averaged conditional exceedance rate (ACER) method is proposed. Suja-Thauvin et al. (2017) presented experimental data from MARIN on a bottom-fixed offshore wind turbine mounted on a monopile in intermediate water depth subjected to severe irregular wave conditions. The quasi-static response accounts for between 40 and 50% of the total load, the 1st mode response between 30 and 40%, and the 2nd mode response up to 20%.

2.1.2 Wind loads

Wind load is important to ships and offshore structures, especially to the ship wind-assisted propulsion system (SWAP) and FOWTs. Kareem et al. (2019) proposes a generalised wind loading chain to describe a complete relationship among wind, force, and response induced by non-stationary wind events such as tropical storms or downbursts to complement the Davenport wind loading chain (Davenport 1961), which was proposed for synoptic winds and primarily focused on stationary winds. Specifically, the five chain components of the fluctuating wind in the Davenport's chain such as gustiness of wind, aerodynamic transfer/admittance, aerodynamic force, structural transfer/admittance, and response statistics are recast as time-dependent counterparts in the time-frequency domain to capture non-stationary winds effects on structures. Berto et al. (2019) have reported the SNAME OC-8 comparative wind load study. The most significant finding is the remarkably low variability in wind tunnel and CFD results relative to the empirical U.S. Code of Federal Regulations (CFR), classification rules, and industry codes for stability calculations. Moreover, only wind tunnel and CFD results were able to accurately quantify the contribution of a lifting force and its effect on the overturning moment. Cheng et al. (2019a) have established a numerical model for fully coupled aero-hydrodynamic analysis of floating offshore wind turbine, in which the unsteady actuator line model (UALM) is introduced for the aerodynamic simulation of wind turbine, while the hydrodynamic computation of floating platform is carried out with a two-phase CFD solver. Cho. et al. (2018) set up a method to estimate the wind and current load on offshore structures using wind tunnels and

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CFD. It is found that the flow field such as velocity profiles and turbulence is major parameter and model setup, and test condition must be described as accurate as possible.

2.1.3 Ice loads

Ice load characteristics

It is well known that when a ship sails in ice-covered regions, the ship-ice interaction process is complex and the associated ice loads on the hull is a stochastic process. Therefore, statistical models and methods should be applied to describe the ice load process. Chai et al. (2018a) presents a novel method for estimating the extreme ice loads which is directly related to the reliability of the vessel. The basic idea for the ACER approach lies in the fact that a sequence of nonparametric distribution functions were constructed in order to approximate the extreme value distribution of the collected time history. For setting up a risk-based design assessment, a new approach is proposed based on a probabilistic framework for modelling loads from individual high-pressure zones acting on local and global areas derived from field measurements by Taylor et al. (2019). Loads from plane ice can be the governing design condition for ice breaker. Ice loading process is essential to understand the mechanics of ice loads. Ice forces are corresponded with ice loading process on the horizontal plane through a series of tests in an ice tank by Zhou et al. (2018a) and a new method is proposed to decompose different ice force components from the total ice forces measured in the model tests. The ice loads acting on a ship are closely related to the failure modes of sea ice. When dealing with the ice failure mechanisms, dynamic effect can be considered if ice is also modelled for example using a finite element method. Otherwise, such failure can be modelled using failure criteria based on quasi-static approaches or empirical formulae, without considering the dynamics of drifting ice and broken ice. The discrete element method (DEM) is adopted by Long et al. (2020) to simulate the ice failure modes and ice loads during the interaction between sea ice and conical structure. It is found a bending failure occurs when the sea ice interacts on the conical structure, and the sea ice breaks into many fragments with different breaking lengths. The ice breaking length increases with the increase of ice thickness. The increase of ice velocity and cone diameter can lead to the change of sea ice failure mode, which can reduce the breaking length of sea ice and increase the ice load. Loads from broken ice can be a key to the north route voyage ship. A numerical simulation of an ice going ship navigating through broken ice field was carried out using the coupled Eulerian-Lagrangian (CEL) finite element method by Kim et al. (2019b). Ice floes with random distributions of size, thickness and shape were modelled, and an efficient numerical simulation method for ice-sea, ice-structure, and ice-ice interactions was proposed for rapid computation. In order to obtain a better understanding of the physical phenomena behind the peak ice load events in shallow water, Lemstrom et al. (2020) have analysed the probability of rubble pile grounding, the rubble pile geometries, and the load transmission from the intact ice sheet to the structure through the ice rubble pile with a two-dimensional combined finite-discrete element method. The parameter effects and the probability and severity of ice encroachment in shallow and deep water are investigated and shown that an interaction process in shallow water may lead to higher peak ice load magnitudes than an interaction process in deep water.

Ice structure interaction

A meshfree method called peridynamics is applied to simulate the progress of interaction between ship and ice (Wang et al. 2018b and Liu et al. 2018d). The uniform time differential and spatial integral equations were used in peridynamics. Crack generation and propagation are obtained naturally without setting extra criteria for crack extension, pre–existing crack routes, or crack branching.

To help naval architects make better-informed decisions in the design of Arctic ships, and to support progress towards goal-based design, Idrissova (2019) analysed the effect of the assumptions behind the Popov Method that is based on the principle of the conservation of momentum and energy in collisions by comparing ice load predictions with corresponding full-scale ice

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load measurements and find that assumptions concerning the modelling of the ship–ice collision scenario, the ship–ice contact geometry and the ice conditions significantly affect the ice load prediction. Ship hull in level ice condition is essential to ice breaking ship. Zhou et al. (2018b) and Zhang et al. (2020a) propose simplified numerical model to predict ice impact force acting on the ship hull in level ice condition respectively. Both ice breaking process and ice accumulation process are included in the numerical model based on physical observation, both bending and crushing failures are considered to calculate ice breaking force during ice interaction process.

2.1.4 Sloshing and slamming loads

Sloshing

Structural assessment of ship structure and the cargo containment system (CCS) under sloshing loads was reviewed in Malenica et al. (2017) for membrane type LNG floaters. The conclusion is that the problem is still open and many steps in the overall structural assessment procedure need improvements. So far only the approximate solutions are in use, and they are based on combined use of numerical methods, small scale model tests and the engineering judgment. The current procedure consists of three main steps: determination of the representative sloshing motions, evaluation of the long-term statistics of the sloshing pressures and the evaluation of the structural response. The first step requires the solution of the coupled seakeeping and sloshing motion problem which can be solved using either the relatively simple linear potential flow modelling of sloshing or using the more complex CFD methods. Recent work on the subject includes Li. et al. (2018d), Saripilli & Sen (2017), Li et al.(2019a), Du et al. (2019) and others. Once the ship/tank motions are determined the detailed sloshing analysis need to be conducted either by the small-scale experiments or by the numerical CFD tools. Both methods have significant drawbacks: model tests suffer from scale effects and the CFD methods suffer from numerical inaccuracies when evaluating the local pressure. When dealing with the sloshing loads the distinction need to be made between the hull structure and the cargo containment system. Hull structural response is usually evaluated by the quasi-static hydro-structural approach using the averaged sloshing pressure loads. The CCS being in direct contact with the liquid the localised impact pressures need to be accounted for, when evaluating the structural integrity of CCS. Due to their impulsive character with extreme maximum values associated with the short duration and short spatial extent, the fully coupled hydroelastic simulations need to be employed. These fully coupled numerical methods are still not fully reliable especially in 3D, even if some progress has been made in recent years (Zhang et al. 2020, Wu 2020, Malenica et al. 2021). That is why the approximate engineering methods are usually employed in practice. One of those methods is the so-called comparative approach which consists in comparing the loading and capacity of the new design with the reference ship which has never sustained critical damage due to sloshing impact loads.

Slamming

The problem of slamming is similar to sloshing in many ways. Both problems are governed by the physics of strong hydrodynamic impact which occur either when the liquid hits the structure (sloshing) or when structure hits the liquid (slamming). From physical point of view only the relative geometry and relative velocity before impact matters so that the same modelling principles, and the modelling difficulties, are valid for both sloshing and slamming. However, slamming appears bit simpler because the impacted structure (hull) is much simpler than in case of sloshing where the cargo containment system (CCS) has very complex structural properties. At the same time the determination of the characteristic design impact conditions also appears to be simpler in the case of slamming and the so-called equivalent design waves (EDW) can be defined. These design waves being of short duration the coupled CFD-FEM (Finite Element Method) simulations becomes possible as discussed in Gatin (2019) where the problem of green water was considered (the same principles are valid for slamming). Different possibilities for

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design waves definition were investigated going from simple regular design wave to more complex response conditioned design wave train (RCW).

In many cases the experimental campaigns are used to evaluate the slamming loads. An experimental investigation of the characteristics of the slamming impact loads on the bow of a ship-type Floating Production Storage and Offloading (FPSO) vessel under breaking and irregular wave conditions was conducted by Ha et al. (2021). Two types of slamming impact loads were identified, and damping was also observed in the slamming impact load with two peaks. Irregular wave tests conducted under oblique wave conditions were further used to investigate the characteristics of the slamming impact loads, and the velocities of the directional sway and roll motions were found to be significant determinants of the slamming impact load.

Recently, slamming received more attention in the context of the wind turbine foundations where some interesting experiments were conducted. Paulsen et al. (2019) investigate the probability of wave slamming and the magnitude of slamming loads on offshore wind turbine foundations. The effect of wave slamming is analysed for a monopile wind turbine foundation. A simple closed form expression for the probability of wave slamming is presented. Manjula and Sannasiraj (2019) investigate the response of the slender vertical cylinder subjected to breaking wave impact by experiment. An empirical relation is established between total impact force and the wave steepness parameter which dictates the intensity of the breaking.

On numerical modelling side some progress was also made recently. Yu, P. et al. (2019) conduct a hydroelastic analysis on water entry of a constant-velocity wedge with stiffened panels. A semi-analytical hydrodynamic impact theory is expanded to perform the hydroelastic analysis and can predict the oscillatory response after flow separation. Numerical uncertainty due to discretization on the Arbitrary Lagrangian-Eulerian (ALE) Finite Element method is investigated by Wang et al.(2021a). The total slamming loads and structural responses on both the rigid and elastic bottom plates are predicted and validated against available experimental data. It is concluded that the uncertainty due to discretization in ALE is not just case-specific, but also parameter specific and a constant Courant-Friedrichs-Lewy CFL number-based refinement are recommended.

Influence of slamming and green water loadings on global ship structural response was investigated in Jiao et al. (2018) where fully coupled 3D time-domain nonlinear hydroelasticity theory was developed. The bow slamming and green water loads acting on the ship in severe regular waves are estimated by the momentum impact method and dam-breaking method respectively.

2.1.5 Turret loads, mooring loads, and towing loads

The turret mooring systems are widely used in FPSO ships. Fully coupled time domain turret/FPSO simulations are conducted by Kim et al. (2020c) using TechnipFMC proprietary software MLTSIM. A multi-body interaction model is developed and analysed, and the bearing connections are modelled with nonlinear springs and frictional damping, and hydrodynamic loads and mechanical coupling loads on the turret are presented. Onishchenko and Marchenko (2019) investigate a mathematical model of the passive floating production units (FPU) turning on a spot under the assumption that the ice cover is described by a rigid-plastic continuum and the high ice loads obtained.

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For determining the forces acting upon wharf structures due to moored ships requires the analysis of a dynamic nonlinear system. A nonlinear static model of an oil tanker in an alongside berth mooring arrangement is adapted by Barros (2018) to a one-degree-of-freedom dynamic model depicting the sway mode, by using numerical time integration algorithms. Sundar et al. (2019) investigates the passing vessel effect and indicate that the mooring hook capacities selected for the environmental loads shall be increased by 25% to cater for the combined effect of passing vessel. A hybrid FE-Boundary Element method is developed to investigate nonlinear interaction between ship waves and slender structures by Cheng et al. (2018). The effects of internal flow and seabed interaction on the dynamic responses of the slender structure also are considered. The coupled analysis results with the combined action due to ship waves as well as wind-generated waves are also presented. To the loads of offshore platforms, a mathematical model associated with wave interaction with a moored floating flexible cylindrical net cage is developed by Mohapatra et al. (2021) based on linear water wave theory. The analytical solution is obtained using Fourier Bessel series solution and least squares approximation method along with matching the velocity and pressure at the fluid structure interfaces. After being validated using experiment results, it is concluded that the analytical model can be used with confidence in the design of a flexible cylindrical net cage for application to offshore aquaculture. Liu et al. (2019c) develop a fully coupled aero-hydro-mooring-elastic tool for floating offshore wind turbines (FOWT). Interactions between the FOWT and fluid flow are also analysed by CFD approach. To increase the horizontal stiffness of asymmetrical mooring system, an optimisation to match the different anchor depth on asymmetrical mooring system is conducted by Qiao et al. (2019). Han et al. (2018) conducted a study on the influence of the mooring angle on the static restoring force and heading of the platform, and the tension uniformity of all mooring lines. An improved Genetic Algorithm (GA) is used to optimise the mooring angle, and the accuracy of the algorithm is enhanced. Lin et al. (2020) applies deep learning to investigate the major driven force on the mooring line tension. A number of environmental conditions are considered and a FOWT model of dynamics was simulated under pre-defined environmental conditions. Results showed that the most loaded mooring line tension was mainly determined by the surge motion. For multi-body condition, the mooring loads are investigated by Lee et al. (2019) and Jung et al. (2018). Numerical and experimental results show that the ship-to-ship mooring safety can be changed according to a ship's cargo loading condition, pre-tension of mooring line, sea depth, encounter angle with the weather, and the weather condition. Yang et al. (2021) presents the experimental results for a 1:50 scaled model of an immersed tunnel element suspended from a twin-barge in tank tests. A compliant four leg catenary mooring system using steel link chains in the physical tests is investigated. The corresponding numerical model is developed to simulate the mooring characteristics. It is found that the maximum mooring load of the tunnel element is significantly affected by the natural frequencies of both the tunnel and twin-barge and the large local peaks in mooring tensions occur at excitation periods of waves close to the tunnel-barge resonance of roll.

To research the influence of towed cable on the motion attitude of the underwater towed body, combined with the specific parameters of a certain underwater towed system, the dynamic simulation of models of towed system during large-radius submarine turn for a constant velocity and in the process of the self-propelled mode of the towed body was established by Zhang et al. (2018a). A tug–cable–barge coupling motion model for bridle towed system is proposed by Sun et al. (2018). The governing equation of towing bridle was established based on finite difference method and the six-degrees-of-freedom equations of motion for tug and barge were adopted according to the Manoeuvring Modelling Group (MMG) modelling theory. Mas-Soler et al. (2021) presents the towing tests of free-float capable tension leg platform supporting a 10 MW wind turbine. The hydrodynamic behaviour of this hull form in calm water and waves is investigated experimentally. It is found that some of the cases display a reduction of average resistance in waves compared to calm water.

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2.2 Accidental loads

Accidental loads, (including collisions and groundings, as well as fire and explosion load) do not occur in routine operation of a ship or offshore platform. Collision and grounding analyses involve global and local dynamics of the structures that are considered in the scenario, which is dealt with a dynamic analysis approach, as well as structural failure mechanisms, which is often treated using a quasi-static approach. Explosion loads are of dynamic property that can also be applied to a structure as quasi-static loads in the form of equivalent pressure, impulse or damage energy with same effect.

2.2.1 Collision and grounding

On the collision load, the probabilistic characteristics must be considered by ship and offshore platform designers. Mujeeb-Ahmed and Paik (2019) propose a new probabilistic method for determining collision design loads. Each input parameter is treated by a probability density function, and a set of 50 prospective collision scenarios is generated using Latin hyper cube sampling (LHS) technique. Numerical computations of ship motions are performed to obtain collision load parameters. The best-fit probability density functions and the exceedance curves are established. Gholipour et al. (2018) investigate the effects of axial load on nonlinear response of reinforced concrete columns subjected to lateral impact load by FEM. It is concluded that the increase of axial load ratio causes the increase of initial peak impact force and the internal forces of the column due to redistribution of the impact load downward in the pier substructure, which leads to the increase of collision intensity, the load severity and shear failures. In order to investigate the influence of stiffeners on the crushing resistance of web girders in ship grounding, Chen et al. (2019a) conduct a series of small-scale test of unstiffened and stiffened web girders by applying local imposed deformations by an indenter. Finite element models are established to calculate the crushing deformations and to analyse the energy absorbing mechanisms. Comparing with the unstiffened web girder, the maximum force measured in the tests increased by 17% and 64% in the stiffened webs with 2 and 3 stiffeners, respectively. Kim et al. (2021) presented a procedure that simulates the influence of strongly coupled fluid-structure interaction (FSI) effects on the dynamic response of ships involved in typical collision and grounding events. The method couples an explicit 6-DoF structural dynamic finite element scheme with a hydrodynamic method based on a Reynolds averaged Navier Stokes (RANS) CFD model. It is confirmed that suitable FSI modelling may be critical for either collision or grounding events primarily because of the influence of hydrodynamic restoring forces. The effects of compressible carried water on the collision characteristics of a hull structure were investigated by Zhang et al. (2021). Collision experiments with a simplified double-layer structure (water tank) were performed, and the corresponding collision process was simulated with the finite-element method. It can be observed that the pressure of the carried water can reduce the displacement of the outer plate and change its deformation shape. The wave loads of a damaged ship is concerned by Li, et al. (2018c) and a Kriging modelling method (Forrester et al. 2008) has been applied for rapid prediction of wave loads for damaged ship with variables of the damaged position, weight added coefficient, ship velocity and wave height. Acanfora and Balsamo (2021) have developed a fast numerical method that exploits different assumptions, in particular on the free surface inclination and on the amount of flooded water in an open-to-sea compartment and capable of modelling the behaviour of a flooded hull in waves.

2.2.2 Fire, explosion and associated secondary loads

Baalisampang et al. (2018) present a detailed review and analysis of fire and explosion accidents that occurred in the maritime transportation industry during 1990–2015. The underlying causes of fire and explosion accidents are identified and analysed. Manco et al. (2021) explore the nonlinear thermomechanical and ultimate strength behaviours obtained by means of two fire approaches that is CFD and Localised Fire with Ellipsoidal Solid Flame (LF-ESF). The proposed LF-ESF approach displays quite accurate thermo load estimates in comparison to

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CFD counterparts. The LF-ESF can be directly modelled in FE-based commercial software and used to obtain the steel temperature variation and thermomechanical behaviour.

A quantitative assessment method for gas explosion loads in process modules of offshore platform is proposed by Shang et al. (2020), including defining a suitable number of leak scenarios quantitatively, defining the explosion scenarios according to dispersion analysis results and designing the explosion loads according to the CFD analysis results and exceedance probability. Xu et al. (2020) introduces an improved method for quantitative risk assessment of unconfined offshore installations subjected to gas explosions. A FPSO is given as an example to present the proposed method. The method for determining the equivalent gas cloud position is illustrated in the conversion between dispersion and explosion scenarios. Maximum and average overpressures are obtained by CFD simulation. And the combination of overpressure and probability method is adopted based on the definition of risk. An experimental and numerical study was undertaken by Bae and Paik (2018) to identify the characteristics of overpressure loads in offshore platform models subject to hydrocarbon explosions, with a focus on the structural congestion and surrounding obstacles. A large-scale (one-half) test model of a FLNG (liquefied natural gas floating production storage and offloading unit) topside structure was used for the experiment. CFD method was used to calculate the overpressure loads in explosions with varying degrees of structural congestion. The overpressure loads tended to be more significant with the increase in structural congestion. The dynamic response of the cargo hold structure of the first Compressed Natural Gas (CNG) carrier under the gas explosion load is studied by Guan et al. (2018). The risk source, source location and leakage amount are determined. The most dangerous condition of the gas explosion load in the hold is obtained.

Though the underwater explosion load is usually more intensive than air explosion, and the load is certainly dynamic, methods have been developed to facilitate a quasi-static approach to structural analysis through calculation of a design load base on the equivalent load. Many papers on dynamic loads and responses of ships to underwater explosion have been presented; however, the presentation of approaches for quasi-static application is seldom found.

2.3 Load combination for response analysis

A similarity theory is proposed by Wang (2019b) to design the scale model for reflecting the progressive collapse behaviours of true ships in ultimate longitudinal bending and torsion loads.

Pile foundations are inevitably subjected to combined vertical-torsional (V-T) loadings in offshore engineering contexts. Zou et al. (2019) propose an analytical method for calculating the V-T response of a single pile in two-layered non-homogeneous soil. It is revealed by use of the method that the loading path (loading sequence) has an effect on load response and deformation. A new finite element model is described by Cao et al. (2020) for monopile-supported offshore wind turbines, including components of soil reactions, wind and wave combinations. This model can simulate the interaction between the large diameter pile and its surrounding soil and reveals more real dynamic responses of offshore wind turbines (OWTs) under stochastic ocean environmental loads. And the effects of wind-wave combination, wind-wave misalignment angle and operational conditions on the structural responses are also investigated. The combination of 90° wind-wave angle and operating condition is found to be the most unfavourable situation.

2.4 Experiments and monitoring

Full-scale test and monitoring

Despite the developments of hydroelasticity and ice-structure interaction methods, the complex phenomena of modelling marine structures are hard to accurately represent by model test or numerical methods; therefore, a full-scale measurement campaign has been considered the most important research to reach a thorough understanding of these complicated physical phenomena. Kim et al. (2018a, 2018b) proposes a data examining method for the full-scale measurement of a large container carrier with a 9400TEU and 13000TEU capacity. Modal parameters

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were examined based upon the measured acceleration data on deck and the evolution of the natural frequencies and damping ratios were also checked and their correlation was explored. The fatigue damage was calculated using the measured strain at deck and the expected long-term fatigue damage was estimated. It is shown that high frequency fatigue damage contributed (hatch corner) by vibration effect was approximately 60% and that by torsion response was not significant during measured voyage period. A novel virtual hull monitoring approach is proposed by Thompson (2020) using full-scale measurements from a naval vessel trial. Stresses calculated using wave hindcast data, ship track information, and stress transfer functions compare favourably to those derived from strain gauge measurements at five structural locations. Wave conditions are represented using a spectrum model along with bulk spectral parameters from hindcast datasets and by reconstructing two-dimensional spectra from hindcast partition data. Both approaches give good agreement with strain measurements but using the more-detailed reconstructed two-dimensional wave spectra yields better results. Results suggest that wave hindcast data are sufficient for accurate structural calculations. After the 2018/19 Antarctic voyage of the S.A. Agulhas II, considerable data of the ship in floe ice fields under various thicknesses, concentrations, and floe sizes are gathered. Li et al. (2021) carry out statistical analysis to seek suitable probability distributions which adequately fit the measured ice load and therefore suitable to be used as parent distributions for long-term estimation. Three categories of probability distributions, namely standard distributions, truncated distributions and mixture distributions are tested. It is found that truncated distributions can fit the load data better than standard distributions bounded at the threshold and mixture distributions are shown to have promising features, which fit the data well and are able to separate distribution components. The estimation results demonstrate that long-term estimations are sensitive to the selection of parent distribution, which addresses the importance of finding correct distribution to model short-term ice loads. As controlled manoeuvring tests were conducted during the ice trials of S.A. Agulhas II in the Baltic Sea, Suominen et al. (2020) have studied the effect of manoeuvres on the characteristics and statistics of ice-induced loading at different hull areas and compared the impact to ahead operations. It is showed that the manoeuvres had minor impact to the magnitude, frequency, and duration of loading at the bow and bow shoulder. But manoeuvres had a clear effect at the stern shoulder and the load magnitude increased as a function of load duration in all hull areas.

For ensuring the structural safety of an icebreaker, the ice load is identified from the strains measured on the frames or plates of the hull along the waterline. The strain sensors are difficult to install at the required locations on the hull because the watertight compartment is cramped. A far-field load identification method is proposed by Kong et al. (2021) to overcome the difficult to install strain sensors at the required locations. To determine the relationship between ice load and ice-induced strains, the least square support vector machine (LS_SVM) method is adopted. A ship-based ice load measurement system installed on icebreaker XueLong is introduced. The experimental application is performed to verify the feasibility of the LS_SVM procedure and establish a full-scale ice load identification model. With this method, the identified ice load is reasonably verified through comparative analysis and case study.

Component and model test technique

According to the structural characteristics of trimaran, structural monitoring and assessment system for multihull is designed and introduced by Tang et al. (2019), and corresponding model test is taken to demonstrate its effectiveness. The self-propelled trimaran model is installed with sensors in different longitudinal positions to monitor the variety of structural responses in irregular waves. And three real-time structural strength assessment methods in the system are used respectively to indicate the structural state about hull longitudinal strength, local yielding strength and fatigue strength.

As offshore wind turbine monopiles increase in diameter, the static load test method becomes increasingly cumbersome to use. A single pile model test under the action of static force and impact was carried out by Wang et al. (2021b). Based on the m-method that measures the

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displacement effect of a load with m value, the dynamic and static transformation relationship of m value in the test was explored, and a new lateral dynamic load test method for offshore piles is proposed. The new method employs the in-situ ship impact impulse test method. The m-value dynamic-static ratio exhibits a quadratic parabolic distribution relative to horizontal displacement and external load. The m value under impact can be converted into the equivalent static m value.

Ice material models often limit the accuracy of ice related simulations. To link experimental data to ice material modelling, where the aim is to identify patterns in the data that can be used by the models, Ehlers et al. (2019) established a common database of ice experiments and using machine learning to understand and predict ice behaviour. Machine learning and statistical tools are applied to identify how parameters, such as temperature, age, region and size, influence peak stress and ice behaviour.

To experimentally examine the effects of passive fire protection application on the fire collapse of steel stiffened plate structures, two full scale transverse frames (primary strength members) of the test structure insulated by Cerawool which is a fire protection material are tested by Paik et al. (2020b) with fire and lateral patch loading. Structural collapse was monitored at discrete time intervals from when the fire started until the test structure entirely collapsed. The effect of fire-protected transverse frames on the structural collapse was investigated by comparison with test results on the structure that was unprotected from the fires. Paik et al. (2020a) present a test data on the ultimate compressive strength characteristics of a full-scale steel stiffened plate structure at cryogenic condition which may be due to unwanted release of liquefied gases. It is observed that the test structure reaches the ultimate limit states triggered by brittle fracture, which is totally different from typical collapse modes at room temperature.

Another important approach in fatigue testing is the crack monitoring in resonance fatigue testing of welded specimens using digital image correlation (DIC) achieved by Friedrich and Ehlers (2019). It is intended as a practical and reproducible procedure to identify macroscopic cracks at an early stage and monitor crack propagation during fatigue tests. By visualizing the crack, the presented procedure allows direct observation of macrocracks from their formation until rupture of the specimen. The procedure is limited to cracks initiating at the surface and is intended for fatigue tests under laboratory conditions. Neuschwander et al. (2018) present an innovative methodology for simultaneous load and structural monitoring of a carbon-fiber-reinforced plastic rudder stock as part of a big commercial vessel using embedded strain sensors. Structural monitoring is based on high-frequency electromechanical impedance spectroscopy combined with dedicated signal processing and surface-mounted piezoelectric transducers. Ali et al. (2021) presented an experimental method based on the sensing of the piezoelectric sensors and finite element analysis method for studying the fatigue cracks in the offshore steel jacket structure including T-type plate, T-type tube-plate, and T-type tube joints. The finite element analysis model is used to compute and analyse the high stress and high strain regions in the T-type joints. The fatigue damage in the T-type joints was successfully detected by utilizing both the finite element analysis and experimental methods. The results showed that fatigue cracks of the three types of joints are prone to appear at the weld toe and spread in the welding direction.

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2.5 Concluding remarks

In this chapter, some of the current research trends in modelling of environmental loads with focus on wave and ice loads, as well as accidental loads, are outlined, from which several concluding remarks are formed. Due to the increasing size of the marine structure and more harsh sea condition, the wave loads are more frequently modelled by nonlinear hydroelastic method for whipping and springing responses. It is found that the recent research focused on the aspects of non-stationary, random and probabilistic characteristics of the wave, wind, current and ice loads. However, some new techniques are introduced to quasi-static load modelling, such as peridynamics which is used for analysis of crack development of ice and marine structure, an improved Genetic Algorithm (GA) that is used to optimise the mooring angle for an offshore platform, machine learning which is applied to identify the ice and wave load parameters from the full-scale voyage measurements data. Full scale measurements of ships in ice-covered regions provide a lot of valuable data for investigating the loading properties and reconstructing real sea load models. On explosion load modelling, rare work was done in equivalence static load of hydrocarbon explosions. On test and monitoring, some new techniques are introduced, such as the least square support vector machine for identify the ice load from strain data, the structural monitoring and assessment system for multihull ship and the DIC method for direct observation of macrocracks from their formation until rupture of the specimen. These technologies are of grand prospect for building up reliable quasi-static load models of marine structure to real sea situations, and the committee hope that research progresses in this direction.

3. STRUCTURAL MODELLING AND RESPONSE ANALYSIS

3.1 Introduction

Significant advances have been made recently in analysing complex ship and offshore structures due to the advent of computational power, development of technology and availability of commercial software. These analyses are generally quite complex and detail in nature, and thus time consuming. As such, in order to have initial design and structural optimisation by efficient means, use of simplified formula based on quasi-static response calculation are not uncommon. Rules of various classification societies are developed based on quasi-static approach, in which a quasi-static load is often considered as the basis of the analysis. This gives designers a great deal of freedom to arrive a suitable design having performed a number of iterative calculations in less time. This chapter focuses on the recent development of structural modelling and response analysis with an emphasis on quasi-static approach. The chapter has been divided into several sub-sections to address simplified analysis, direct calculation, optimisation-based analysis, fatigue stress, whipping, new materials and corrosion.

3.2 Simplified analysis/first principles

Despite the sustainable development of numerical methods, design formulas and simplified analysis methods related to quasi-static response are still valuable for Classification Society Rules as well as initial design of ship and offshore structures.

The intersection between stiffeners and primary supporting members is one of the most critical details in ship hull structures. Okada et al. (2018) developed a consistent theoretical formula taking account of all the structural components affecting the load share of each member, in combination with the combined load effect of direct force from the longitudinal stiffener and shear force on the primary supporting member. Rational evaluation of the strength of slot cut-out structure is possible using the proposed formula. Gu et al. (2020) developed a theoretical formulation to represent the stresses at the root of the web stiffener due to the load from both the longitudinal stiffener and the shear force on the primary supporting member in the double hull structure. Good accuracy of the proposed formula was verified by comparing with FE results.

Park et al. (2018) investigated cylindrically curved panels under axial compression and lateral pressure via nonlinear FE analysis. They revised Faulkner's formula and developed new de-

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sign formula for ultimate strength of curved panels taking into account the effects of curvature, initial deflections, slenderness and aspect ratio, boundary conditions and secondary buckling behaviour.

Zhu et al. (2020) investigated nonlinear elasto-plastic response of stiffened steel plates loaded quasi-statically by a central rigid rectangular indenter. The concept of applying the elasto-plastic method to the design of deck plates under wheel patch loads is introduced. A simplified design formula to determine plate thickness is proposed based on an acceptable level of permanent set. Comparisons are made between the thicknesses derived using the proposed design formula and those found from Lloyd's Register (LR), Bureau Veritas (BV) and DNV (formerly DNV GL) rule requirements. The proposed formula is useful to designers of ro-ro/cargo ships, helicopter-carrying ships and offshore platforms which deck structures suffer heavy vehicle or helicopter wheel loads.

Pan et al (2017) researched crushing force of a 5000DWT bulk carrier with the simplified method and quasi-static simulation respectively, and it is found that for the inclined angle of an element greater than 40 degrees, the existing effective crushing distance and reduction factor are no longer applicable. Thus, the effective crushing distance and reduction factor for the element having a large, inclined angle are modified, and their effectiveness in application has been validated.

Wang et al (2021d) proposed a simplified analytical method for the structural response assessment of ship side structures by raked bow under oblique collision scenario. The explicit dynamic FE analysis was used to determine the crashworthiness, and based on that analytical model has been proposed, that could be used in early design stages.

Wang et al. (2019c) proposed a generalized global motion reconstruction method for large displacement but small deformation problems, assuming that the global motion can be divided into quasi-static motion and dynamic vibration. Comparison between the measured and numerical simulation results suggests that there is a significant drag amplification due to the existence of the vessel motion-induced vortex-induced vibrations (VIV).

To develop safe and reliable structures, simplified methods are investigated on analysis the seakeeping behaviour of closed fish cages in waves and the structural response to the wave loads. As a new concept in marine aquaculture, closed fish cages can be categorized as flexible membrane structures (fabric), semi-flexible structures (glass fibre) and rigid structures (steel or concrete). Strand and Faltinsen (2017, 2019, 2020) proposed linear theory of a 2D semi-flexible closed fish cage in waves and investigated the structural response of the semi-flexible closed cage in waves. The results indicated that quasi-static assumption was conservative within the given frequency range for all examined stiffnesses and frequencies, except the frequencies very close to the second sloshing frequency.

3.3 Direct calculations

3.3.1 Direct strength analysis

Direct structural strength calculations by finite element analysis (FEA) are given more attention in both design and approval process. The calculations on global FE model of the ship are usually required by Classification Society rules in which quasi-static analysis is usually performed.

Rörup et al. (2017) presented concurrent methodology for strength analysis of ship structures as required by DNV rules. They concluded that the correct application of the boundary conditions and loads into a cargo hold FE model, torsional response for open deck ships (such as container ships) with realistic warping are still a challenge.

Im et al. (2017) evaluated a design of a 19,000 TEU ultra large container ship with novel mobile deckhouse for maximizing cargo capacity by quasi-static approach.

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Non-linear FEA is also used to evaluate ultimate strength of the structures. Material strain rate model, constitutive equation for ice materials, correct application of boundary conditions and loads into FE model are recent research hotspots.

Kahraman and Tayyar (2017) proposed a simple method using just the initial imperfections and material properties as input data, the residual strength of structures with permanent de-flections is calculated. The method uses the curvature values, which represent the strain distribution are taken from the deflection curves of the geometry. Validation is done by comparing the results with FE analysis results of a rectangular bar for inelastic bending.

Naruse et al. (2017) studied the ship hull girder ultimate strength considering biaxial compression in bottom stiffened plates. FE analysis of stiffened plate under biaxial compression was carried out, the results were compared to the Common Structural Rules (CSR) and a new formula was proposed.

Naruse et al. (2021) presented a method for deriving the practical collapse strength against lateral pressure of stiffened plates using non-linear FEA calculations. In this study, the authors defined “collapse” to be the condition in which residual deflection develops up to a defined criterion after unloading. Utilizing this criterion, the practical collapse strength against lateral pressure is investigated and compared with the assessment formulae for hull local members specified in the International Association of Classifications Societies’ (IACS) CSR. The effects of the axial loads acting together with lateral pressures are also studied.

Yu et al. (2017) used a quasi-static non-linear finite element method to calculate the ultimate strength of a semi-submersible platform. Different load conditions were applied to the three-dimensional model of the structure in intact condition. The analysis was also carried out for collapsed condition using explicit dynamic solvers. It was found that, time dependent dynamic analysis is a reliable method which can be used to find the ultimate strength of complex structure under different load conditions and loading rates.

Sano et al. (2017) conducted a study on a non-spherical tank of an LNG carrier, where under partially filled condition the buckling strength of the tank was found out. It is observed, when the tanks are filled partially, more stress is acting on the structure than the fully filled tank condition. In this study combined meridional tension and circumferential compression is considered for the partially filled condition and membrane shell theory was used for derivation of analytical solution of pre-buckling stress distributions.

Metsälä et al. (2017) investigated the local buckling and non-linear behaviour of ship structure using a method based on adaptive stiffness matrix. The use of adaptive stiffness matrix was essential because the constant stiffness matrix used in single layered models can only predict the deformation globally and hence for local buckling it was used. It was seen that the results were in good comparison with the three-dimensional FE model.

The ice-strengthened ships used in Baltic Sea generally follows the Finnish Swedish Ice Class Rules (FSICR) which considers the pressure and load distribution between frame members as uniform over a rectangular patch. However, Kõrgesaar et al. (2017) conducted a study to show that the length of pressure patch and the load distribution affect the capacity of the frames used in the hull structure, and that the present FSICR rules are not the most conservative ones when comparing with DNV guidelines.

Quasi-static strength analysis is also applied to the estimation of strength related to accidental limit state.

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Chen et al (2019a) designed a series of small-scale specimens of unstiffened and stiffened web girders and tested by applying local imposed deformations by an indenter. These quasi-static experiments reveal the crushing behaviour of vertical stiffeners in web girders. Finite element (FE) models are established to calculate the crushing deformations and to analyses the energy absorbing mechanisms. Good agreement is observed between the numerical results and experimental measurements, leading to the conclusion that the developed FE model can be effectively used to predict the crushing behaviour of ship structures in stranding.

Xu et al. (2017) simulated the collision process of a Suezmax oil tanker with a semi-sphere geometry iceberg using finite element method and the factors affecting the collision process were identified like the velocity of vessel, angle of collision and the position at which collision occurred. Residual strength of the damaged hull girder is calculated subsequently.

Parunov et al. (2017) investigated the residual strength of an Aframax double hull oil tanker after collision damage by nonlinear finite element method. The investigation was done for two cases. For the first case, only the outer shell was considered damaged but for the second case, both the inner and outer shell were considered damaged. Both hogging and sagging loading conditions were considered. The damage was considered to propagate from the main deck to 80% of the ship's depth. In the analysis the effects of rotation of neutral axis to the hull collapse is also studied.

3.3.2 Impact and collision analysis

The impact and collision of structures are usually analysed by quasi-static method with FEM model.

Ringsberg et al. (2017) presented the influence of high-speed impact using linear-elastic and nonlinear beam models, as well as a nonlinear transient dynamic finite element analysis idealisation. Comparisons of the methods presented against experimental results led to the conclusion that the nonlinear quasi-dynamic beam approach accounts for the influence of the dynamic effects of strain by suitably idealizing the effects of nonlinear geometric stiffness.

Truong et al. (2021) presented a benchmark study on the slamming responses of offshore structures' flat stiffened plates. The objective was to compare the fluid-structure interaction (FSI) simulation by commercial software (i.e., LS-Dyna ALE, LS-Dyna ICFD, ANSYS CFX, and Star-CCM+/ABAQUS) in predicting slamming pressure. Wet drop test data on flat-stiffened aluminium plates of light-ship-like bottom structures was utilized for validation of the FSI modelling. Moreover, equivalent static slamming pressures resulting in the same permanent deflections, as observed from the FSI simulations, were reported and compared with analytical models proposed by the Classification Standards and existing experimental data for calculation of the slamming pressure.

Gan et al. (2018) demonstrated that the BSMPM (the material point method enhanced with B-spline basis functions) outperforms the generalized interpolation material point (GIMP) and convicted particle domain interpolation (CPDI) methods in term of the accuracy of representing stress waves to solve plate impact.

Wan et al. (2019) investigated ship collision with bridge piers. The quasi-static compression test and numerical simulation of a simplified bow model were carried out to study the static stiffness characteristic of the ship bow for further comparison with the dynamic ones. And parametric studies were carried out to investigate the effects of the dynamic parameters and impact velocity on the impact force and ship bow crush depth.

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Liu et al. (2019a) presented an experimental, numerical, and analytical study on the crushing of web girders, to provide insights into the behaviour of a ship's structure in a collision or grounding incident. Four scaled double hull specimens were crushed in a quasi-static manner, and nonlinear finite element method analyses were also conducted to predict, compared with the experimental results. The typically applied approach of equivalent plate thickness is not optimal, particularly when the web stiffeners are in line with the striking indenter.

Liu et al. (2018c) evaluated the steel plate plastic response until failure with quasi-static and dynamic manner to investigate the importance of the material strain rate for the material characterization in numerical analyses of similar plate structural components used in the ship-building and marine offshore industry. Cowper–Symonds material strain rate model (Cowper et al. 1957) is verified to be suitable for the analysis of ship–ship collisions and/or ship collisions with offshore platforms.

Jagite et al. (2019a) presented numerical results of the dynamic collapse analysis for different stiffened panels extracted from 16 container ships. The quasi-static capacity of these panels was determined and was used to define dynamic load time scenarios for two typical periods associated with wave and whipping. The dynamic ultimate strength of stiffened panels was evaluated considering real loading scenarios associated with wave loads and whipping response.

Yang et al. (2018b) proposed a modified Bressan-Williams-Hill (m-BWH) criterion to evaluate the failure criteria of collision and grounding. Comparison of Constant strain (CS) criterion combined with linear damage evolution model, the BWH and m-BWH failure criteria which are combined with the bilinear damage evolution model has been performed in the simulations. Although the BWH criterion is more precise than the constant strain criterion in comparison with the experiment results, its errors will increase with rising of strain ratio. The m-BWH criterion improves the accuracy of the simulations when the strain ratio is high.

Structural crashworthiness analysis is required to evaluate the characteristics of structural deformations and impact energy dissipation at the event of collisions between ships or offshore platforms and icebergs. The constitutive equations of both steels and ice materials should be characterised for numerical computations as the collision impact energy is dissipated by the two colliding and deformable bodies, namely not only ships or offshore platforms but also icebergs. Ince et al. (2017) proposed a new constitutive equation used for ice materials associated with quasi-static and impact responses.

3.4 Optimisation-based analysis

In this section, recent development of optimisation procedure using quasi-static response analysis is reported.

3.4.1 Optimisation with structural response analysis

Shin & Ko (2018) presented minimum weight design method for corrugated bulkhead of chemical tankers by applying evolution strategy as an optimization technique. Multi-individual searching methods need excessive time if they connect to 3-D FE model for repetitive structural analyses. In order to resolve this issue, 2-D beam element connected to deck and lower stool is substituted for a corrugated structure.

Jang et al. (2019) proposed a Finite Element Analysis (FEA) based optimization of semi-submersible floater using an in-house software for an automatic strength assessment considering buckling and yield strength for stiffened structure. Stress estimation formulas to predict stress changes for the design scantling changes are proposed to reduce the burden of FE analysis. An attempt to decompose scantling variables into groups and to execute the optimization of the groups in a sequential manner is made to reduce the optimisation cost.

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Raikunen et al. (2019) presented an optimization method for concept design state of passenger ship with focus on utilisation of efficient finite element modelling, evolutionary optimisation algorithm and indirect constraint relaxation. The response is analysed using global finite element (FE) model with 3D coarse mesh, where stiffened panels are modelled using equivalent single layer elements and the primary stiffeners are modelled with offset beam elements. Local stress peaks are allowed to exceed the rule-based strength limits, i.e., stress constraints are relaxed indirectly. The results showed that stress relaxation has significant effect on the obtained total mass.

Lin et al. (2019) presented scantling optimization of an internal turret area for mooring system of FPSO. The Radial Basis Function (RBF) model is built as a surrogate for computationally expensive FEM analysis to improve the efficiency of the optimization. The evolutionary strategy is applied to the optimization.

Andric et al. (2020) presented implementation of optimization procedure on the bulk carrier structural design according to all requirements of IACS CSR for Bulk Carriers. An in-house structural design support system OCTOPUS-CSR was developed for the concept and preliminary design phases to fully realize all benefits of a formal optimization procedure. Developed tools and methodology enables the structural design team to optimize structural designs while in parallel satisfying the CSR requirements of structural safety.

Murali et al. (2017) provided an evolutionary based optimization method to solve structural optimization problem in an efficient manner. Having done a case study on the quattro pod offshore jacket structures, it is proposed that even for complex structures the proposed meth-od could be used for obtaining a reliable design with better utilization of fatigue life for a minimum structural weight.

3.4.2 Multi-objective optimisation

Optimization techniques are powerful tools for improving traditional structural designs in many real applications. Moreover, multi-objective optimization is a solution to ensure the increasing accuracy requirements of optimization analysis.

Prebeg et al. (2018) proposed tanker structural design methodology that leads to improved structural safety with multi-objective optimization using hull girder ultimate strength and ship crashworthiness quality measures as objectives in addition to the traditionally used weight or cost quality measures. In this study, the authors used response surfaces method as surrogate modelling method and nondominated solutions technique to reduce the problem to the most important objective.

Andric et al. (2019b) presented a novel decision support methodology for concept and preliminary design of a complex ship structure together with its application to the structural design of large a RO-PAX ship. The multi-criteria, multi-stakeholder design problem was solved using the suggested methodology through three design phases with the support of a ship-owner, Classification Society and a shipyard. For each design step different structural FEM models, load models and optimization models have been established. Decision making implied multi-objective decision making (MODM) and multi-attribute decision making (MADM) procedures based on dual sequential linear programming (SLP) and multi-objective particle swarm optimisation (MOPSO) optimization algorithms all combined with the stakeholders' subjective decision making (selection) on the generated Pareto frontiers.

Samanipour & Jelovica (2020) developed a new constraint-handling approach for multi-objective evolutionary algorithm that improves algorithm's efficiency and quality of results. The approach was implemented on a genetic algorithm and used to optimize the main frame of a chemical tanker. Class rules were followed, and semi-analytic stress analysis was performed considering global and local loads. Improved algorithm provided additional weight savings in comparison to the one with constraint-handling approaches from literature and advanced genetic algorithm based on decomposition.

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In order to assess the sensitivity of different primary stress distributions, influenced by the different topological variants on optimized structural scantlings of passenger ships, Andric et al. (2021) introduced topological aspects – such as the size of side openings, number and length of longitudinal bulkheads, the geometry of superstructure, deckhouse and recess, etc. – as the first step in the overall optimization procedure. The design framework was based on two main steps: Topology exploration using Taguchi concept and multi-objective scantling optimization.

3.4.3 Topology optimisation

Topology optimization is the method to optimise material layout in a given design space and uses finite element analysis, which is different from usual shape optimisation concept. Basic concepts of the topology optimisation are presented in the book by Bendsoe & Sigmund (2002) and Azegami(2019). In recent years, the topology optimisation method is being applied to practical ship structural design.

Liu et al. (2019d) proposed a two-stage optimization method for the conceptual design of stiffeners in a ship's prow. In the first stage, the authors adopted SIMP (Solid Isotropic Material with Penalization) interpolation scheme to perform topology optimization method for determining a potential stiffener distribution based on the optimal results. In the second stage, size optimization based on parametric modelling is conducted to optimize the plate and stiffener sections simultaneously based on a parametric model.

Jia et al. (2019a) performed topological optimization of a bulkhead reinforcement in a trimaran. Strength was ensured following rules for the classification of trimarans. The results showed that there is no correlation between the maximum stress and the volume reduction ratio of the reinforcement. The maximum stress cannot be reduced simply by increasing the mass of the structure.

A lightweight design of trimaran bulkhead was proposed by Jia et al. (2019b) based on structural topology optimization method. In this article, seven structural strength checking conditions of trimaran are designed based on rules for the classification of trimarans. Variable density topology optimization method is applied to calculate the bulkhead structure of trimaran before and after optimization under different working conditions. The optimization results show that the distribution of the connecting material of the optimized bulkhead is consistent with the actual trimaran bulkhead design.

Zhao et al. (2020) proposed a new layout optimization method to consider high-cycle dynamic fatigue constraints. The topology optimization model to minimize the structural weight subject to the dynamic fatigue constraints was formulated. The authors introduced the Kreissemeier–Steinhauser (KS) aggregation function to reduce the number of dynamic fatigue failure constraints. To overcome stress concentration phenomenon, the P-norm aggregation function was introduced to the objective function as a penalty term.

Recently, topology optimization using the level-set method has been becoming a hot research spot, which was originally applied in by Osher and Sethian (1988).

Li et al. (2021) proposed a parallel distributed an open-source framework for full-scale 3D structural topology optimization, which can be achieved by properly combining parallel computing and mesh adaption techniques by adopting a reaction–diffusion equation (RDE) based level-set method. The use of RDE allows to simultaneously update the design variables and alleviate the overestimation of optimal shapes, at the same time, it can result in a more complex topological configuration.

Kambampati et al. (2021) proposed a methodology for computing boundary sensitivities using the discrete adjoint method based on the level-set method for topology optimization under stress constraints. The adjoint equations are constructed using the discretized governing field equations. The authors perturb the boundary implicitly by locally modifying the level set function around a given boundary point. These local perturbations are combined with the derivatives of

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the objective function with respect to the volume fractions of individual elements to compute boundary sensitivities.

A methodology to extend the bi-directional evolutionary structural optimization (BESO) method for topology optimization problem under volume constraint and maximum von Mises stress constraint was proposed by Han et al. (2021). In this study, a scheme was introduced to determine the Lagrange multiplier so that the maximum von Mises stress can be effectively constrained. The adjoint method was employed to derive the sensitivity numbers for the purpose of updating the binary topological design variables.

Additive manufacturing (AM) is the technique to implement the result of topology optimisation into reality. However, the latest technologies of AM are far from perfect in ensuring the mechanical properties and dimensional accuracy of the products. Miki et al. (2021) proposed a topology optimization method that accounts for the distortion in AM. The topological derivative of the objective function is approximated using an adjoint variable method, it is then utilized to update the level-set function via a time evolutionary reaction-diffusion equation.

3.5 Fatigue stress

Researchers tried to document the development in fatigue design for ships and offshore structures. Here in this section, the research of fatigue analysis especially related to quasi-static stress analysis are reported.

Li et al. (2017) conducted research for fatigue evaluation of trimaran cross structure with the influence of slamming. Finite element method and rain flow counting program were applied for calculation of stresses and the stress cycles. It was found that even when the frequency of slamming was low, the degree of cumulative damage was increased by ten times, which shows the importance of taking into account the slamming loads on cross structure under different wave conditions in a trimaran ship for the calculation of fatigue damage.

Li et al. (2018a) analysed the effects of welding residual stresses on the vibration fatigue life of a ship's shock absorption support by power spectral density method and Miner linear cumulative damage theory. On analysis it was seen that the residual welding stresses have a large influence on the vibration fatigue life of the shock absorption support of the ship and hence it is required to prevent this vibration fatigue in the support structure. This can be done by reducing the residual stress in critical areas and adjusting the welding locations away from these areas.

Amirinia and Jung (2017) studied the effects of hurricanes on low cycle fatigue of tower and blades in offshore wind turbines by quasi-steady analysis. Wind and wave fields were simulated according to Saffir-Simpson typhoon wind scale (which rates the windspeed based on maximum sustained windspeed), and analysis was carried out using modified NREL-FAST (Fatigue, Aerodynamics, Structures, and Turbulence) package.

Lotsberg (2019) gave a detailed description on the development of Fatigue Design Standards for Marine Structures. The paper showed that there has been a significant development in the standards of marine structures since the development of first standards in 1974. It also point-ed out that there is still a potential for improvement of analysis methodology in the fatigue analysis as the computer efficiency is being increased through which detailed analysis can be performed.

3.6 Whipping

With the increasing size of container ships in recent years, the whipping phenomenon which is the vibratory transient response induced by bow slamming need to be evaluated during the design stage. To assess the whipping response, the advanced hydro-elastic model needs to be applied leading to full coupling between the structural and hydrodynamic models. However, to simplify the analysis, so-called whipping factor could be added to wave bending moment. Here, papers which may contribute to such simplified analysis are reported.

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Gaidai et al. (2018) presented the results of extreme hydroelastic response for large ships based on real measurements. The measurements were compared to IACS URS11A requirements. The whipping factor has been estimated by Hanada et al. (2020), where 5-year measurements done in 8600 TEU container ship have been analysed. It was found that the whip-ping magnitude on the torsional and horizontal bending components is much smaller than that on the vertical bending component.

The numerical analysis of hydroelastic response with different types of structural and hydrodynamic models could be found in: Im et al. (2017), Jagite et al. (2018) and Takami et al. (2018). Based on these analyses, the bending moment with consideration of whipping phenomenon could be even 35 % higher compared to bending moment without consideration of whipping.

McVicar Jason et al. (2018) found that hydroelastic coupling between the fluid and hull whipping response was small with the choice of structural parameters having minimal influence on the slam force, but significant changes to the estimated hull bending.

Malenica et al. (2008) presented a method based on the full coupling of 3DFEM structural model and 3DBEM hydrodynamic model for springing and whipping analyses of ships. The choice of the full coupling with the 3DFEM structural model is necessary due to the structural characteristics of the container ships, in particular their open midship section, which is hard to model using non-uniform beam model. The 3DFEM model gives the direct access to the structural response (stresses and strains) at any required location. The stresses at the structural details are investigated using a so called top-down analysis, and the total stress response is separated into quasi-static and dynamic parts in order to improve the convergence.

The whipping-induced stresses have a higher frequency than the ordinary wave-induced stresses, some authors have suggested that dynamic effects, i.e., inertia and strain rate, provide additional hull girder ultimate capacity in the context of whipping. Even if it is known that the dynamic effects are important in the case of collision or grounding, there is no evidence that it is true for whipping.

Jagite et al. (2019b) examined dynamic effects on the hull girder ultimate strength of ultra large container ships. The dynamic ultimate strength of the hull girder is compared with the quasi-static ultimate strength in order to obtain a proper estimator of the dynamic collapse effect. Nonlinear finite element method is used for the analysis of three frame-bay models, representing the structure of two different container ships. The numerical results obtained from nonlinear finite element analyses showed that under a real wave plus whipping loading scenario, the stiffened panel's capacity is increased by 0.4% to a maximum of 1.3% comparing to a real wave loading scenario. The similar study, though related to stiffened plates was presented in Jagite et al. (2020). The dynamic load factors were derived as the ratio between the dynamic capacity and quasi-static one. It shows that simplified scenarios tend to over-predict the increase of the panel's capacity due to whipping.

The whipping-related structural response of double bottom was studied in Chen et al. (2020). The full-scale measurements were used to verify, that double bottom is subjected to bending due to whipping phenomenon. The correlation between hull girder bending stress and double bottom bending stress was studied, which may be useful in simplified analyses.

3.7 New metallic materials, composites and sandwich panels

The development of novel materials for the construction of marine structures continues with an accelerating pace. In this section, the properties of new metallic materials, composite and sandwich structures are reported which may be useful for quasi-static response analysis. Also, papers related to strength analyses for composite structures are also reviewed.

Polyurethane foams are widely used as thermal insulators and also as energy absorbers in radioactive material shipping casks. It could be used as a protective coating for undersea pipelines.

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Mane et al. (2017) conducted an experimental to research the change in impact response of rigid polyurethane foam at different strain rates. It was found that energy absorption characteristics of foam are altered with change in strain rate. Lobanova et al. (2018) proposed a model of liquid flow to determine the rates of filling the defect cavities with polymer composite and metallic materials, and based on this, to choose optimal control modes. Vestrum et al. (2018) presented a series of indentation experiments carried out on offshore steel pipes covered by a multi-layer polymeric coating solution. The polymeric coating is found to absorb a considerable amount of the kinetic energy delivered by an impacting object. Townsend et al. (2018) study the viscoelastic layer into the GFRP panels. The structured combination of a polymer with high deformation capacity with domains of a second, rigid polymer, dampens the impacts and delays the damage progression, improving the dissipation of impact energy, thus protecting the structure of the hull and increasing the service life of the high-speed crafts.

Although the marine industry favours steel as a material, lightweight construction can achieve by seeking new topologies via sandwich construction. Kharghani et al. (2018) tested composite-to-steel hybrid balcony overhang of cruise ships. The steel component is a channel type of structure made of two plates that serve as external supports of the sandwich plate. The results include load-deflection and load-strain curves with the maximum value of the shear and bending loads. The critical locations and failure loads have been investigated too. Luo et al. (2020) proposed an auxetic re-entrant blast wall (ARBW) based on the indentation resistance effect of auxetic materials. Based on the numerical analysis method verified by the explosion experiment of a conventional steel corrugated blast wall (CBW), the failure mechanisms of ARBW, steel honeycomb sandwich blast wall (HSBW) and CBW were investigated under distributed impulse (quasi-static) loads. Computational results demonstrated the excel-lent anti-explosion performance of the proposed ARBW design. The stress distribution of the connection illustrated the different energy absorption and transmission modes of the three blast walls.

Tomlinson et al. (2018) investigated the scale and manufacturing effects on the tensile strength of marine grade sandwich composite panels and joints to aid in the fabrication of large modular ship hulls. This is done by researching transverse sandwich composite joint de-sign, experimental tension methods, and scale and manufacturing effects on tensile strength. Andric et al. (2019a) presented the design of a car carrier where three upper fixed vehicles decks have been designed as a hybrid concept, i.e., a combination of steel deck grillage and composite sandwich panels. For a predefined sandwich panel geometry and interaction with the supporting deck steel grillage, structural capability and compliance with the relevant Bureau Veritas (BV) rules of various feasible configurations were evaluated, whereby structural response was determined using the finite element method (FEM) on the local (panel) level. On the global level, composite sandwich panels do not contribute to the hull girder bending, so longitudinal and racking strengths of the new structural concept have been evaluated using the complete full ship FEM model.

The transient nature of slamming loads can cause stress rates that are high enough to affect the strength of the core material, particularly for polymeric foams. There is a lack of understanding of how core materials fail in transverse shear during slamming events, and also only very limited knowledge of how the core shear strengths measured using standardised, often quasi-static material coupon testing relates to their behaviour in a panel-slamming situation. Battley (2019) contributes to two novel areas; controlled experimental characterisation of the failure mechanics of sandwich panels subjected to water slamming to understand and quantify the strength of different polymeric core materials, comparison of the failure modes and trans-verse shear strength of slam-loaded sandwich panels to predictions from material coupon properties. Core types include low, medium and high elongation polymeric foams. The results demonstrate that the more ductile foams perform better as panel structures under slamming relative to their quasi-static properties compared with the more brittle cores. Prediction of the strength of a panel is shown to be highly dependent on the load distribution and whether the static or dynamic core strength is considered. The results support empirical experience that ductile foams perform well

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under slamming loads, and that high-elongation materials can per-form better in slamming situations than predicted by their quasi-static strengths.

Elmushyakhi et al. (2019) examined the mechanical characteristics and the failure mechanisms of seawater-accelerated weathering GFRP composites followed by low intensity fire/heat damage. The effect of fire-induced damage under different heat fluxes on strength and modulus before and after 120 days of seawater exposure is experimentally investigated. The fabric architectures and seawater exposure influence the post-fire residual properties.

Kai et al. (2020) investigated ultimate tension failure behaviour of sandwich composite L-joints for ship structures experimentally and numerically. Simulations were conducted using a progressive damage method that could differentiate between matrix and fibre tension damage. Maps of damage process and failure modes were provided, accounting for the interaction between failure modes.

Li et al. (2019b) compared sandwich structures with hourglass truss and pyramidal cores experimentally and numerically. It is shown that the natural frequencies of the hourglass sandwich structures are much higher than that of the pyramidal sandwich structures under free-free boundary condition and equal relative density of the truss cores. It is indicated that the hourglass sandwich structures exhibit better vibration isolation performance than the pyramidal sandwich structures.

Li et al. (2020b) proposed a new generalized shear deformation theory for the static response of functionally graded plates. A small exponential function with a shape parameter is multiplied to a classical trigonometric shear strain shape function to make more accurate distribution of the transverse shear strain in the thickness direction of the functionally graded plates. The novelty of this work is that the shear strain function with the shape parameter m is assumed to vary with power-law indexes. The effect of gradient index, side-to-thickness ratio and aspect ratio on the static response is studied.

3.8 Corrosion

Corrosion degradation is one of the most influencing phenomena, which decreases the capacity of various structural elements in ship and offshore structures. Though a lot of research has been carried out in this area, the problem is still vital. In this section, corrosion wastage models of uniform and pitting corrosion are reported which are important for structural analyses of corroded structures. Also, the papers which investigated the influence of corrosion to the strength are also reviewed.

The advanced time-dependent corrosion degradation model was proposed by Kim et al. (2020a), where not only mean thickness of corrosion loss is predicted, but entire probability distribution too. In Kim et al. (2020b), the proposed methodology was used to predict the corrosion of the ship's ballast tank based on the available measuring data. Zayed et al. (2018) developed a simplified method for predicting the corrosion level of the different ship panels, accounting for the different corrosion types on each side of the plate and based on the available data. Lampe and Hamman (2018) also developed the model for corrosion prediction for different structural elements, which could be adjusted based on the available data. However, to include occurring uncertainties, the nominal model is extended by means of probabilistic representation. Both of models are based on the Guedes Soares and Garbatov corrosion mod-el. Presented models could be used in various types of quasi-static analysis. The probabilistic model for corrosion rate of fuel tank structures in bulk carriers based on the real measurements were developed by Ivosevic et al. (2019). They found that the best distribution to represent the corrosion rate is Weibull distribution. Similar observation could be noticed in Moham-Madrahimi and Sayebani (2019), where they used Bayesian updating for time-dependent corrosion wastage model for deck panels. Their approach updates the corrosion model coefficients based on the new data providing better and more accurate model. Garbatov (2020a) pro-posed the methodology for risk-based corrosion allowance for oil tankers. The time-dependent exponential model

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was adjusted based on the measurements from operating ships. The corrosion margins were derived, taking into account severe consequences of failure and closed-form solutions were established, that could be easily adopted in the design.

When we consider corrosion wastage for structural response analysis, not only thickness reduction is related to the corrosion degradation. Additional discussion is related to the mechanical properties of steel elements subjected to nonuniform corrosion. During last couple years some investigations has been made in mainly experimental but also in numerical domain. Garbatov et al. (2019a) tested corroded specimens subjected to tensile loading and different cleaning methods. The results show that corrosion degradation can reduce the mechanical properties (yield stress, Young's modulus, ultimate stress and total elongation). Li et al. (2018b) performed tensile test of pre-stressed and corroded specimens and the effect of mechanical properties reduction was magnified with comparison to only corroded specimens. Similar observations of the reduction of mechanical properties with respect to corrosion could be seen in Mountassir et al. (2019).

Most researchers agree that the corrosion is caused by the non-uniform distribution of corrosion pits. In case of marine environment, the non-uniform corrosion is most common one and this phenomenon cannot be neglected. The influence of corrosion morphology in the mechanical properties was investigated by Wang et al. (2017), Qin et al. (2016) and Zhang et al. (2020b). With the increase of corroded surfaces roughness, the mechanical properties were more reduced. Additionally, the FE modelling of specimens with reproduction of real corrosion morphology led to similar results with respect to experimental ones. The spatial corrosion wastage modelling of steel plates was proposed by Garbatov et al. (2019b). Furtherly, Woloszyk et al. (2020a, b & c) explored the possibility of corrosion modelling with the use of random field approach. The results of FE analysis of small-scale tensile coupons were compared with the available experimental data showing good agreement. Despite the founding's that the corrosion implies the mechanical properties reduction, the level of this reduction varies between different research works. In this view, the further experimental and numerical work is needed to develop some more practical models. The effect of corrosion into the crashworthiness of corroded ship was investigated by Liu et al. (2018a), where combination of thickness reduction model with material properties changes was adopted. The results show significant reduction of ship bottom strength up to 35%.

3.9 Concluding remarks

In this chapter, recent progress in structural modelling and response analyses are reported especially related to simplified analysis, direct calculation, optimisation-based analysis, fatigue stress, whipping and new materials and corrosion. As reviewed in this section, structural analysis based on quasi-static analyses and usage of simplified formula based on quasi-static analyses remain important in the design of ships and offshore structures, even though complex dynamic analyses can now become to be used using high-speed computers. This is because the quasi-static approach can provide rapid analysis results and suitable accuracy to develop structural designs.

In the previous report of II.1 (ISSC 2018a), some research areas related to structural response are recommended as future research topics, for example, the development of design curves or equations for assessment of failure modes of structures, and applications of FE analysis, CFD and combined FSI approaches, and evaluation of corrosion and fatigue for assessment of strength. The reviews in this chapter 3 shows that there has been a lot of research on those topics over the past few years.

General recommendations for future research topics related to chapter 3 are as follows. To enable rapid and cost-effective design process in the detailed design phases, we recommend that researchers continue to consider the development of design curves or equations to assess the failure modes of structures under complex analysis conditions. It is expected that complex nonlinear structural analysis, dynamic structural analysis, and FSI approaches will become more

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advanced for the next while. These research topics are also very important for future research, because they can provide an understanding of complex phenomena and can be used to develop new formulations which can be used in quasi-static manner. Load combinations and failure mode interaction are important topics for this committee. Especially with regard to aged ship and marine structures, corrosion and fatigue play an important role in the failure mode analysis so that the status of the research related to these topics needs to be carefully monitored.

4. QUASI-STATIC APPROACHES TO STRENGTH ASSESSMENT

This chapter examines the role of quasi-static response methods in Strength Criteria for which stress, deflection, and other parameters are subsequently compared to for failure assessment. While there are other committees, including III.1 Ultimate Strength and III.2 Fatigue and Fracture, that focus on similar topic areas and themes as the ones presented here, this chapter seeks to highlight the implementation of quasi-static methods as applied to these issues. Such methods provide design and analysis engineers with time-efficient tools to estimate structural strength when it is not feasible to employ dynamic methods requiring longer and more complex calculation. Reasons for such a decision to employ quasi-static methods to strength assessment may include acceptable accuracies required for particular problems, time limitations, limited computing and personnel resources, parametric modelling requirements, and unfinalized designs seeking optimisation, among others.

4.1 Buckling and ultimate strength

4.1.1 Stiffened plates and panels

Comprehensive technical review on existing empirical formulations that predict the ultimate limit state (ULS) of a stiffened panel under longitudinal compression was conducted by Kim et al. (2018c). Existing methods to predict the ultimate compressive strength of a stiffened panel were comprehensively reviewed and the applicability of each method was investigated in comparison with analytical and numerical methods. Xu et al. (2018) investigated the influence of lateral pressure and stiffener type on the collapse behaviours of steel stiffened panels through FE analysis. Based on the numerical results, the empirical expressions are derived for the ultimate strength assessment of stiffened panels under combined in-plane axial compression and different levels of lateral pressure. The proposed regression formulae include the plate slenderness ratio and column (stiffener) slenderness ratio as design parameters. Ozdemir et al. (2018) proposed a new approximate method based on analytical formulas to estimate the ultimate strength of stiffened panels by investigating collapse mechanisms of the stiffened panels. Based on the performed elastoplastic large deflection FEA results, an efficient method is proposed to estimate the ultimate strength of stiffened panels based on Elastic Large Deflection Analysis (ELDA) with the initial yielding concept. In the ELDA, the deflection modes are defined as the sum of overall buckling mode plus local plate buckling mode. The calculated results by the proposed method and the nonlinear FEA are compared, and a very good agreement is obtained for all collapse scenarios investigated.

For thin-wall structures, scale experimental models obtained by complete geometrical similarity might not be economical or practical to test. The study performed by Song et al. (2019) aims to figure out an approach to determine the dimensions of small-scale models, which have similar collapse behaviours and load carrying capacity with full scale prototypes under longitudinal compression. For that purpose, the partial similarity methods have been used to design the dimensions of scale stiffened panels considering the influence of collapse modes, which could be employed for the experiment in laboratory condition. In Bhudia (2019) the effect of the plate edges on the buckling strength was investigated by comparing the plate buckling strength for simply supported and rotationally restrained edge conditions. First, a sensitivity analysis was conducted for two different design parameters: the plate thickness and dimensions of longitudinal support members. Second, a Finite Element (FE) model was developed to validate and compare the buckling strength interaction relationships of a stiffened panel subjected to biaxial compressive loads. The results demonstrate that the plate edges should be considered as a

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rotationally restrained condition to reduce plate thickness while satisfying buckling design safety criteria.

Buckling strength often dictates the ship design scantlings, particularly for thin plated ships such as passenger ships and roll-on roll-off (Ro-Ro) ships where optimizing steel weights are highly demanding. Zhang et al. (2019) evaluated buckling and ultimate strength assessments of thin plated structures. Both non-linear finite element analysis and experimental tests are carried out to establish the buckling capacity of the thin palate structures in axial compression. The goal of this study is to investigate if the same CSR methodology can be used for thin plated ships, such as passenger ships and Ro-Ro ships. As the hull plates of these ship types are relatively thin compared to conventional oil tankers and container ships, the CSR methodology has not been proven to be used in such thin plates and lack of application experience. Thus, it has a significant high risk of using such approach without further verifications. It is clearly shown that current LR ship rules are underpredicting the buckling strength at a great deal, at least for the discussed thin plates. However, the CSR approach overestimates the ultimate strength results. LR have subsequently published revised rules to align calculation results more closely to the experimental results and remove the apparent over conservatism of the existing method (LR 2019a revised LR 2021a).

Elastic local buckling strength analysis of stiffened aluminium plates with an emphasis on the initial deflections and welding residual stresses have been studied by Mohammadi et al. (2019). The energy-method based Fujikubo–Yao's algorithm is modified such that the assessment of the elastic local buckling strength of the stiffened aluminium plates becomes possible, focusing on the specific characteristics of welding residual stresses and initial deflections.

Evaluation of large structural grillages subjected to ice loads in experimental and numerical analysis has been carried out by Kim et al. (2018e). The experimental tests allowed for an evaluation of highly non-linear structural behaviour and overload capacity considering the simultaneous failure of ice. The experiments led to unique insight into the overload response and load carrying capacity of a large structural grillage as well as the effect of prior plastic damage on the structural behaviour. The FE analysis results show a strong agreement with the physical experiments, which confirms that nonlinear FE analysis is a suitable tool for the analysis of ice-strengthened ship structures subjected to extreme ice loading.

Saad-Eldeen et al. (2018) experimentally investigates the influence of different opening sizes and shapes, different steel materials and structural configurations on the ultimate strength of steel plates. A series of experiments have been carried out for unstiffened plates and stiffened panels having an opening of different shape and size in addition to different constructional steels, high tensile and mild steel. The effect on the ultimate load carrying capacity of the opening sizes and shapes, different steels and structural configurations, post-collapse deformations and strain energy density are investigated and analysed. Several relationships of the ultimate stress ratio, ultimate load carrying capacity ratio for different steels as a function of the residual breadth ratio are presented and discussed. A relationship showing the effect of different structural configurations on the ultimate load carrying capacity ratio is presented.

4.1.2 Hull girder ultimate strength

The chronology of critical break-in-two accidents of ships has been reviewed over the last 100 years by Sumi (2019), where not only the technological causes of such accidents but also their backgrounds are taken into considerations. Except for the substandard ship problems, as underlined by the author, most of the break-in-two accidents occurred in relation to some innovative designs responding to the societal needs arising in the respective era.

It has been identified that hull girder ultimate strength of container ships is still under great care of many researchers. Wang et al. (2018a) focused on the ultimate strength characteristics of the ultra large container ship (ULCS), and a typical 10,000 TEU container ship has been adopted for the case study. The ultimate strength behaviours of hull girder under pure vertical bending

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moment, pure horizontal bending moment and pure torsion, and ultimate strength interaction relationships between two load components each and between three load components has been investigated using numerical non-linear FEM (NLFEM) simulations and partial 3D FE model. Design equations for the prediction of the hull girder's ultimate strength interactions have been proposed. In Wang et al. (2019a) investigation of ultimate hull girder longitudinal strength characteristics of ULCS through experimental and numerical analysis has been carried out. A detailed model test regarding ultimate strength of a similar scaled model for a typical 10,000 TEU container ship under pure vertical hogging bending moment was introduced. The comparison between calculated and measured results was studied to investigate the accuracy and reliability of NLFEM considering the comparison of horizontal neutral axis, ultimate strength value and progressive collapsed behaviours. Effect of bottom local loads on ultimate strength of container ships subjected to hogging hull girder bending moment has been studied by Tatsumi et al. (2020a) using nonlinear FEM. Buckling collapse behaviour of bottom stiffened panels during the progressive collapse of a hull girder is closely investigated. It has been found that major factors of the reduction of ultimate hogging strength due to bottom local loads are: (a) the increase of the longitudinal compression in the outer bottom and (b) the reduction of the effectiveness of the inner bottom, which is on the tension side of local bending of the double bottom. In the follow-up paper Tatsumi et al. (2020) extending Smith's method for pure bending collapse analysis of a ship's hull girder, as a simplified method of progressive collapse analysis of ultimate hogging strength of container ships considering bottom local loads is developed and validated with nonlinear FEM analysis from the companion paper, Tatsumi et al. (2020b).

Hull girder ultimate strength of cruise ships with many decks and extensive superstructure is still very complex issue to be calculated. A simplified, fast and reliable method is still missing, so the NLFEM is still the only method that ensure acceptable level of accuracy. Valuable discussion on the action mechanism in nonlinear interaction of hull-superstructure for guiding the structural design of cruise ship is given in Shi and Gao (2019). In this paper, a simplified FE modelling approach has been implemented to model the complicated structures of a whole ship. The hull girder ultimate strength and failure mode is analysed by using nonlinear FE analysis, and the variation characteristics of superstructure's effectiveness from elastic state to limit state have been summarised. Influence of bottom lateral load in reduction of hull girder ultimate strength in hogging condition has been studied.

In general, ultimate longitudinal strength of conventional monohulls has been investigated very extensively. Nevertheless, the design of SWATH (small waterplane-area twin hull) ships and catamarans mainly depends on the transverse bending strength rather than the longitudinal strength due to their special sectional configuration, i.e., wide deck and small hull cross-section at the waterline. Hence, the transverse ultimate strength becomes critical for those ship types. In Liu et al. (2018b), an experiment has been performed to examine the transverse ultimate strength of a one-eighth scaled SWATH ship model subjected to transverse loads. The experimental results are compared with nonlinear finite element simulations. The ultimate strength of the actual SWATH ship is evaluated according to scaling laws, and the ship safety margin is analysed. Similar type of investigation, experimental and numerical analysis of ultimate strength, has been performed by Xu et al. (2019) for inland catamaran subjected to longitudinal vertical bending moment. The inland vessels are designed with a shallow draught and a relatively small section modulus and moment of inertia of the hull cross-section, which makes the ultimate longitudinal strength much more critical.

4.2 Residual strength

As well known, the residual strength of a structure (ship or offshore platform) is its capability to support external loads after a change of its resistance with respect to the nominal one established in the design phase. This variation can be caused by a normal structural ageing due to time dependant processes (e.g., corrosion and fatigue), a structural damage due to accidental events (e.g., storms, fire or collisions) or a change in design loads imposed by new regulations. The quantitative amount of such a change, can be determined by different approaches which

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involve the study of the whole structure history, and the creation of an updated FE model to be compared with that of the new structure (design phase) with the same loads assumed in the design phase. The evaluation of the residual strength becomes essential for those structures for which, arrived in proximity of the end of their design life, an extension of the design working life is required. This subject has been extensively examined in the ISSC 2015 and 2018 reports of the II.1 Quasi-Static Response Committee (ISSC 2015a, ISSC 2018a) and in the ISSC 2015 & 2018 reports of the V.7 Structural Longevity Committee (ISSC 2015b, ISSC 2018c).

Among different types of damages which can cause a capacity loss of a ship can, deep interest exists on the evaluation of the residual strength of grounded ships. Tekgoz et al. (2018a and 2018b) analyse the case of a grounded container ship for which the grounding event causes asymmetrical bending loads and, as a consequence, a translation and rotation of the main section neutral axis. The analysis has been carried out by FE technique on three different models corresponding to as many bottom damage extensions, obtained from the IACS harmonized rules. In the three cases the area reduction is similar (about 25%) but the damage location shifts from the ship centre to the ship side. As the grounding is shifted transversely, the impact on strength reduction increases.

A method to predict the hull girder residual strength of double-hull oil tankers by considering probabilistic collision damage scenarios has been set up and presented by Yossuef et al. (2017). The collision damage is characterised by the Collision Damage Index CDI (ratio of vertical moment of inertia for intact vs damaged hull cross section) and the residual strength by the Residual Strength Index RSI (ultimate bending moments for the intact vs damaged hull cross sections). Ultimate bending moments in intact and damaged conditions have been calculated by the FE specific software ALPS/HULL (Ma, 2015) for four types of double-hull oil tankers – VLCC, Suezmax, Aframax and Panamax in order to determine a correlation between CDI and RSI. Eight RSI–CDI diagrams are obtained for the four double-hull oil tankers under hogging and sagging load directions. A linear regression is performed for each diagram to generate empirical formulations that present the RSI as a function of CDI as a 2nd degree polynomial.

Parunov et al. (2018) investigated the residual ultimate strength of an Aframax-class double hull oil tanker and damaged in a collision and subjected to combined horizontal and vertical bending moments. The damage extension has been idealised as a rectangular box starting from the main deck; The ship residual strength has been investigated by a nonlinear FE analysis under vertical bending and combined horizontal and vertical bending moment. Interaction equations and curves of the ultimate strength for the intact and the damaged tanker and for two different damage extension (40% of the ship's depth for only outer shell damage and for both outer and inner shell damage) are produced.

Campanile et al. (2018), in their study on reliability analysis of bulk carriers damaged by collision events, considered the time-variant residual strength. The work starts from the results provided by HARDER and GOALDS EU-funded projects, in which a large amount of newly reported damages has been collected and analysed to update the existing IMO database and develop more reliable statistics for damage location, length, depth and height, after collision events. Two different collision models have been applied: the CSR-H one, actually embodied in the Harmonized Common Structural Rules (CSR-H) for Oil Tankers and Bulk Carriers and the GOALDS database statistics for oil tankers and bulk carriers. The time-variant hull girder residual strength has been determined by an incremental-iterative method taking into account the neutral axis rotation due to the cross-section asymmetry after collision, in order to investigate the incidence of damage statistical properties on hull girder mean values, variation coefficients and probability distributions. After that the reliability analysis has been carried out by Monte Carlo simulation.

Given the availability of new routes through the Arctic Sea due to melting of the north polar ice cap, Kim et al. (2019a) considered the consequences of grounding events at very low temperatures in a range between -20°C and -80°C. The study has been performed on Panamax class

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oil tankers. A modified Residual strength versus grounding damage index (R-D) is presented. It is concluded that since material yield strength increases with decreased temperature, the ultimate longitudinal strength behaviour of the ship's hull damaged by grounding is increased. Though it is noted in the study that the role of material toughness versus temperature was not considered as a factor.

In the offshore field the residual strength of platforms and pipelines is assessed by studying the structural behaviour of cylinders. Ring and stringer stiffened cylinders are the most recurrent structural components (legs, columns, braces) of various types of floating, semi-submersible and fixed offshore structures. During their operative life they are subject to damages caused mainly by collisions with any kind of floating objects or support vessels. Cho et al. (2017) presented an experimental and numerical analysis on the residual strength of ring-stiffened cylinders damaged by typical collision accidents suffered by offshore platforms. Three ring stiffened cylinder models with large dimensions (outside diameter 800mm and overall length 1060mm) have been fabricated and to two of them a dent defect has been applied by a drop indenter. The damaged and intact models have then been tested in a pressure chamber by application of external hydrostatic pressure until collapse. Numerical calculations have been carried out as well demonstrating a good correlation with experimental results. The investigation showed that the ultimate strength of the damaged models was significantly reduced with respect to the intact one. Do et al. (2019) continued the study on the prediction of residual strength of stiffened cylinders affected by dent defects and loaded by combined axial compression and external pressure by using a numerical approach. Comprehensive parametric FEM calculations have been carried out considering the R/t ratio (cylinder radius vs shell thickness), the D/R ratio (dent depth vs cylinder radius), the collision velocity and the mass of the striker body. From the calculation results the authors set up simple formulas to predict the extension of the denting damage and the corresponding residual strength.

Mooring chains are critical components for the safety of floating offshore units and the strength reduction caused by pitting corrosion is the reason for which current Code requirements impose their removal and replacement when the chain capacity loss exceeds a limit value. Farrow et al. (2019a and 2019b) presented the software Chain FEARS (Finite Element Analysis of Residual Strength) by Joint Industry Project (JIP) aimed to develop guidance for the calculation of the residual strength of mooring chains affected by uniform or mega pitting corrosion. The method is based on FE analysis on the degraded and as-new chains validated by a number of physical break tests.

For what pipelines are concerned Cai et al. (2017b) presented a comprehensive literature review in which the latest research progress on residual ultimate strength of metallic pipelines with structural damages is discussed. After a description of pipeline installations types, loads and damage categories (dent, metal loss, crack) the usual methods for strength evaluation are presented. Experimental methods for pipe strength evaluation which mostly attracted the interest of researchers are described, bursting test, external pressure test and bending test. Numerical methods are considered as well with a detailed discussion on most important requirements such as mesh creation, material properties and boundary conditions. The paper closes with a roundup of analytical method for strength prediction, covering strength under external pressure, bursting and bending capacity, strength under uniaxial loading and combined loading. More than 100 paper are quoted in the references.

The same authors, on the base of a previous experimental campaign on large-scale pipe specimens, Cai et al. (2017a) carried out a numerical investigation on the ultimate bending strength of metallic pipes with metal loss (Cai et al. 2018a) and on pipes with metal loss combined with structural damage such as dent and crack (Cai et al. 2018b). A complete resume of the whole experimental and numerical investigation is presented in Cai et al. (2019) where the result of this long activity is detailed. The investigation showed that the damage location (on the compressed or tensile side of the cylinders) has a significant influence on the strength reduction of

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the cylinder. The parametric analysis gives to designer a useful database to evaluate damage effects on cylinders with similar geometry and D/t ratios (dent depth vs shell thickness).

Do et al. (2018) compared the ultimate strength of dented versus intact stringer-stiffened cylinders under hydrostatic loading. Arc-welded and cold-bent cylinders with stringer-stiffeners were utilised for the experiments. Dents were produced by a knife-edge indenter with drop-test procedures. The results indicated that the effects of dents on the ultimate strength of stringer-stiffened cylinders were quite low. The collapse tests revealed that the shell failed several times after an initial failure, as shown by a sudden decrease in pressure. Subsequently, the shell recovered and reached a higher-pressure level prior to the final collapse failure. The tests were well-correlated with an ABAQUS simulation which validated the experiments and modelling.

Pournara et al. (2018) examined the behaviour of dented steel pipes with a combined bending and pressure load applied. The paper assessed the structural integrity of smoothly dented steel pipes by experimental testing correlated by numerical simulations. Ten experiments on X52 steel pipes were conducted, with dented steel pipes subjected to bending and pressure loading, in order to estimate their residual strength and remaining fatigue life. Six specimens were subjected to cyclic bending loading, and four dented pipe specimens, following cyclic pressure loading, were pressurized to rupture to determine their ultimate pressure capacity. The numerical simulation of the testing procedure and loading pattern of each specimen was performed so that local stress and strain distributions at the dented region were accurately characterized. From the finite element results, a fatigue assessment methodology to estimate the remaining fatigue life was formulated, and predictions were found to compare well with the experimental results. Strain concentration factors (SNCFs) for dented pipes subjected to bending were also calculated, to be implemented in fatigue life assessments.

Chujutalli et al. (2018) compared experimental and numerical analysis of stiffened ship hull panels with indentations on the stiffeners. The ultimate strength of such stiffened panels is reduced due to both initial flaws and residual stresses present at construction. While in service, the stiffened panels experience plastic deformations and localized residual strength, further reducing the ultimate strength of damaged panels. To consider this in the design process and preserve structural integrity, the paper provided analyses of the effect of damaged stiffened panels on the ultimate strength considering the residual stresses caused by indentation variables depth and location. A small-scale model representative of a full-scale bottom panels from a cargo compartment at the midship of a typical Suezmax tanker were utilized for the experiment. Experimental tests of the indentation were conducted on the intersection plate-stiffeners, where the force-displacement responses were analysed. After the indentations, the panels were submitted to uniaxial compression experimental tests to evaluate reduction in ultimate strength versus an equivalent intact panel. To compare with the experimental results, a finite element model was developed for ABAQUS with three sequential loading steps: panel indentation, indenter taking off, and uniaxial compressive loading. Plastic strains and residual stresses caused by the indentation were incorporated in the ultimate strength analysis of the panels. Initial imperfections and maximum denting depth of the panels were measured in the experiment and correlated well to the finite element model results. A parametric study revealed a relation between dent depth, location, and residual strength following the damage.

4.3 Fatigue strength and cracks

Quasi-static methods often form the basis of calculation processes for fatigue analysis, with developments in the use of such methods for fatigue failure assessment presented in this section.

4.3.1 Fatigue strength analysis

A spectral fatigue analysis to examine the fatigue sensitivity of a high-speed light naval craft was utilized by Magoga (2019a). Due to the lightweight nature of their construction and high-g loadings, Naval high speed light craft (HSLC) are particularly susceptible to fatigue. Operational readiness of naval craft is important, and fatigue cracking reduces availability and

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increases vessel life-cycle costs. The author utilised spectral fatigue analysis (SFA), which accounts for both the operational profile and wave environment explicitly. The loads were accounted for in a linear formulation. Utilising trial data, the paper validates the SFA, as well as conducts a study of the sensitivity of fatigue damage incurred in a naval HSLC to various parameters. Fatigue damage was shown to be most sensitive to significant wave height, but the relative importance of the speed and heading increased when operational parameters and environmental loads were accounted for. Magoga (2019b) also investigated the design fatigue service life for a vessel, accounting for assumed value factors such as construction quality, loads, material performance, and operational profile. Reduction in capability and increase in life-cycle costs are resultants of failure of structural components from fatigue crack propagation. The method presented in the paper utilised in-service data, fleet maintenance reports, and Finite Element Analysis to predict the remaining service life of a ship. The fatigue lives of various weldments were predicted using an S-N curve approach, utilizing operational data measured on-board via a hull monitoring system.

Khan and Ahmad (2018) conducted a fatigue reliability assessment of risers based on a bilinear relationship that gives the crack growth linked failure criterion to describe the interaction between fracture and plastic collapse. Part of the design process for deep-sea oil extraction are requirements of structural failure criteria, including rupture loading, fatigue failures, buckling or an unstable fracture. Results relating to fatigue reliability and crack growth were modelled with Monte Carlo simulation. The bilinear crack growth model was shown to give longer fatigue life estimation when compared with the linear fracture mechanics model. The results suggest inspection schemes for components of the marine structures which seek to minimize unexpected events due to wide scatter of the fatigue phenomenon in marine environment.

Zou et al. (2018) presented a fatigue management approach which accounts for fatigue design, inspection and maintenance decisions affecting the life cycle management of a marine structure. The approach proposed utilises a risk-based optimization of fatigue design, inspection and maintenance based on a fatigue deterioration model. The two optimization parameters are fatigue design factor (FDF) and inspection intervals, with a goal of minimising the projected life cycle cost (LCC). The authors present as an example a fatigue-prone detail in a ship structure to determine the best trade-off point between structural safety and life cycle costs.

The current rules used the quasi-static approaches for fatigue assessment. The material and geometrical non-linearity are neglected since small-scale yielding and small deformations can be assumed for thin-walled structure, where plate thickness is above 5 mm. For smaller plate thickness e.g., thin deck structures, this fundamental assumption is violated, and this causes special challenges for the response analysis (Remes et al. 2017).

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At present, the fatigue assessment of large structures such as ships is carried out by using the structural stress approach. The idealised finite element model is created without modelling the welding-induced distortions. Then, the stress increase due to the distortions is considered separately using the stress magnification factor km. This engineering approach has been successfully applied in the fatigue design of welded structures for several decades in the case of thick flat plates. For plate thickness less than 5 mm, the distortion shape is observed to be curved as illustrated in Figure 1. Furthermore, the geometrical non-linearity (i.e., km is depended on the applied load level) is significant for thin and slender plates; see Lillemae et al. (2017) and Niraula et al. (2019). Therefore, the existing km factor formulations, derived according to the flat distortion shapes, cannot properly apply to the fatigue assessment of thin plates.

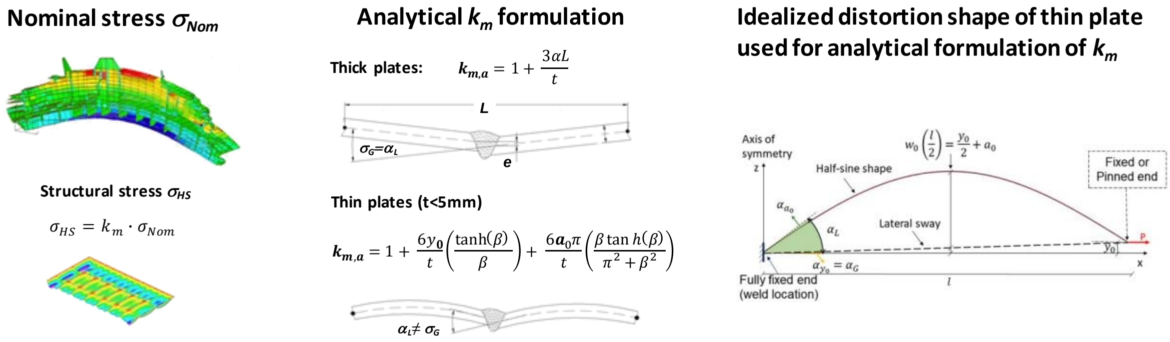

Figure 1: Response analysis of ship structures, where welding-induced distortions causes secondary bending stress. The existing formulation of the stress magnification factor km for thick plates is further developed for curved thin plates, modified from Mancini et al. (2020).

To further develop structural stress analysis methods, Shen et al. (2019a, 2019b) introduced a modified stress magnification factor km. The magnitude and shape of curvature is modelled with a quadratic function, and the proposed model has been validated against finite element analysis for fixed and pinned boundary conditions. A different approach has been proposed by Zhou et al. (2019, 2020). Equivalent dummy loads are applied to a straight beam in order to account for a non-linear distortion. The model is validated against numerical solutions, with both tensile and compression loading. These studies have shown to be valid geometrically non-linear analysis approaches for the structural stress problem, but their engineering use is challenged by the complexity of the analytical formulations. Thus, Mancini et al. (2020) developed a more compact solution using non-linear beam theory and the von Kármán kinematic assumption. The developed analytical solution applies a linear lateral deflection superimposed to a half-sine curvature. These recent research studies provide valuable development steps in improving the analytical solution of the stress magnification factor for welded thin plates with curved distortions.

4.3.2 *Reliability approaches for fatigue*

The area of structural health monitoring is an important tool for those managing the service life of vessels. For ships serving late in their designed lifespan, efficient choice of inspection intervals is critical for best usage of often shrinking maintenance budgets. Doshi et al. (2017) applied fracture mechanics-based fatigue crack evaluations to create reliability-based inspection plans for a Very Large Crude Carrier (VLCC). Probabilistic techniques were utilized to account for the uncertainty in parameters related to fatigue crack growth. The authors present a compelling case that reliability-based inspections are a viable technique for integrity management of ship structural details while allowing for an economical inspection interval and maximizing vessel availability.

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A reliability approach for local fatigue damage and buckling and ultimate strength of a ship's hull was applied by Garbatov et al. (2020b). It was presented that compressive collapse and fatigue damage probability could be used in conjunction with repair cost estimates to allow for design of the ship structure. The authors utilize a first-order reliability method (FORM) in order to estimate a reliability index based on the structural component topological data. When compared to the original design, a 9% reduction in the area of the best design solution of the optimized section was realised.

Another use of FORM was the assessment of structural reliability of offshore wind turbine (OWT) structures utilizing a damage tolerance modelling approach by Shittu et al. (2020). The OWT are subjected to pitting corrosion-fatigue, and the authors employ a probabilistic approach that includes uncertainties in shape factor, aspect ratio, and pit size, in addition to random variation in environmental corrosion and cyclic loading. The reliability of the structure is calculated via a proposed non-intrusive formulation. A Finite Element Analysis utilizing stochastic parameters generates results that were processed by an Artificial Neural Network response surface modelling technique. A First Order Reliability Method (FORM) was then instituted to calculate a component reliability index. The BS7910 design standard was presented as a theoretical benchmark, among other methods, The FEA results are in very good agreement with results obtained from analysis steps outlined in design standard BS 7910 and other references designated as 'theoretical analysis methods' in this study.

Zareei and Iranmanesh (2018) examined the usage of crack detection and measurement data gathered during crack inspections to update fatigue reliability equation parameters. They use such measurements to update the statistical distribution of the parameters, driving fatigue reliability-based inspection planning intervals. Both initial crack length and crack growth equation material parameters were updated with the technique.

Johnston (2017) described the statistical concepts which can be applied to find a reliable fatigue life. Regression analysis was used for the statistical analysis of fatigue test data to calculate the mean of test data. All the relevant statistical concepts were well explained for usage by engineers to find a reliable fatigue life of a marine structure.

4.3.3 Crack propagation and corrosion fatigue

Sadananda and Vasudevan (2020) performed a detailed analysis of pit to crack transition during corrosion fatigue considering corrosion pits as ellipsoidal notches with the associated stress concentration factors, Kt. Both S-N and fatigue crack growth (FCG) data are analysed using the proposed unified approach that considers the R-ratio effects. The Kitagawa-Takahashi diagram, as shown in Figure 2, is used to connect the fatigue life of a smooth specimen to that of a fracture mechanics specimen. Internal stress and safe-life regimes are identified using the diagram.

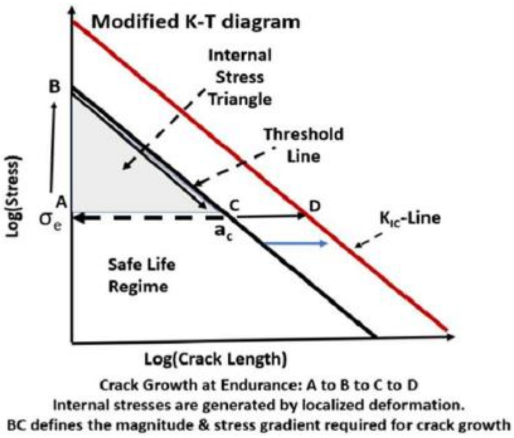

Figure 2: A modified Kitagawa-Takahashi diagram, from Sadananda and Vasudevan (2020).

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Feng et al. (2020) performed nonlinear finite element study to investigate how coupled corrosion and crack damage influences the ultimate strength of ship plates. It is presumed that the crack is through-thickness and symmetrically distributed inside and on both sides of the corrosion pits, and no contact of crack faces occurs at the ultimate limit state. It is stated that the combined effect of crack and corrosion in the plate is less severe for the ultimate strength reduction than when they exist alone.

Lui et al. (2020) proposed a risk-informed framework that determines the optimal end-of-life strategies for ships. A cost-benefit analysis is integrated into the framework to account for deteriorating ship performance, including fatigue crack propagation and corrosion wastage. The proposed framework is applied to two categories of oil tankers to highlight the effect of ship size on the cost-effectiveness and net benefit of different end-of-life strategies. A sensitivity analysis is conducted to identify the critical factors in the decision-making process.

Igwemezie et al. (2018) presented fatigue crack growth test results of advanced S355 TMCP (Thermo-Mechanically Controlled Processed) steel in air and seawater, comparing the results with studies on commonly available S355 steel, aiming to improve the wind turbine support structures. The results showed that S355 TMCP steels generally offer higher fatigue damage tolerance than normalised S355 steels in air, and the factor decreases and tends towards a common value with increase in stress intensity factor range. However, in seawater there is no significant difference in fatigue crack growth rates for all the S355 ferritic steels considered in the study.

Den Besten (2018) presented an overview of fatigue strength modelling for marine structures, and physical effects governing crack initiation and propagation. Fatigue damage criteria developed over time have been classified with respect to type of information, geometry, parameter, and process zone including plane and life region annotations. The criteria are evaluated regarding model capabilities and limitations, showing up to what extent the governing physics are accounted for in the fatigue damage criteria.

Zhang et al. (2018c) proposed a method based on spectrum analysis for predicting fatigue crack propagation of a crack in marine structures. Stress intensity factor (SIF) transfer functions were evaluated through detailed structural analysis for different crack sizes, and the short-term SIF distribution was obtained. Fatigue crack propagation life was then calculated from numerous short term SIF distributions and the improved Paris formula. A sub-model technique was integrated, facilitating SIF re-analysis due to crack growth, and an Improved Euler method was adopted to reduce the computational steps.

Fatigue generally occurs due to fluctuating or cyclic loads. These can be of two type first is High Cycle Fatigue (HCF) where fatigue is caused by small elastic strains under high number of load cycles and second is Low Cycle Fatigue (LCF) where fatigue is caused by repeated plastic deformation where the load is higher, and the number of cycles is lower. Most of the studies, experiments and research have been done considering that a ship is experiencing only high-cycle fatigue. Gledic et al. (2019) investigated the possibility that due to low-cycle high-stress fatigue caused by fluctuating wave loads there is damage propagation in a damaged hull of ship during the salvage period. They conducted a case study on an Aframax double hull oil tanker damaged in a collision in a specific wave environment and for the analysis part a finite element model is created for intact ship and stress concentration factors were calculated for fifty random damaged conditions which were generated based on historical data. Strain life approach according to DNV classification notes is used to calculate the number of wave load cycle of constant amplitude required to initiate fatigue crack and Monte Carlo simulation is used to estimate the accumulated low cycle fatigue damage. Parametric study was done to investigate the sensitivity of results to material properties, wave environment and salvage duration. A method was proposed for calculation of fatigue damage accumulation in damaged ship structure as a consequence of the low cycle high stress fatigue caused by fluctuating wave loads.

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Fatigue cracks that are generated in ship structures are one of the main causes of failure in ships. The primary reason for the generation of these cracks is the cyclic stresses arising from encounters with the encounter of different sea wave loads. As each vessel is operating in different sea conditions the fatigue crack initiation and propagation is different for each vessel. Thompson (2018) presented a study on the fatigue damage variation within a class of naval ships. Spectral fatigue analysis was used to assess the variation in fatigue damage. The analysis was conducted on ten naval vessels in a class for which four different structural locations were considered and used the operational history to examine the variations in experienced wave environments and corresponding fatigue damage estimates at four structural locations. Although corrosion is not considered in this study, knowing the fact that corrosion can accelerate the crack initiation. For the analysis the fleet of naval ships were divided into two groups: one based on the East Coast of Canada, operating primarily in the North Atlantic, the other on the West Coast of Canada, sailing mainly in the North Pacific. It was found that the ships based on the East Coast experienced conditions with higher calculated significant wave heights than the ships based on the West Coast which led to greater fatigue damage estimates and more variability between ships. It was noted that the differences in fatigue damage estimates within each coastal fleet are small but for East Coast ships are 40–50% greater than for West Coast ships.

It is very important to understand the growth of fatigue cracks which are generated because of cyclic wave loads for an accurate fatigue life prediction. Xiaoping et al. (2018) discussed the effect of fatigue loading spectrum on crack propagation in a ship detail where the effect of loading sequence on the crack growth life was investigated. The aim of the study was to find a physical engineering method to generate fatigue loading spectrum for ship fatigue assessment. In analysis the long-term distribution of fatigue loading, and the unique crack growth rate curve model were used and a study on the deck crack in a container ship as an example was done to demonstrate the application of proposed method and the results showed that the shape parameter affects the fatigue life significantly if the long-term distribution of wave-induced stress range is modelled by two parameter Weibull distribution. These results were compared with the shape parameter values determined by empirical formulas, and it was found that spectral analysis used to get the shape parameter values is more reasonable, but the major drawback of this method is its complexity. It was concluded that more accurate fatigue life predictions of a ship structure can be made by combining the fatigue crack growth life prediction with the unique curve model and fatigue load spectrum based on spectral analysis.

Pavlou (2017) presented a study which showed the weaknesses of the tools which are used in the present day for fatigue related calculation. For example, Miner's rule which is used for crack initiation, and Paris law modifications which are used for crack propagation investigations. Methods were discussed and the advantages and disadvantages of the non-linear methods, which can be used for the same purpose as the standard methods, were presented. By the above analysis it was found that physical mechanisms of fatigue were not taken into account in the case of linear models for fatigue crack initiation and propagation. Hence, the predictions made by them may be inaccurate. Further the results of linear and non-linear methods were compared, and both were encouraging. It was noted that the non-linear methods provide a more accurate estimation than the linear ones, where the factor of safety is raised to account for inaccuracies, leading to heavier or more bulky structures.

Floating structures are exposed to many cyclic environmental and dynamic loads during their service life. With the depleting fossil fuel storages people have started searching for renewable sources of energy. Wind energy is one type of such renewable energy which is being utilised the most. For this many Floating wind turbine (FWT) are being set up for the generation of energy using the wind energy in the oceans. Wu et al. (2017) presented a study that gives a comparison between the fatigue life predicted by Fracture mechanism (FM) based approach and the S-N curves-based approach and the impact of the variation of initial crack depth, critical crack depth and stress concentration factors on the ratio of the fatigue lives predicted by the two approaches with various material constants recommended by BS7910 and DNV guidance

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was investigated. A FM based fatigue assessment for the tower base of a 5 MW FWT supported on a spar platform is performed for this purpose. The fatigue life of the floating wind turbine is calculated according to ABS guidelines for fatigue assessment of offshore structures. The fatigue strength is then determined by the standard Palmgren-Miner's rule. Whereas in the fracture mechanics analysis the crack growth is predicted based on the Paris' law and the crack depth. Time-domain analysis is conducted to obtain the stresses on the structure. It was found that the fatigue lives predicted by the FM based approach are generally more conservative than SN curves-based approach predicted fatigue lives and the fatigue life is highly sensitive to the material constant of the material.

4.3.4 Ice-induced fatigue

Ice induced fatigue is critical for ships navigating in ice-covered regions because it may lead to oil leaks or even catastrophic failure. However, the research activities about ice induced fatigue damage for ship structure have not been performed in rich way compared with wave induced fatigue damage. Han and Sawamura (2017) used a discrete element method (DEM) to obtain the time series of peak value of ice induced loads in pack ice regions considering the interaction between drifting ice floes and moving ship. Ice load peaks was described by Weibull distribution and the cumulative density functions of peak value of ice load for several conditions were calculated by numerical simulation. They found that the calculated fatigue damage results were much smaller than the one in level ice and concluded that the numerical simulation method is considered to be promising for the calculation of the fatigue damage since the ice conditions and ship hull can be changed easily.

Kim et al. (2019c) proposed a numerical model using finite element method to simulate interaction between ice floes and ship structure, targeting fatigue damage estimation on the ice-going vessel. Long term analysis was carried out through the application of numerically efficient periodic media analysis method and convolution integral. Time series of contact pressure on outer shell of the ship hull was converted to time series of hot spot stress by convolution integral using the Impulse Response Function (IRF) on the target fatigue point. Stochastic Weibull model was adopted to obtain probability distribution of stress amplitude and fatigue damage was evaluated using the Palmgren-Miner rule. They applied the methodology to the fatigue damage assessment of the ship for the Kemi route in the Baltic region and it was compared with the results using the LR method. It turned out the fatigue damages calculated by the LR method were larger than that of the proposed method by a factor of 2, potentially due to the conservatism of LR method.

Zhang et. al. (2018c) carried out fatigue life assessment for a jacket structure in the Bohai sea using field measurement data. By using field measurement data, such as ice-induced vibration responses, ice forces for numerous offshore structures, interaction between ice and vertical structure, the vibrational characteristics under various ice velocities were studied. In addition, the ice-induced fatigue analysis of jacket platform was carried out as a case study. Finally, the parameters of ice fatigue environmental models and their long-term impacts were assessed, and the fatigue damage of an offshore structure under steady state and random vibrations conditions were compared.

Ice ridges are commonly found features in most sea ice region and they are the reasons of critical obstacle that affects the design load for ships operating in ice region. Han and Sawamura (2018) applied a semi-empirical method to develop numerical model for the calculation of fatigue damage caused by ridged ice field, considering ship-ice interaction in level ice and consolidated ice ridges region. Rankine's plasticity model was introduced to calculate ice loads in ridge keels and the peak value of ice load was described by statistic Weibull model. They calculated the structural stress via beam theory to convert distribution of peak value of ice load into the distribution of stress amplitudes. By applying S-N curve and probabilistic distribution of ice thickness, fatigue damage was calculated through the Palmgren-Miner's rule and it was

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found that fatigue damage is much higher than the one in level ice condition because of the high loads imposed by consolidated layer and ridge keels.

Chai et. al.(2018b) introduced the probabilistic methods for estimating ice loads and resulting fatigue damage. To predict the extreme value, the average conditional exceedance rate (ACER) method was applied to approximate the distribution of exact extreme value and the short-term fatigue damage was calculated based on the S-N curve approach. In addition, three-parameter exponential distribution and Weibull distribution were applied to approximate stress ranges distribution. They found that the interaction between ice and ship occurs more frequently in the bow-intermediate region than the bow region and much severe fatigue damages have been observed in this region.

4.4 Concluding remarks

Quasi-static methods continue to be utilised for the strength assessment of ship and offshore structures, with developments presented for ultimate strength, buckling, and fatigue of intact and damaged structures. Methods provide computational benefits to the analyst, though approximations implemented within methods may lead to conservatism in calculated limit states. This conservatism is repeatedly presented when compared to more detailed methods or experimentation and should always be considered when selecting appropriate analysis methods. This conservatism may be accepted in the design of ship and offshore structures where safety of the structure is critical and potential over design may be acceptable, provided appropriate methods are being selected and the true failure modes of the structure are not being neglected.

5. CLASSIFICATION SOCIETY APPROACHES TO QUASI-STATIC ANALYSIS

This chapter provides an overview of the developments of international regulatory bodies, classification societies and international standards. The content is focused on quasi-static method developments; however, more generally the last years saw developments in fields like autonomous shipping, stricter requirements on the demolishing of ships, cybersecurity, and emissions, most notable the Sulphur restrictions. Direct quasi-static developments were more minimal.

Classification Society rules and industry standards are mostly based on quasi-static approaches for hull construction, and they typically show the procedures for scantling calculation of plating, stiffeners, and primary supporting members. Further, rules that apply for specific ship types are also published. Development of these rules was primarily incremental over the last years, although several updates are discussed below.

Nevertheless, new guidelines and recommendations related to ship and offshore structures were issued, many supporting more detailed analysis procedures. Therefore, only those relevant to the committee mandate have been presented in this review.

Section 5.1 contains an overview of developments of rules and regulations, the focus in section 5.2 is on classification society issued software systems.

5.1 Developments of international and classification rules and standards

IMO

Three bodies of the IMO met in total 10 times since 2017, MSC (Maritime Safety Committee), MEPC (Maritime Environmental Protection Committee) and the Assembly. The main decisions are, for MSC:

1. Increase of survivability of passenger ships after damage, MSC res. 421(98) (1/1/2020).
2. Introduction of new fire rating for structural integrity – "H" class leading to new types of insulation and increase of body mass for life saving appliances to 95 kg, MODU code, MSC res. 435(98) (1/1/2020).
3. Introduction of cyber risk management into safety management systems, MSC res. 428(98).

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4. Update of the references to INMARSAT to a more generic reference, allowing other systems to be used. Several references, (1/1/2020).
5. Revised guidelines on the prevention of access by stowaways and the allocation of responsibilities to seek the successful resolution of stowaway cases, MSC Res.448(99).
6. Framework for the regulatory coping exercise for the use of maritime autonomous surface ships (MASS).
7. Required prewash of cargo tanks when carrying cargoes which are regarded as persistent floaters and complete revision of the list of cargoes and their carriage requirements, MSC res. 460(101) (1/1/2021).
8. Complete revision of survey requirements for oil tankers and bulk carriers and making them mandatory, MSC res. 461(101) (1/1/2021,).
9. Complete replacement of IMSBC code for the carriage of bulk cargoes due to new hazard classification, MSC res. 462(101) (1/1/2021).

IACS

IACS introduced some minor updates to its main structural rules, the CSR-H (IACS 2021) and the UR-S family (Unified Requirements – Strength of Ships). The later taking effect in July 2021 and mostly related to rudders, material requirements and longitudinal strength.

ABS

The Guide for Alternative Requirements for Hull Construction of Vessels Intended to Carry Vehicles with length greater than 130 m (ABS 2019a) was issued by ABS in 2018. The intention of this guide was to reflect the industry trends by including requirements based on ABS SafeHull, total strength assessment and hull girder ultimate strength. In general, the guide includes the alternative method to obtain the web thickness of side transverses and stringers in single side shell using the direct beam analysis in lieu of the formula to determine the shear force and revised load cases for Global Finite Element Analysis as well as fatigue analysis.

In 2019, ABS issued guidance for building and classing aquaculture service vessels (ABS 2019b). The requirements are specially devoted to structural design, stability, fire protection, equipment and machinery for different type of fishing vessels, such as Fish Farm Support Vessels, Live Fish carriers, etc. In terms of hull structure, the guideline sets several recommendations related only to this type of ships. Additionally, the guide related to Offshore Fish Farming Installations was issued in 2018 (ABS 2018).

The Guidance notes on Thermal Analysis of Vessels with Tanks for Liquefied Gas (ABS 2019c) were issued in September 2019. The document is the response for challenges with storing cargo at very low temperatures. It is providing procedures for heat transfer analysis of liquefied gas vessels or gas-fuelled ships and subsequent stress analysis.

Recently, more attention was paid with regards to retrofitting of steel structures with the use of composites. Especially in case of Offshore Production Installations, there remain in operation for long time and traditional welding work for corrosion repair could stop their production process. This will not take place when composites are used. To reflect this issue, ABS issued Guidance Notes on Composite Repairs of Steel Structures and Piping (ABS 2019d).

BV

Bureau Veritas published tentative rules for rolling out the equivalent design wave (EDW) approach to all cargo ships over 65m (BV NR467). They defined 26 different EDW's, each maximising a different environmental load. Buckling requirements have also been brought in line with CSR, incorporating a plastic methodology. Plastic scantling requirements are currently already applied to impact pressures and updated. New guidance notes to support autonomous shipping and hydro-structural calculations in general and parametric roll in particular have been published. Following the successful certification of the first 3D-printed propeller, supporting guidelines for the WAAM (Wire Arc Additive Manufacturing) technique have been published.

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CCS

The Rules for the Construction and Equipment of Liquefied Natural Gas Floating Storage and Regasification Units were issued by CCS in 2018 (CCS 2018a). These rules apply to the new ship-type or barge-type LNG floating storage and regasification units and sets the construction, strength and fatigue requirements dedicated to these types of units.

Other Rules, dedicated to Diving Systems and Submersibles were issued by CCS in 2018 (CCS 2018b) to meet the demands of marine exploitation, shipbuilding and related manufacturing industries. The detailed requirements with regards to materials, calculation of acting pressures and instructions of Finite Element Analysis for pressure hulls are presented, including calculation procedure of ultimate strength.

Apart from Rules, different Guidelines related to selected topics were also issued. The Guidelines for Spectrum-Based Fatigue Assessment of Hull Structure were issued in 2018 (CCS 2018c). These apply to large membrane LNG carriers, container ships and ore carriers and apply spectral approach with regards to fatigue analysis. In 2018 (CCS 2018d), the Guidelines for Whipping analysis were issued, where detailed instruction about coupled hydro-structural analysis is presented. This document is mainly applicable to containerships.

With regards to increasing interest of global maritime industry in autonomous shipping, in 2018 CCS issued Guidelines for Autonomous Cargo Ships (CCS 2018e). In terms of hull construction and safety, basic regulations related to hull stress monitoring system, stability monitoring, etc. are provided.

IRS

Indian Register of Shipping (IRS) published a number of guidelines recently in shipping and offshore fields.

Guidelines on Maritime Cyber Safety (IRS, 2018a) are intended to provide requirements for evaluating and managing the Cyber Risk of Ships and mobile offshore units. The intent of these guidelines is to provide a framework by which an organization can implement a Cyber safety programme on board a ship/ offshore unit.

With a view to promote the use of alternative fuels in shipping in order to reduce greenhouse gases and NOx and SOx emissions, use of methanol as fuel is being encouraged by Governments worldwide. Accordingly, Guidelines on Methanol Fuelled Vessels (IRS, 2018b) is prepared for taking into account the developments at IMO regarding amendment to the IGF Code (International code of safety for ships using gases or other low-flashpoint fuels) to include the requirements for Methanol as fuel.

Prescriptive regulations may sometimes restrain the level of innovation that is feasible in design. An essential prerequisite for widespread use of innovation and the use of alternative and/or equivalent design is a reliable, transparent and reproducible process of submitting and approving the design, making full use of state-of-the-art risk assessment tools and techniques. Guidelines on Alternative and Risk based Design Evaluation, (IRS, 2019a) have been prepared with an aim to provide guidance to ship owners, shipyards and ship designers on the procedures to be followed, analyses to be performed, acceptance criteria to be established and documentation to be submitted for alternative designs/ arrangements in lieu of prescriptive requirements.

Guidelines on Battery Powered Vessels was published by IRS in 2019 (IRS, 2019b). These guidelines are applicable to battery installations on board vessels, where batteries are used for powering main propulsion systems. These guidelines are to be used in conjunction with applicable IRS rules.

Guidelines on Certification of Software for Computer based Control Systems (IRS, 2019c) provide requirements for quality assurance certification of computer-based control system software for shipboard applications. The requirements focus on the functionality of the software. The procedures and criteria indicated in these guidelines are intended for various stakeholders

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involved in design, development and maintenance of software. The objective of these guidelines is to reduce the software related incidents, which if not addressed can affect the safety of the vessel.

Guidelines for Spectral Fatigue Assessment for Ship Structures (IRS, 2020a) were developed. Cyclic loads are computed based on 2-D strip theory and 3D panel method. Spectral analysis is performed accounting the appropriate mean stress effect, thickness factor and rain flow correction factor. A suitable bi-linear S-N curve is used for given butt joints.

Guidelines on High Voltage Shore Connection Systems for Ships, (IRS, 2020b) are applicable to vessels equipped with a high voltage shore connection system designed to power the vessel with shore power alone, enabling the shipboard generators to be shut down while in port/ at berth. The Guidelines indicate requirements related to the design, installation and verification of high voltage electrical connections.

LR

In 2019 Lloyd's Register (LR) issued revised rules for Structural Design Assessment of Primary Structure for Passenger Ships and Naval Ships under Category NS2 (typically described as cruisers, frigates, destroyers, corvettes or similar) for conducting global stress analysis by FEA (LR 2017b re-issued LR 2019b & LR 2017a re-issued LR 2021b). The rules implement a quasi-static approach to ship loading through application of hydrostatic pressure loading on the hull-form, in conjunction with appropriate boundary conditions to induce the required design wave bending moment for hull girder bending assessment. Assessment can be undertaken using the LR software ShipRight, facilitating pre and post processing as well as solving via the integrated VAST solver, or exporting in NASTRAN format. The software also incorporates a buckling analysis routine referred to as LR buckle I or LR buckle II. LR Buckle I reviews stress distribution within plate panels against rule criteria. In 2019 LR issued new guidance for conducting buckling analysis with specific influence on buckling capacity of thin plate structures (LR 2019a). The procedure was implemented under the LR Buckle II routine and considers plate and plate-stiffener buckling criteria. The buckling procedure was re-issued (LR 2021a) to incorporate guidance specific to Membrane LNG and Ro-RO ships, linked to SDA procedures for these vessel types.

In conjunction with the SDA and FDA (Fatigue Design Assessment) procedures, LR issued rules for Ships Prone to Whipping and Springing (LR 2018). The Rules implement a ship motion response-based analysis (RBA), deriving modified hogging and sagging correction factors for application to bending moment and shear force distributions used within the global FEA analysis generally implemented within the SDA and FDA procedures.

ClassNK

ClassNK has published many Rule amendments and Guidelines. Among the Rules and Guidelines recently published by ClassNK, the main ones related to hull structures are as follows.

The first is Guidelines for Liquefied Gas Carrier Structures - Membrane System - issued on Oct 2020 (ClassNK 2020). The Guidelines specify the requirements for strength evaluations for membrane type gas carriers and are composed of the Guidelines for Direct Strength Analysis which specify the requirements for evaluating the yield and buckling strength of the net scantlings of the primary structural members by direct strength calculation, as well as the Guidelines for Fatigue Strength Assessment which define the requirements for fatigue strength evaluation for stress-concentrated parts.

The second is Guidelines for Hull Monitoring issued in June 2021 (ClassNK 2021). The Guidelines consist of a main section, Appendix A and Appendix B. The main section stipulates the requirements for individual devices constituting a hull monitoring and for the entire system as well as the procedure of Surveys. Appendix A summarizes the function for evaluating the fatigue strength on the assumption of utilizing it for maintaining and managing the ships, while

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Appendix B summarizes the function for utilizing measurement data on the assumption of assisting ship operation in the rough conditions.

5.1.1 Autonomous shipping

With the advent of technology, autonomous shipping has received a significant importance recently. Various organizations are working in this field and their contributions are discussed below. This topic was recommended for review by the previous ISSC Committee II.1 (ISSC 2018a). The regulatory framework has been updated, but at no means finalised. The implementation is not directly linked to quasi static response; therefore, no corresponding literature is presented.

IMO

The IMO commenced work to investigate various aspects of Maritime Autonomous Surface Ships (MASS) operations which may be addressed in IMO instruments. The technical body of IMO, the Maritime Safety Committee (MSC), endorsed a framework for a regulatory scoping exercise. This exercise will include preliminary definitions of MASS and degrees of autonomy, as well as a methodology for conducting the exercise and a plan of work.

The scoping exercise will be carried out in two steps. As a first step, the exercise will identify and assess the applicability of present provisions in an agreed list of IMO instruments to ships with varying degrees of autonomy and/or whether they may impede MASS operations. As a second step, an analysis will be conducted to determine the most appropriate way of addressing MASS operations, taking into account various factors including the human element, technology and operational factors. In this context, IMO published an Interim Guidelines for MASS Trials in 2019 (IMO, 2019).

IACS

International Association of Classification Societies (IACS) is closely following the work through various forums and class societies are involved in scooping exercises carried out by IMO. A Position Paper on MASS was published by IACS in 2019 (IACS, 2019). IACS has included the following agenda item in its strategic Action Plan, having noted the importance of MASS-related issues for the shipping industry.

i. Review all IACS Resolutions and Recommendations with the intention to identify and address possible requirements which may hinder the technical development of Smart ships/Intelligent ships/MASS and monitor regulatory development in that area (2017-2018).
ii. Address possible issues which may hinder the technical development of Smart ships/Intelligent ships/MASS and contemplate a need to reform the existing IACS Resolution structure to accommodate Smart ships/Intelligent ships/MASS, and how best to complete such a reform process (2018-2019).

As a key technical advisor to IMO, IACS will use its knowledge and expertise in establishing as safe a future as possible for shipping working industries.

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Researchers/Shipyards/Ship Designers

Im et al (2018) have designed a smart autonomous ship architecture that enables Unmanned Ship by using intelligence Information Technology (ICBMS + AI). They derived the technology through the analysis from various angles such as components of ship, characteristics of shipping logistics, duties and roles of crew, and applications of intelligent information technology.

As per the information provided in the official website (Kongsberg, 2020), Kongsberg is developing self-driving ship control systems for Maritime Autonomous Surface–Ships - MASS / unmanned ships. They are involved in several projects, focusing on integrated sensor technology, and automated collision avoidance and they hold the world's first contracts for commercial delivery of an autonomous vessels. As informed on the website (NYK, 2019), (Nippon Yusen Kaisha (NYK) has conducted the world's first Maritime Autonomous Surface Ships (MASS) trial in 2019 performed in accordance with the IMO's Interim Guidelines for MASS trials.

5.2 Development of software

Developments in Classification Society software was well covered within the previous committee's report (ISSC 2018a). It is appreciated that updated versions of the discussed software have been issued during the term of this committee. However, only notable developments or issue of new software related to quasi-static analysis has been discussed below.

BV

To facilitate the EDW approach BV has updated its rule scantling software MARS and FEA package Veristar-Hull. The small ship software Starboat is updated and now includes the scantling criteria for yachts. BV is running pilot projects in 3D approval, an interface software package to transform most CAD extensions into BV's Veristar-Hull FEA package and MARS software is developed, omitting the need to submit 2D construction drawings.

ClassNK

ClassNK has developed its hull structure evaluation software "PrimeShip-HULL" based on abundant experience of drawing approval and system development. It is more than just a mere rule checking tool, incorporating design support software that has intuitive UI as well as fast processing speed. In recent years, ClassNK has released the version for gas carriers and improved the data exchange interface with the 3D ship design system "NA-PA Designer".

Hydro-Structural Software

The development of the nonconventional ships and offshore platforms, for which the classical rule approach (with prescribed loads) cannot be safely employed led to the development of the independent hydro-structure interaction software to be used within the so-called direct calculation approach. Up to recent years, the hydrodynamic software was mainly based on the potential flow approach which employs the Boundary Integral Equation method to calculate the hydrodynamic pressure. Thanks to the quasi-static assumptions for the structural response, the technical difficulties associated with the coupling reduce to the development of an efficient numerical procedure for transfer of the hydrodynamic pressure from hydrodynamic model to the finite element model of the structure. Most of the Classification societies have their own direct calculation software (Bureau Veritas – HOMER, DNVGL – SESAM, ABS – Nload3D, Lloyd ShipRight, CCS – COMPASS, class NK's Hydro-Structural – PrimeShip-DLSA) but several independent software were also developed such as: WISH, THAFTS, ANSYS – AQWA, and others. At the same time, due to the rapid improvements of the CFD methods based on solving directly Navier Stokes Equations, and despite their relatively high computational cost, the coupling of these methods with the 3D finite element structural models is also rapidly developing. However, due to their computational cost these CFD based tools cannot be used alone, because the design verification procedure should cover the entire life of the structure, and this is not

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practically possible using the CFD tools exclusively. That is why the combined use of the potential flow and CFD solvers is recommended.

5.3 Concluding remarks

The quasi-static rules and standards issued by classification societies remain the primary standard for a vessel's structural design. Increasingly, guidance is being issued on more direct approaches via hydro-structural coupling, made possible by the computational power of computers. Besides the rule updates mentioned in this chapter, the focus of regulatory bodies was/is in the energy transition in the drive towards lower emissions, which in time may have more direct impact on quasi-static approaches, particularly where innovative methods for alternative fuel storage may be required.

6. UNCERTAINTY IN THE USE OF QUASI-STATIC RESPONSE APPROACHES

6.1 General aspects about Quasi-Static Approach and its uncertainty assessment

In the ISSC report of the last term (ISSC 2015a, ISSC 2018a), uncertainty assessment and reliability analysis of ships and offshore structures using quasi-static response analysis approaches were discussed. The focus was given to the uncertainties in environmental loads, responses and strength modelling and different structural reliability calculations when a quasi-static approach was used. In the recommendations of the last ISSC report of this committee (ISSC, 2018a), uncertainty assessments and quantifications for loads, load effects and structural strength are considered as important future research topics. Therefore, the current committee wants to review the recent work in this direction and report the findings in this chapter.

From the reliability analysis point of view, a proper model quantifying the uncertainties in different stages of loads, responses and strength analyses is needed. In principle, one needs to explicitly address all possible aleatory and epistemic uncertainties in environmental conditions, prediction of loads and responses (extreme responses for ULS design and fatigue damages for FLS design) and prediction of structural strength (ultimate and fatigue strength), in order to do such structural reliability analysis. Moreover, typically numerical tools and numerical simulations are used to obtain responses of the considered systems. Therefore, the model uncertainties in connection with these numerical assessment methods should be addressed (DNV 1996). It is one of the aims in this committee to review the research work with qualitative and preferably quantitative assessment of the uncertainties in connection with the quasi-statics approaches for response analysis.

A quantitative assessment of the model uncertainty (X=R_T/R_QS, DNV (1996), where R_T is the true response, while R_QS is the response estimated using the quasi-static approach. X is the model uncertainty, which is typically characterized by a Gaussian random variable) requires a comparison of the quasi-static approach with the most accurate numerical methods or the measurements from model tests or field tests and is expressed as a probabilistic distribution or the statistical mean value and standard deviation assuming a Gaussian distribution. In general, there are limited work that address such uncertainties and directly derive a probabilistic model, that can be used in structural reliability assessment. However, many researchers compared the accuracy of the quasi-static approaches with other reference approaches or experimental work, in terms of underestimation or overestimation by a certain percentage, referring to the mean value of such probabilistic distribution of the model uncertainty. On the other hand, the scatter of such accuracy with respect to different environmental conditions and load cases are not often reported or evaluated, but in general required for model uncertainty assessment.

It is very rare that engineers do structural design by calculating explicitly the structural reliability or failure probability of the system. Uncertainties are often taken into account in the reserve factors (load factors and material factors) in design format of design rules, e.g., DNVGL-OS-E301 Position Mooring (DNVGL 2018). Typically, a higher load factor is used when a quasi-static approach was used to obtain mooring line tension responses, as compared to a dynamic approach, to reflect higher uncertainties that are involved in using a quasi-static

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approach. Or for lifting assessment in accordance with DNVGL-ST-N001, where a Dynamic Amplification Factor (DAF) is utilised to account for the increased load seen in lift points and rigging arrangements due to dynamic motions during a lifting operation (DNVGL 2020).

It is difficult to generalize the accuracy or the uncertainty of quasi-static approaches for response analysis. However, a practical way is to evaluate the uncertainties in different stages of assessment for loads, responses and strength under the quasi-static (quasi-steady) assumptions and then combine these uncertainties for the approach for final response analysis.

The remaining part of this chapter is organised so that the uncertainties in using the quasi-static assumptions or approaches for environmental loads analysis, motion and/or structural response analysis as well as strength analysis are assessed. At the end, a section is included when probabilistic models of loads, responses and strengths are explicitly used in reliability and risk assessment.

The presentation of this chapter differs from other chapters, in a sense that the references cited here clearly indicate the accuracy/uncertainty of the quasi-static approach in terms of mean value, standard deviation or probabilistic distributions.

6.2 Environmental loads modelling and its uncertainties

As for gravity loads or operational loads like ballast, which typically do not vary in time or slowly vary in time, quasi-static approaches can be well used to address the responses that are induced by these types of loads. However, for structures with rotating components, such as wind turbine rotor, ship propeller, tidal turbine, even gravity loads can induce deterministic dynamic load effects in the structural components. Moreover, most of the ships and offshore structures are subjected to environmental loads due to wind, waves, current, earthquake or ice-structure interactions, which has a time-variant and even stochastic nature. These loads are dynamic and from the response point of view, only when the loading frequency is much lower than the natural frequencies of the structure motions or vibrations, a quasi-static approach can be used (DNV 2010).

In some aerodynamic and hydrodynamic problems, viscous effect might be important for the global loads and response analysis of offshore structures. Such effect, both excitation and damping, is traditionally modelled as drag force using a quasi-static (or more precisely quasi-steady) formulation, as a function of the inflow velocity or the relative velocity due to structure motions. In most of the cases, a predefined constant drag coefficient is used for short-term time-domain analysis, although it is possible to use Reynolds (Re) and Keulegan-Carpenter (KC) number dependent drag coefficient for each time step in such analysis (DNV 2010). In such method, the unsteady dynamic effect due to the change in inflow condition or the motion of structures is neglected. Such method is suitable for efficient global loads and response analysis. In recent years, there are some publications on this topic.

6.2.1 Quasi-steady approach for analysis of damage stability and damaged ships in waves

Damage stability should be considered in design of ships and floating oil & gas platforms. Damage stability analysis and response analysis of ships or floating platforms under damaged condition often require a simulation of inflow/outflow through the damage opening and their effect on stability or motion responses. Rodrigues & Guedes Soares (2017) studied the transient still water vertical loads progression for a shuttle tanker in full load condition during the flooding process as a result of ship collision. The flooding progression is numerically simulated by a quasi-static version of a generalized adaptive mesh pressure integration technique code for progressive flooding of floating objects, see Figure 3. The still water vertical loads are calculated by neglecting the inertial effect since it is a slow process. It is observed that the bending moment increases more as the section evaluated is closer to the damage location.

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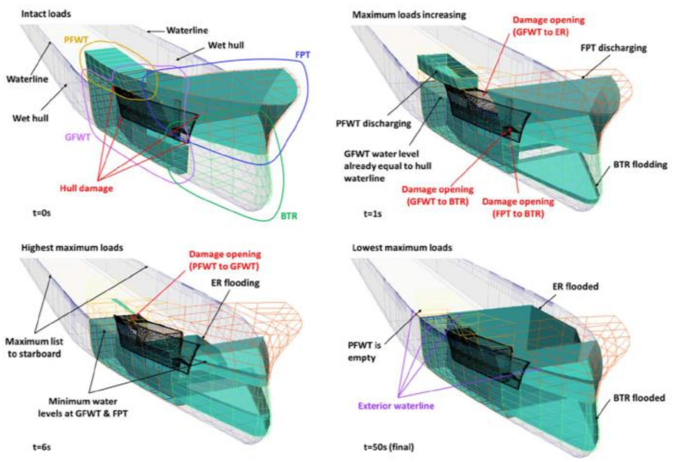

Figure 3: A quasi-static approximation of progressive flooding for dynamic analysis of damaged ships, from Rodrigues & Guedes Soares (2017).

Moreover, in a study regarding ships in waves under damaged condition, Siddiqui et al. (2020) did an experimental study to assess the motions of a ship cross-section in waves under the damaged condition and a numerical model based on a strip theory considering the viscous effect was developed and validated against the model test results. The hydrostatic restoring effect due to the inflow and outflow of the water through the opening is modelled using a quasi-steady approach and it is only dependent on the rotational position of the ship cross-section, which is found to be a reasonable assumption.

In Parunov et al. (2020), the six codes used in prediction of the global linear wave loads on damaged ships were compared. Two main aims of the study were to acquire valuable information regarding damage modelling in seakeeping analysis and to quantify the uncertainty of linear seakeeping tools. The uncertainty analysis was performed with the use of Frequency Independent Model Error (FIME) by comparing the numerical predictions with available experimental data. It was found, that in general, vertical bending moments and shear forces show larger dissipation with comparison to vertical motion components. Additionally, the strip theory significantly overestimates the global loads values.

6.2.2 Wave and current loads on aquaculture fish cage net

Hydrodynamic loads on fish cage net are very complicated due to the dominance of viscous drag force and the large deformation of the net. It is also a computational challenge to model individual lines in a net structure. Screen model proposed by Kristiansen & Faltinsen (2012) has been successfully developed and applied to predict the current loads on fish cage net, in which both lift and drag forces on a net panel are determined based on the quasi-steady flow condition relative to the net panel in terms of flow angle and Reynolds' number.

In a recent paper by Chen et al. (2017), a numerical procedure coupling a flow solver based on a porous media model and a structural solver using a lumped mass model was developed, in which constant hydrodynamic loads considering a quasi-steady state flow condition was assumed for each time step, while large net deformation was solved by iterations within each time step. The numerical results were compared against experimental data for both steady and unsteady flows, giving satisfactory results of 10-15% underestimation.

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6.2.3 Wake effect of wind turbines and tidal turbines

In design of offshore wind turbines, coupled aerodynamic and hydrodynamic load and response analyses are often performed using time-domain simulation tools, in which Blade Element Momentum theory with engineering corrections to consider dynamic wake and dynamic stall conditions is applied. In an early study of dynamic responses of spar floating wind turbines, Karimirad & Moan (2012) demonstrated that the motion response statistics (in terms of mean value, standard deviation and 1-hour extreme value) obtained using a simplified approach (based on a quasi-steady relation between wind speed and thrust force) only have a maximum 10% difference as compared to the full BEM method. Moreover, in some consideration, a quasi-steady approximation of the aerodynamic forces acting on the blades is used to derive an efficient linearized aerodynamic load model to be used in an optimization analysis, which typically requires a parametric modelling of the loads and responses with respect to design parameters (Hegseth et al., 2020). Such quasi-steady approximation is normally carried out for a given mean wind speed with sufficient accuracy. Similar approach is also used when developing more advanced model-based controller for floating wind turbines (Fontanella & Belloli, 2021).

In Leroux et al. (2019), the thrust and power coefficient of a tidal turbine and the velocity in the wake were analysed using CFD based on a quasi-steady simulation approach and a transient simulation approach. The comparison against measurement from a model test was also performed. In the quasi-steady CFD simulation approach, the governing equations of motions are solved in the reference frame that is rotating with the rotor speed and as a result, while the transient simulation approach solves the equations of motions in the normal reference frame. As compared to the experimental results, the quasi-static approach underestimates the thrust coefficient by 16% and the power coefficient by 5%.

6.2.4 Ice loads and ice-structure interaction

Ice-structure interaction may lead to complex loading conditions on the structures due to different ice failure mechanisms and can induce strong vibration problems. Details about ice loads are discussed in Chapter 2. In dealing with failure of level ice due to bending, the extended finite element method (XFEM) in combination with linear elastic fracture mechanics (LEFM) was used by Li et al. (2020a) to simulate the cracking in level ice due to bending loads at the ice edge. In particular, the inertial effect of ice on the bending failure was investigated. It was found that the crack initiates slightly earlier and needs slightly more energy to propagate to the top of ice surface, when using the quasi-static assumption in which the ice inertial effect is neglected. In conclusion, a quasi-static approach can be used to simulate the ice bending failure as long as the ice moving speed is low, in the order of 0.5 m/s. Furtherly, based on the large number of simulations executed in FE software, the meta-model using neural networks is created. The uncertainty analysis with respect to modelling assumption is performed, leading to quantification of model uncertainty. This type of models could be used in ship-ice interaction problems and especially in reliability analysis.

6.3 Response analysis and its uncertainties

When considering a structural system under the applied continuous environmental loads, a quasi-static approach for response analysis can be used if the inertial effect of the system is small. From the excitation frequency and system natural frequency point of view, such method is applicable when the excitation frequency is much smaller than the natural frequency. This is the basic design consideration for the dynamic performance of ships, offshore bottom-fixed or floating platforms. Depending on the ratio between the excitation frequency and the natural frequency, a dynamic amplification factor when using the quasi-static method can be applied to obtain the correct response.

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From structural stress analysis point of view for bottom-fixed structures, one has to check whether the external loads excite vibrational modes or not, while for floating structures, it also matters whether the external loads excite only resonant rigid-body motions or both resonant rigid-body motions and structural vibrations. In the latter case, structural vibrations need to be explicitly considered in the global load and response analysis. Normally, in the follow-up structural stress analysis, both external loads and inertial loads due to these resonant behaviours should be applied to obtain structural stress time series using a quasi-static approach.

Impulsive hydrodynamic loads, such as wave slamming, may induce both global vibrations or motions of offshore structures as well as local deformations or vibrations of structural plates. In such conditions, one has to compare the loading frequency with the natural frequencies of both global modes and local structural vibration modes. However, if the impulsive loads duration is larger than the highest natural period of the vibration of local plates, a quasi-static approach can still be valid for local stress analysis (Ringsberg et al., 2017).

6.3.1 Response analysis of bottom-fixed structures

One of the important issues for bottom-fixed structures under wind and wave loads is related to soil-pile interaction which can be very complex, depending on the mechanical property of the soil and the structural property of the pile. Typically, the soil reaction force is modelled as 2D or 3D nonlinear springs and in some cases with a hysteric loop to reflect the soil damping effect, for which the inertial effect is neglected. However, soil will degrade under cyclic loadings, which leads to a load-history dependent property. In a recent paper by Liang et al. (2018), a method using a hyperbolic p-y backbone curve and considering the soil stiffness degradation with the average shear strain is developed to establish a quasi-static p-y hysteric loop. The developed hysteric loop is analysed with constant, variable and mixed amplitude displacement loadings and can reflect the soil-pile separation and the soil degradation reasonably well.

In analysing the structural responses of bottom-fixed structures under extreme wave loads, a quasi-static approach is often used for structural response analysis due to non-breaking waves and the Morison-type loads considering nonlinear wave kinematics can be applied. However, in case of breaking waves, a combination of a quasi-static and a fully dynamic approach is considered, in which structural responses due to the underlining nonlinear wave loads are estimated based on a quasi-static approach, while the global responses due to the impulsive slamming loads are calculated using a dynamic approach. Such method is developed and illustrated for a jacket foundation for offshore wind turbines under steep and breaking waves by Wang et al. (2020). However, the peak response obtained by the quasi-static approach with slamming loads excluded underestimate the total peak response by about 25%.

Moreover, when designing structural components under water pressure loads, a quasi-static structural stress analysis is often used, and the vibrations of the local structures are neglected. For example, Harper et al. (2015) carried out a study for design of composite tidal turbine blades. A quasi-static structural analysis of the blade under extreme loads was performed considering a dominant failure mechanism of composite materials, i.e., the interfacial failure (delamination) between the composite layers (plies).

6.3.2 Response analysis of floating structures

For floating structures such as floating oil & gas platforms, floating wind turbines or ships, a dynamic global analysis considering environmental loads due to wind and waves is always performed to predict the floater rigid-body motion responses. Stresses in structural components of the floaters are often obtained by a local quasi-static analysis based on a finite element method, following the global response analysis and applying the inertial loads due to global rigid-body motions and vibrations and environmental loads as external loads. In some cases when hydroelasticity becomes important, a flexible structure should be considered in the global response analysis (Malenica & Derbanne, 2014).

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Similar as discussed for bottom-fixed structures, methods for predicting stress responses of a floating structure under wave slamming loads are also of great interest in recent years. An interesting benchmark study was performed in the previous ISSC II.1 Quasi-Static Response committee (ISSC 2018a), regarding structural stress analysis of a free fall lifeboat due to water entry impact loads using different numerical methods as compared to the experimental results. One of the comparisons were made for quasi-static and dynamic nonlinear finite element analysis methods. The impact loads were idealized pressure loads with a long (quasi-static) and a short (dynamic) duration. The strain responses are then compared using different numerical methods. As compared to the strain responses from the experiment, the quasi-static linear-elastic approach seems to give reasonably good results since the water energy impact loads are mainly carried by membrane stresses and the effect of plate bending is small and the strains are below the limit of plastic responses.

When predicting motion responses of a moored floating structure, a catenary mooring system is often modelled considering only the restoring effect, meaning that the effects due to the inertial loads, the drag forces and the sea bottom friction forces on the floater motions are neglected. In other words, the mooring system effect is modelled using a quasi-static approach and such analysis is referred to as uncoupled analysis. When calculating the mooring line tension considering the fairlead motions and the direct wave loads on lines, a dynamic model of the mooring line is used. As an improvement of the quasi-static mooring line model, Fan et al. (2017) developed a mooring line damping model based on a quasi-static mooring line configuration under the floater motion excitations. As compared to the model test results, the developed model agrees well with the test results of mooring line damping considering both the mooring line drag and sea bottom friction induced damping effect. An averaged error between their model and the experimental results is about 2-3%.

6.4 Strength assessment and its uncertainties

6.4.1 Ultimate strength assessment

An ultimate strength analysis, either using experimental methods or numerical methods, is referred to as an analysis to determine the maximum allowable load that a particular structure or structural component can take under a given load patten. They represent the strength of a structure, which is in many cases independent of the actual loads that are applied on the structure. However, they might be characterized as stress (like yielding stress) or as load (like often used for buckling strength). For a complex structure, a progressive collapse analysis is often performed with the inertial effect neglected.

Ultimate strength assessment of stiffened plates is important for ship hulls and offshore plate structures like semi-submersibles. Traditionally, ultimate strength assessment is based on empirical formulae or nonlinear finite element analysis considering a quasi-static approach, in which the dynamic effect, especially the strain rate effect on the yielding stress of the materials is neglected. In the recent paper by Yang et al. (2018a), dynamic ultimate strength of stiffened plates under in-plane compression and lateral pressure was addressed using nonlinear finite element methods. It was observed that the dynamic ultimate strength increases with the increase of strain rate, indicating that the quasi-static approach underpredicts the ultimate strength of the stiffened plate and therefore is conservative for design. Moreover, the lateral pressure has a significant effect on the quasi-static ultimate strength, while has limited influence on the dynamic strength.

In another paper by Yang et al. (2019), dynamic ultimate strength of simply supported rectangular plates under compressive impact loads were studied using nonlinear finite element methods. The dynamic ultimate strength depends strongly on the ratio between the impact duration and the bending natural period of the plate. A quasi-static approach can be used when this ratio is larger than 2, for which it gives about 10% underestimation of the ultimate strength.

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6.5 Probabilistic Modelling of Loads, Responses and Strength, Reliability Analysis and Risk Assessment

In recent years, for design and analysis of ships and offshore structures, probabilistic modelling of the aleatory uncertainties in environmental conditions (such as stochastic wind and waves) and/or degradation conditions (such as corrosion) and their effects on loads/responses and structural strength have been further developed. However, the epistemic uncertainties associated with the quasi-static approaches, as discussed above, are not emphasized and systematically investigated in most of the studies. Many quasi-static approaches are directly applied in response analysis in combination with the environmental loads uncertainty model in order to perform a structural reliability calculation.

In Gaggero et al. (2020), the uncertainties related to estimation of hull girder still water loads of bulk and dry cargo ships were analysed. With comparison to wave loads, which are stochastically originated, the still water loads are usually calculated during the design stage in deterministic way. However, the observed loading/unloading conditions are often very from those assumed by a designer. In referred study, the Monte Carlo simulations, as shown in Figure 4, were carried out based on the information taken from operating ships leading to still water bending moment probability density distributions. This kind of distributions can be directly applied in reliability analysis and further extension of this type of studies for other ship types will be valuable.

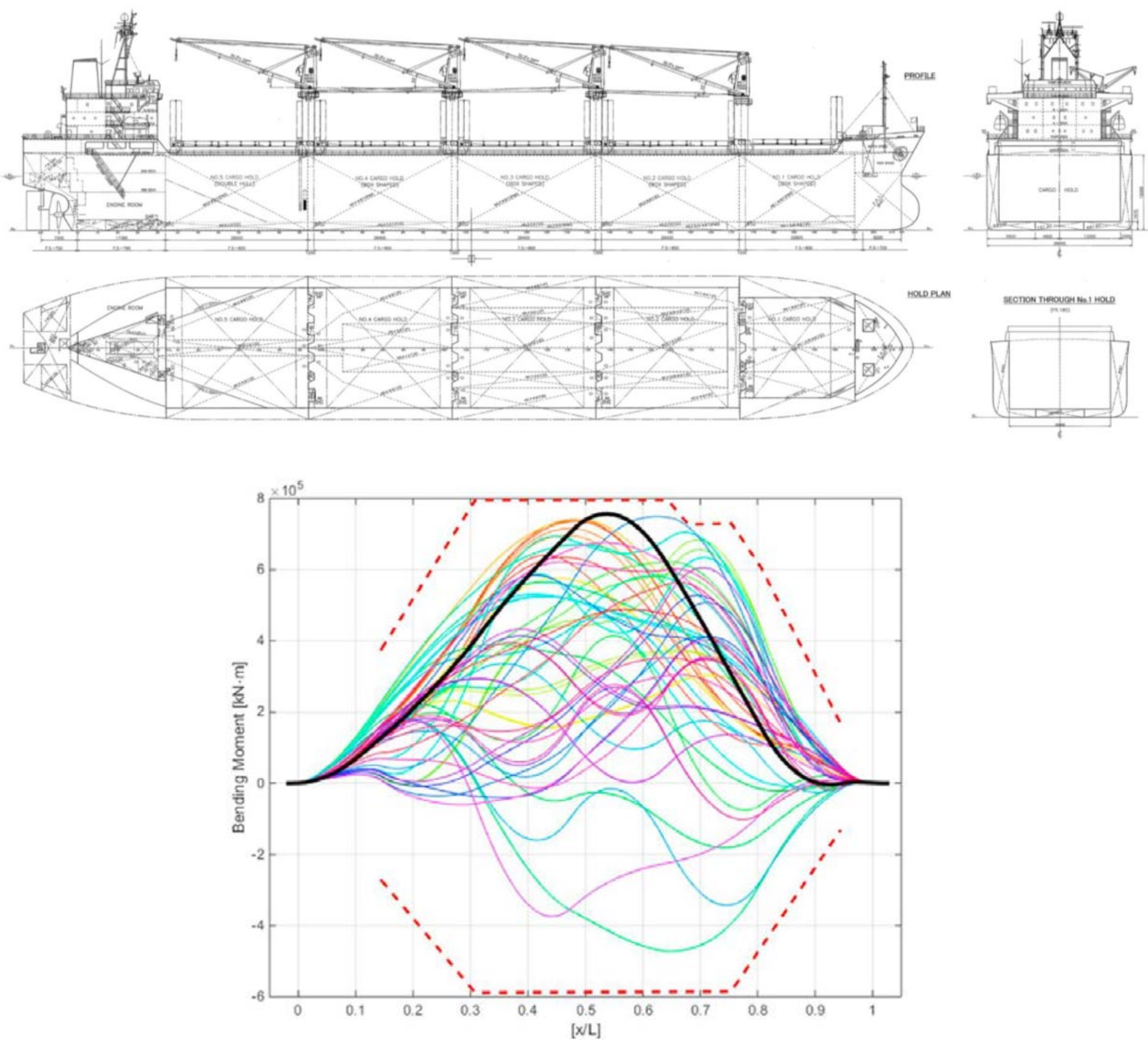

Figure 4: Bulk and dry cargo ships (left) and Monte Carlo simulated still-water bending moments (right) due to different operation conditions, from Gaggero et al. (2020).

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For ship operations, one might be interested in establishing a data-driven model which predicts the ship motion statistics or probabilistic distributions based on the operational settings for stochastic environmental conditions, considering a quasi-static relation. Cheng et al. (2019b) developed a framework for sensitivity and uncertainty analysis of ship motions in offshore operations. In this work, the surrogate model is established based on the real ship operational data. The sensitivity and uncertainty analysis are performed based on the weights that are generated by artificial neural network (ANN) model. As a result, the probability density functions of ship motions are derived.

A hull girder ultimate strength reliability assessment and reliability-based optimization of a typical 20000TEU container ship was proposed by Zheng et al. (2018). In this article, the authors perform hull girder ultimate strength assessment by Smith's Method, then First Order Reliability Method (FORM) and Particle Swarm Optimization (PSO) were employed to solve the weight reduction optimization problem with reliability constraints and multi-objective optimization to search for the Pareto front.

Doshi et. al. (2017) introduced the applications of fracture mechanics-based fatigue crack evaluations to prepare reliability-based inspection plans for a Very Large Crude Carrier. Probabilistic considerations have been applied taking into account the uncertainty in various parameters related to the loads, materials as well as the parameters of fatigue crack growth. Bayesian approach was used for updating of reliability of a given ship structural detail. Various cases such as no-detection of crack, detection of crack with & without repair have been considered, then, the results have been also compared with the reliabilities in the current practice of fixed periodical inspections.

In a similar study, Khan et. al. (2018) outlined a probabilistic fracture mechanics approach to predict the fatigue life of welded steel details in the presence of cracks under random environmental loading on an offshore structure, i.e., marine riser. The probabilistic bilinear fracture mechanics model is undertaken with the help of recently published data in support of bilinear crack growth relationship. A nonlinear 3D dynamic analysis has been carried out in time domain for each sea states, then, the probability of failure and reliability indices obtained for long-crested random sea plus vessel/ platform motion using FORM and Monte Carlo simulation.

De Garcia et al. (2019) compared the two statistical wave models that are used to derive the fatigue loads in ship structural analysis. By comparison of long-term distributions of significant wave heights with comparison to class guidelines it was concluded that the differences in fatigue damage calculations can reach even 100% of overestimation. Additionally, the wave models were compared with real measurements from the container ship equipped with a ship-hull monitoring system showing a good agreement. The statistical scatter of the analysed fatigue damage based on the wave models were derived showing their capabilities in more realistic fatigue life predictions.

6.6 Concluding remarks

In this chapter, recent research work that addressed the accuracy or the model uncertainty of the quasi-steady assumptions in environmental loads prediction and the quasi-static approaches for structural response analysis are reviewed. An attempt is made to identify the publications that highlight these issues and result into a quantitative model uncertainty assessment in terms of mean value, standard deviation or probabilistic distributions. Not so many papers are found to directly address these issues. Most of the research focused on using directly quasi-static approaches in different stages of analyses for complex problems, knowing or assuming that the accuracy of such approximation is sufficiently good. Even in some studies, where the comparison between quasi-static approaches and more advanced approaches or measurements from experimental or field tests was made, limited discussions about the model uncertainty of such methods for different scenarios and environmental conditions were made. Similarly, as concluded and recommended by the previous committee (ISSC 2018a), future research is needed to explicitly assess uncertainties that are related to the different methods for assessing loads,

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load effects and strength for ships and offshore platforms to provide useful inputs for further structural reliability analysis. For the research topics that are relevant for this committee, more systematic accuracy/uncertainty assessment of quasi-static approaches for different applications should be carried out.

7. CONCLUSIONS & RECOMMENDATIONS

7.1 Conclusions

The committee reviewed recent publications related to quasi-static response analysis applied to ship and offshore structures, as defined by the committee's mandate. The report consists of discrete sections covering structural response and strength analysis, approaches to load modelling, as well as uncertainty quantification in the use of quasi-static methods. A further section provides a review of the development of quasi-static methods within Classification Society Rules, procedures, and guidance documentation.

Although ship and offshore structures spend their in-service life in a changeable stochastic loading environment, the ability to simplify the design process provides significant benefits to structural designers. For this reason, quasi-static methods continue to be relevant to the structural design process, forming the basis of wide-ranging rules and regulations across the marine industry.

With increasing computational power and development in calculation processes in available software packages, it can generally be seen that presented research is more heavily weighted to the time-domain approach, often directly coupling loading and structural response and considering fully the dynamic effects of the responses due to external or internal excitations. Whilst these approaches, when implemented well, will provide a much better representation of the structural performance of ship and offshore structures, they are by nature time-consuming, do not lend themselves well to analysis in early design phases where structural definition may be immature, and as such the results of time-domain analysis may not provide any greater understanding of the structural performance than a more simplified approach. For these, and other reasons, development of quasi-static approaches continue, though designers and analysts must recognise where the limits of application exist. This is particularly relevant where quasi-static methods are utilised as the basis functions of methods such as optimisation and reliability analysis, where the uncertainties in the quasi-static method could be as important as the specific variables to be assessed. Nevertheless, as a short summary, quasi-static methods are found suitable for the following situations for structural stress analysis in the design process for ships and offshore structures:

- Early-stage or conceptual design of floating structures when the focus is on the global load and motion response analysis.
- Design optimization when a significant number of design parameters and efficient design analyses need to be considered.
- Structural stress analysis when the design loads are given, and the structural dynamic effects are limited.
- Assessment of fatigue stress concentration factor when the far-field stress distribution is given.
- Determination of global or local structural ultimate strength under the given load patterns.

On bottom-fixed structures, as long as the wave loads do not excite the resonant vibration of the structure either in steady-state or transient conditions, a quasi-static analysis can be performed to obtain the stresses in the structure due to wave loads. On floating structures, from a motion analysis point of view, both low-frequency and wave-frequency motion responses have to be considered using a dynamic analysis approach, while structural stress analysis can still be performed using a quasi-static approach applying hydrodynamic pressure loads and rigid-body motion induced inertial loads. Exceptions are hydroelasticity problems, or where natural

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frequencies of the structural response are coupled with the loading frequency. Similar considerations are applicable to the wind or ice induced loads and structural responses.

Developments in Classification Society rules and procedures continue to be founded on quasi-static methods, though development over the reporting period has generally been shown in Chapter 5 to be incremental, though it can be seen elsewhere in the report that research continues across broad topics in this field.

Chapter 2 presented developments in load modelling, and how advances in complex analysis methods can provide further benefits to simplified methods. The presented research indicated continued developments in environmental loading from waves, wind and ice, as well as development in sloshing and slamming where precise dynamic modelling is complex and difficult to achieve. Developments also continue in accidental load quantification. Some new techniques are introduced for load analysis and identification, such as peridynamics, Genetic Algorithm (GA) and machine learning.

Presentation of structural response analysis in Chapter 3 highlights the continued importance of quasi-static methods in the design and analysis of ship and offshore structures directly, or as the basis to optimisation and reliability methods. Developments are presented in direct analysis through the derivation of empirical formulations or factors to modify load curves to account for the influences of phenomenon such as springing and whipping.

In strength assessments reviewed in Chapter 4, quasi-static methods and empirical formulations have been derived across buckling, ultimate strength (intact and residual strength), and fatigue analysis. Where local strength or buckling capabilities are considered, derivation of empirical formulas may be through the use of non-linear FEA. Such derivations rely on quasi-static assumptions to enable application in the assessment of ship and offshore structures, and it is these types of formulations that have led to rule developments.

Design formulations for global strength are more complex to derive due to the potential variations in structural arrangements and local scantlings. However, research has been presented in these areas, as well as in the development of the progressive collapse method, which implements an incremental loading to a section of ship structure, discretised in to stiffened-plate elements. The progressive collapse method continues to feature in Classification Society procedures for ultimate strength assessment, despite the advances in the ability to undertake non-linear ultimate strength assessment by FEA.

In fatigue analysis, there is a procedure to obtain hot-spot stresses or stress concentration factor when normal stresses in the structure are already obtained. Such analysis, either based on empirical formulae or finite element analysis with refined mesh, often neglects the dynamic effect since there is very limited local vibrations in the hot-spot areas and therefore is a quasi-static analysis.

Most of the Classification society's rules and recommended procedures use calibrated partial safety factors (PSF) or load multipliers in their formula/methodologies, limiting true understanding of the structural response by the analyst. This fact should always be kept in mind when the hydroelastic effects, for example springing and whipping, are introduced in the analysis.

As discussed in Chapter 6, there are very limited research publications, purely focusing on the development and validation of quasi-static methods for particular problems. Most of the research in the field of ships and offshore structures concentrate on the development of more advanced methods that can handle dynamic (both transient and steady state) effects, as well as nonlinearities in loads and responses. However, in analyses which requests very efficient calculations, for example conceptual design and comparison, design sensitivity and optimization, structural reliability assessment, quasi-static methods are directly used with some justification in choosing such methods. Assessment of the uncertainties associated with methods is important to enable appropriate selection of analysis methods as well as their applications in structural reliability assessment.

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7.2 Recommendations

Due to the continued and widespread use of quasi-static methods across the marine industry, it is the view of the committee that research into the development of these methods should continue.

Noting the continued increase in presented articles implementing time-domain analysis, researchers should continue to investigate the potential to develop quasi-static methods as a further step to such analysis work. It is also relevant for researchers to inform where quasi-static or other simplified methods can't, or shouldn't, be used, such that the industry can be suitably informed on their use and applicability.

Where quasi-static methods are developed, quantification of the uncertainties in, or reliability of, the method itself should be considered and presented, which may be achieved through comparison to experimental tests or from real world data sources. This will allow analysts to further consider the suitability of methods for direct use, or within optimisation or reliability methods. These considerations and the identified gap in such presented information could form the basis of a benchmark study consideration for this committee in future terms.

The work presented within this report has grouped and reviewed publications related to different types of analysis (stress, strength, fatigue, etc.). Future committees may wish to consider whether a review of methods in relation to their suitability for use within different phases of the lifecycle of the marine structures presents a differing view on the suitability of methods, or to allow identification of future research areas from a different perspective. In future the use of quasi-static methods may expand, for example being useful in the identification of structural faults and/or defects in conjunction with digital-twin models for through life performance monitoring.

To implement a cost-effective and rapid design process in the detailed design phases, it is recommended that researchers consider the development of quasi-static design loads that can be used to assess the safety of marine structures under more complex dynamic loadings. Future efforts should focus on quasi static approach on the real sea complex wave loads, ice loads, wind loads and their combination. In fact, collision loads, fire and explosion load all are dynamic loads that usually cause dynamic responses. The maximum response and the final condition to these accident loads is concerned in assessment process that can be equivalent to a quasi-static loading.

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