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COMMITTEE IV.1

DESIGN PRINCIPLES AND CRITERIA

COMMITTEE MANDATE

Concern for the quantification of general sustainability criteria in economic, societal and environmental terms for marine structures and for the development of appropriate principles for rational life-cycle design using these criteria. Special attention should be given to the issue of Goal-Based Standards as concerns their objectives and requirements and plans for implementation. Possible differences with the safety requirements in existing standards developed for the offshore, maritime and other relevant industries and of the current regulatory framework for ship structures shall be considered. Role of reliability-based design codes and requirements as well as their calibration to established safety levels

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CONTENTS

1. INTRODUCTION

Design principles and criteria form the overall framework for assessing marine structures against societal sustainability goals for economic, social, and environmental performance. Recent ISSC Committee IV.1 reports have focused their coverage on the extensive developments in the areas of both sustainable design approaches and the emergence of goal-based standards at the IMO. Over the last two decades, developments in these areas have been rapid. However, as seen in the shorter ISSC IV.1 report of 2015, fundamental developments for addressing such goals appears to be tapering off. During this mandate period, the committee found the focus switching to implementing and verifying goal-based standards and regulations.

Thus, the structure of the current committee report reflects these developments. First, this report reviews the developments in the framework for both sustainability and goal-based standards during our mandate period. Then, following the shift into implementation in these areas, the committee's work focuses on recent developments in several areas relating to design principles and criteria. A special chapter on using on-board monitoring data for both decision support and rule development is presented. As the cost of gathering weather and structural response data for vessels at sea falls dramatically, the best ways to use such data in support of structural integrity requires careful exploration. In-service updating from such monitoring systems could allow improved lifecycle performance, including longer asset lives, enhanced safety, and reduced environmental and property risks from in-service failures. As the marine structures themselves change, such as the recent explosion in containership sizing, the ability to weave in-service measurements back into design criteria has become essential.

Two additional focus chapters provide further insight into the development of rules and criteria in related areas. Accidental load estimation is covered, as the direct simulation of marine structures in accidental conditions is becoming increasingly common. Such analysis can further reduce the negative impact of marine structures by directly minimizing adverse outcomes in accidental conditions. Then, a review of Polar criteria, including a brief summary of ice load prediction methods and a review of the comparisons between different rule sets is presented. Complementing the longer chapters, shorter sections review developments supporting sustainability design. A short section on in-service reassessment for life extension covers recent criteria and procedures for both offshore oil structures and the emerging challenge of aging offshore wind turbine structures. A review of inland navigation developments and reliability-based design approaches are included. Finally, a review of the role of human error in engineering analysis, and methods to control and prevent such errors when establishing design methods and criteria are also included in the report. This report should be read in conjunction with several additional ISSC reports which cover fundamental developments in related fields. The work on in-service re-assessment and on-board monitoring is complemented by the work of specialist committee V.7 on Structural Longevity, especially their Chapter 3. The work in both Polar and accidental loading is complemented by specialist committees V.6 and V.1 respectively. Finally, owing to the tight coupling between design principles and design tools, the report of committee IV.2 also complements the work here.

2. CONCEPTS AND DEVELOPMENTS IN PRINCIPLES AND CRITERIA

2.1 Sustainability and Lifecycle Principles

The foundation on Sustainability and lifecycle principles remain the same from the 2015 Committee's work in this area, and the introduction to that report is reproduced here to provide a consistent background definition:

> The present report, as the previous ISSC reports of Committee IV.1, follows the same general definition of sustainability that was given by the Brundtland Commission of the United Nations: "economic development which meets the needs

of the present generation without compromising the ability of future generations to meet their own needs"(UN-WECD, 1987).

A sustainable development of the maritime transport involves therefore a detailed consideration of all the negative implications such transport mode has for the human society (social costs) and a proper assessment of compliance to the general sustainability target, based on a cost/benefit analysis.

As stated by Korzhenevych et al. (2014), transportation contributes significantly to economic growth and enables a global market. Transport modes, however, also produce negative effects. Shipping traffic, in particular, contributes to air and water pollution and shipping accidents to losses in terms of human lives, economical losses and ecological damages. These effects give rise to costs that can be expressed in monetary terms and affect in various ways the Society: health costs caused by air pollution (due to NOx, SOx, PM, …), lives lost and loss of biodiversity in traffic accidents, costs related to the world scale climate impact of shipping, etc.

These societal costs are referred to as external costs, that sum up to those directly borne by the transport first and second parties (private or internal costs, such as: wear, tear and energy cost due to the ship operation, own time costs, transport fares and transport taxes and charges (port fees, pilot, insurance, etc.)). The same kind of classification applies to benefits: first and second parties take advantage of most of them, even though society also experiences a gain.

The external costs of transportation are generally not paid by transport actors and hence not taken into account when they take a decision about a transport activity. Internalization of external costs means making such effects part of the decision-making process of transport first actors. This can be done directly through regulation, i.e. issuing specific requirements in terms of operational and/or design control measures, or indirectly, providing suitable incentives to transporters with market-based instruments (e.g. taxes, charges, emission trading, etc.). Combinations of these basic types are also possible.

In other terms, the role of the Regulator is to assess if and under which conditions a transport activity is acceptable from a Societal viewpoint and to establish a Regulatory Framework able to control the societal losses and redistribute their costs in a balanced way, in particular on the first actors of the transportation process (internalization of the external costs). In a technical analysis of sustainability, it is important that all external costs are included. All kinds of costs incurred during the lifetime of the product must be assessed. Additionally, some social costs are incurred also long after the product lifetime has expired, as is the case for the CO_2 emitted during the lifetime of the product. It is also important to include external costs of all raw materials that goes into the product, like e.g. the steel used to construct a ship. In a comparison of sustainability of e.g. different transport mode, it is also important to properly account for the differences in tax regimes. The key point of this concept is a proper evaluation of the external costs, (also called social or implied costs) that are now not directly perceived as such by the actors. This means, in a first place, the identification of all implications (negative and, in case, positive) of the transportation process and a quantification on a monetary scale.

The design principles described in ISSC IV.1 committee from 2015 have been applied in a recent study on damage stability for passenger ships (Hamann, 2015). Prior to this study, which is based on the EU Impact Assessment (IA) Guidelines (EU, 2009), a Formal Safety Assessment (FSA) per IMO (2013) had been carried out by Vassalos et al. (2016). Both the IA and the FSA used the same risk acceptance criteria as recommended in Spouge and Skjong (2014), also published in Spouge et al. (2015). The difference between the two approaches, FSA and IA, is described in Skjong (2015).

The main technical difference between the approaches is that the IA include all external costs in the analysis. This is not normally done in an FSA, although there is nothing in the IMO FSA Guidelines that indicates that this shall not be done. For this specific case of damage stability, the Risk Control Options (RCOs) that were considered involved design changes that would change the fuel consumption and the steel weight of the ships. Per the FSA Guidelines the increased cost of fuel and steel had been included. However, per the IA Guidelines the external costs of the fuel had to be included also (Mainly CO_2, SO_x, NO_x, NMVOC, and PM) as well as the external costs of steel (from steel production). Since the issue mainly related to investing in increased safety, the key question was therefore: Would the inclusion of external costs (largely from environmental impacts) change the recommendation?

The basis for the recommendations are in both cases the Net Cost of Averting a Fatality (NCAF).

$$NCAF = (\Delta Cost - \Delta Economic\ Benefits)/\Delta PLL$$

ΔCost is the life cycle cost of the RCO, ΔEconomic Benefits are the life cycle economic benefits (e.g. the reduced risk of loss of ship) and ΔPLL is the reduction in Potential Loss of Life. The difference between the two are due to the external costs. Table 1 contains the results for small cruise ships. In Hamann (2015), there are results for large cruise ships and for small and large Ro-Pax ships. There are also sensitivity studies, and the RCOs are described in detail.

Table 1: NCAF (€ million) per the FSA and IA Guidelines respectively (Small Cruise Ship)

	RCO 1	RCO 2	RCO 3	RCO 4	RCO 5	
NCAF (FSA)	-0.11	6.6	8.9	7.7	9.9	
NCAF (IA)	-0.11	6.6	9.9	8.4	13	
	RCO 6	RCO 7	RCO 8	RCO 9	RCO 6 (C+G)	RCO 9(C+G)
NCAF (FSA)	14	31	28	7.8	2.8	1.5
NCAF (IA)	20	42	39	9.4	3.7	1.8
C+G implies that the effect of the RCO for both Collision and Grounding are included						

RCO 1	Sill increased on external weathertight aft doors
RCO 2	Vs.01 + Deck 3 made watertight for comp n.2 and n.3
RCO 3	Vs.02 + Cross flooding section within DB void spaces improved adding pipes
RCO 4	Vs.03 + Two weathertight door added and a watertight door added on BK deck
RCO 5	Vs.04 + Increased Beam by 0.2m (new B=20.2m)
RCO 6	Vs.04 + Increased Beam by 0.5m (new B=20.5m)
RCO 7	Vs.06 + Increased freeboard by 0.25m
RCO 8	Vs.07 + Increased Beam by 0.5m (new B=21m)
RCO 9	Vs.04 + Increased Beam by 0.1m (new B=20.1m)

Assuming a criterion of €7million per life saved, the recommendation from the IA and FSA would be identical (green). Assuming a criterion of €8million, RCO4 and RCO9 would change from being recommended per FSA, but not per IA (yellow). It should be noted that the NCAF for RCO1 is negative. This is because the RCO can be recommended for commercial reasons (the economic benefits are larger than the costs), in addition to the resulting life saving.

The damage stability case is unique in respect to the formulation of the regulatory requirements. Since SOLAS (IMO, 2009) damage stability requirements have been probabilistic. The implication is that the requirement is a so-called Required Index, R. The attained index, A, is a reflection of the conditional probability that a ship survives (not sinking or capsizing) a collision with water ingress. The requirement is thus simply A>R. The RCOs mentioned in Table 1 are therefore only used as examples of how to demonstrate that the damage stability can be improved, and make it possible to calculate the improvement and the costs. A designer is free to choose any other RCOs or design options as long as the requirement is fulfilled. At the Maritime Safety Committee of the International Maritime Organization the recommendations were adopted in June 2017 and will enter into force in 2020. The required index R, is a function of the number of people on board.

The IA carried out in EMSA III had a reduced scope, as only the RCOs identified by FSA was subject to a reanalysis based on the IA Guidelines. In a complete IA, there might have been other RCOs that could be recommended.

There are currently many cases of regulations where there is a conflict of interest between ship safety and environmental protection. To extend the IMO approach in the FSA Guidelines to including all external costs in the assessment of regulatory options would therefore have clear advantages and constitutes a consistent and transparent regulatory philosophy.

2.2 Goal-Based Approaches

The work at the International Maritime Organization (IMO) relating to Goal Based Standard (GBS) was initiated in 2002 with a submission by Greece (Greece, 2002) 'Building Robust Ships'. The paper argued that "competition for newbuilding orders between classification societies makes it imperative to have unified standards on all fundamental aspects of ship design and construction". The paper referred to the fact that by SOLAS II-1/3-1 IMO delegated the task of monitoring, verification and certification of the design and construction of ships to classification societies, but that this was not enough. In the view of Greece, IMO should invite the International Association of Classification societies (IACS) to complete without delay the development of Unified Standards and to submit them for consideration and endorsement by way of an MSC Resolution, with a view to amending SOLAS regulation II-1/3-1 and making their application mandatory through reference to the Resolution.

The later development of Goal Based Standards for Bulk Carriers and Tankers are described in in Section 5.1 of the 2015 report of this committee. The audit process of the Rules of the Classification Societies was carried out per plan. Twelve IACS member societies submitted their rules, and the IMO Maritime Safety Committee (MSC) spring meeting in 2016 marked a critical milestone. Unexpectedly, the audit resulted in five non-conformities in the common IACS structural rules etc., whose main component is "Common Structural Rules for Bulk Carriers and Oil Tankers" (IACS, 2015a), and one in the Lloyd's Register submission. However, having fully considered the GBS audit reports (IMO, 2016a) as well as IACS' plans to rectify non-conformities (IMO, 2016b) etc., the MSC "overwhelmingly confirmed that the information provided by the Submitters (12 IACS member ROs) demonstrates that their rules conform to the GBS Standards." (IMO, 2016c) It was agreed that "the identified non-conformities are to be rectified" and "requested the ROs to address the identified observations in the future, taking into account the recommendations made by the audit teams and the Corrective Action Plans" (IMO, 2016d).

Upon receipt of the document MSC 98/6/1 submitted by IMO Secretary-General, containing the GBS non-conformities verification audit report, the IMO Maritime Safety Committee confirmed that the request of MSC 96 that the identified non-conformities be rectified and that the whole process of the initial verification audit was successfully completed in accordance with the GBS Verification Guidelines (IMO, 2017a).

Peschmann et al. (2017) summarized the above and highlighted some of the challenges noted during the implementation and verification of the GBS Standards based on the latest investigations carried out by IACS with respect to safety margins within the rules and the principles of rule validation and benchmarking. The current work at IMO relates to amending the audit process based on the experience gained. Specifically, this relates to amending “Guidelines for Verification of Conformity with Goal Based Ship Construction standards for Bulk Carriers and Oil Tankers” (IMO, 2010). This work is scheduled to be completed in the spring meeting of MSC in 2018.

The MSC is also discussing how to conduct GBS maintenance verification audits and agreed that IACS and its member societies should submit rule change information by 31 March 2018 and then the outcome of the first maintenance audit will be considered in the autumn meeting of MSC in 2018 (IMO, 2017b).

IMO also developed the ‘Generic Guidelines for Developing IMO Goal Based Standards’(IMO, 2015a), and there is a clear tendency at IMO to develop new Codes in a goal based format. For example, the recent ‘IGF Code’ (IMO, 2015b) and ‘Polar Code’ (IMO, 2015c, 2014) are both goal based and entered into force on January 1st 2017. It seems that the trend of developing goal-based codes is firmly established. The codes are mandated by anchoring them into the conventions.

The work at IMO, has also inspired the ‘Naval Ship Code’ to be developed in the Goal Based format, see http://www.navalshipcode.org/.

The development of the Goal Based Standard/Safety Level Approach (GBS/SLA) as an alternative to the Generic GBS is also described in the 2015 version of this committee’s work, Section 5.1. This approach, which is formally risk based and linked to Formal Safety Assessment (IMO, 2015d) is still debated at IMO MSC. Draft guidelines are available.

It is to be noted that the current probabilistic damage stability regulations described in Chapter 2.3 is already based on GBS/SLA principles. The requirement to damage stability (the Goal) is simply to comply with the required index (R). There is full freedom of the designer how to achieve this. There are verified software tools available. The method is probabilistic, and as explained in Chapter 2.3 the required index for passenger ships has been justified by FSA (and EU Impact Assessment).

2.3 In-Service Reassessment for Life Extensions

While most work on structural design principles and criteria addresses newbuildings, there is growing interest in extending the service lives of existing ships and offshore structures beyond their original design life. Such extensions typically require reassessment of the structural adequacy, while making allowances for both the service life of the structure to date, and changes to structural design codes since the structure entered service.

Extending the life of offshore oil and gas platforms remains one of the most active areas of research into structural criteria. Chapter 4 of the report of specialist committee V.7, Structural Longevity, covers analysis framework and sensor development in this area, this section focuses primarily on the development in assessment criteria and regulations for these structures. By 2005, the majority of the fixed offshore platforms worldwide were already operating beyond their design life (Moan, 2005). Initial work before the current mandate period on North Sea oil platforms provided criteria for life extensions. This includes an Aging and Life Extension (ALE) project conducted by the United Kingdom Health and Safety Executive from 2011-2013 under the name KP4, and Norwegian standards N-006 and U-009 dealing with platforms and subsea components respectively. Within the mandate period, mainly periodic updating of these approaches was observed, such as a new edition of N-006 in 2015. Nezamian and Nicolson (2016) provided a recent overview of strategies for FPSO life extension, including an example for a FPSO operating off of Africa. Notably, they highlight the need to manage platform integrity beyond classification-society based criteria to maximize the profitability of the platform for the owner.

During the period of the committee's mandate, oil platforms in the Gulf of Mexico were the focus of progress in life-extension criteria. Compared to the North Sea platforms, the Gulf of Mexico platforms have several unique challenges. In U.S. waters, the floating infrastructure is only now beginning to approach their design life, with many platforms still less than 20 years old (Phillips and Martyn, 2016). Life extension regulations did not exist for this sector at the beginning of the current mandate period, and the committee has been able to trace the development of criteria over the last three years. Additional challenges in U.S. waters include a fractured regulatory approach, where both the U.S. Coast Guard and the Bureau of Safety and Environmental Enforcement (BSEE) are responsible for oversight, with the Coast Guard focused on the hull system and BSEE focused on mooring and production systems. Neither agency is equipped to directly approve life-extension plans but wish to approve a review of the plans conducted by a third-party certified verification agent (CVA). Classification societies have been proposed as CVAs, but CVAs are not formally limited to such organizations. Finally, and perhaps most significantly, the ocean environment in the Gulf of Mexico is now more severe than assumed during the initial design of many platforms in the 1990s. This change is partly a result the frequent significant hurricanes observed in the 2000-2010 period. This results in higher environmental loading on the platforms, which must be assessed during the service life extension (Hua et al., 2017; Rosen et al., 2016).

Phillips and Martin (2016) provide an initial overview of the criteria for life extension, and historical failure data underpinning the U.S. Coast Guard's efforts in this area. This was followed by official guidance and criteria for re-assessment of platforms within the United States jurisdiction in the Gulf of Mexico presented in the form of a letter from CAPT JD Reynolds, dated 19 January 2016 (Reynolds, 2016). The letter outlines a three-step approval process consisting of: an initial plan for the life extension, a baseline survey to establish the current condition of the platform, and an engineering and risk assessment. These three steps will be reviewed by both the United States Coast Guard and BSEE. The letter further recommends review by a third-party CVA such as a classification society. The flowchart is shown below in Figure 1. Of note, production process equipment and subsea equipment is not typically assessed in this process (Hua et al., 2017). Two published accounts of moving a platform through this process have also recently appeared. Hua et al. (2017) present an overview of the life extension process for the *Neptune* spar, the world's first production spar, installed in Viosca Knoll in the Gulf of Mexico. This 215m classic spar was installed in 1996 with a 20-year design life, and Noble Energy wished to extend the life at least three years. While the inspection and condition of the spar was generally satisfactory, the site-specific design storm condition had increased significantly. The 100-year storm calculated in 1995 had 12.1m significant wave height with a 39 m/sec wind speed. By 2014, these values had increase to 14.8m and 43.8m/sec respectively. For this spar, the higher values were not problematic as the effective weight of the platform had been reduced as many risers had been removed from the platform, but it does highlight the potential role of new design storms in complicating service life extensions.

Gallagher et al. (2017) provide a similar overview for the *Genesis* spar, another classic spar installed in 1998 with a 20-year design life. In this case, a 10-year life extension was proposed based on remaining field conditions. Given the spar's location, the design storm conditions did not change to the extent of the *Neptune* spar. A proprietary risk matrix develop by Chevron was used in this analysis, and an important finding of the assessment was that there are significant financial risks to the owner during the life extension that should also be assessed along with the safety risks. The authors note that this is caused in part by the standard operating procedure of shutting down production and evacuating the platform for an approaching hurricane. This significantly reduced the life safety and environmental risks associated with the platform, but the financial risks of remain. The authors noted that their philosophy was to track both risks, and while only the safety risk required regulatory approval, before investing in the life extension, the financial risk also needed to be controlled. The American Bureau of Shipping has served as the CVA on several life extension projects in the Gulf of Mexico. In support of this role, during the mandate period, they released a first guidance note on the life extension process, which was then updated in May of 2017 (American Bureau of Shipping, 2017). During the mandate period, little research into new principles to apply for life extension appeared. There were many publications extending and refining existing assessment methods for life extension such as spectral fatigue (e.g. (Aeran and Gudmestad, 2017)), but the review of such calculation-specific methods primarily belongs to other ISSC committees. Tan et al. (2016) was one of the few exceptions, proposing to apply a novel DHGF-based theory to life extension decision making. This paper includes an example of the life-extension of a shallow water platform with a 15-year design life in the Bohai Bay.

Interest in life extension plans for offshore renewables is also growing, especially as the age of the oldest major offshore wind turbine farms begins to approach their design life. Ziegler and Muskulus (2016) note that in the early 2020s the first major windfarms such as "Anholt" and "London Array" will begin to reach their second decade of service. In general, maintenance modeling and optimization of such farms during operation as received extensive attention, as well as determining when the end of useful life is likely to occur (see Shafiee and Sørensen (2017) for a recent review paper on these topics). However, there appears to be a gap in methodology at the present for the structural system. Most such work in the past has focused more on the mechanical system of gearboxes, generators, and auxiliary equipment on the turbine and less on the turbine structure itself. Onshore wind farms are ahead of offshore wind farms in developing solutions, with expectations of strong market demand for life extension strategies in the next five years (Ziegler et al., 2018).

During the current mandate period the first research and criteria for structural life extension have begun to appear, starting the process of filling this gap. Work at NTNU has begun to look and offshore wind turbine crack growth for life extension (Ziegler et al., 2016; Ziegler and Muskulus, 2016), including the impact of load sequence and seasonality on interpreting inspection results. DNV-GL has issued guidance notes on life extension for both onshore and offshore wind turbines (DNVGL, 2016a), while Bureau Veritas has issued a white paper on life extension (Bureau Veritas, 2017). Bureau Veritas divides the life extension approach into three categories depending on how much in-service and site-specific data is available. The Danish strategic industry-government-industrial partnership Megavind has also issued a white paper on life extension (Megavind, 2016), including location-specific failure modes and areas of concern. Megavind divides life extension strategies into four categories depending on the type of monitoring data available, ranging from no measurements through complete multi-year load, wind speed, and turbulence measurements. The similarity between this approach and the Bureau Veritas approach further highlights the growing need for through-life data collection to support cost-effective life extension. Life extension considerations for other offshore renewable energy systems seems largely unexplored at the moment, reflecting perhaps that these systems have lagged wind turbines in large-scale adoption. However, a PhD thesis exploring the component reliability drivers for tidal stream devices has recently appeared (Delorm, 2014). Such initial work may lay the foundation for future efforts to address wave and tidal devices as well.

Commercial and naval ship life extensions criteria development have not been as active as the offshore criteria, perhaps a reflection of the challenging economic conditions for commercial shipping during this mandate period. The papers that appeared mainly dealt with calculation methodologies, not principles and criteria, and thus the primary review of this information can be found in Committee V.7. Looking at the higher-level trends from these papers, there is some similarity to the developments in the offshore world that are worth commenting on. A spectral fatigue re-analysis of a Moss-type LNG carrier to support service life extension was presented in a Korean-language paper by Park (2016). Similar to the offshore oil and wind turbine life extension approaches proposed, this method relied heavily on customizing the wave exposure to the known routes of the ships. Soliman et al. (2016) provide a probabilistic framework to plan inspection, monitoring and repair against the three objectives of service life, life-cycle cost, and the delay in detecting potentially critical defects. This approach is partly adapted from the bridge maintenance approaches. As the approach focuses more on operational decisions, the principles explored are possible to apply for mid-life updates as well as design-stage studies. Naval vessel publications that focus on service life extensions also appear rare. Most of what has been proposed has focused on building optional service life extension in at the beginning of the design life. Temple and Collette (2017) provided a framework to trade between different cost aspects during design assuming probabilistic service life extension profiles, while Knight et al. (2015) proposed a variant of real-option theory to evaluated include extra structural capacity in a naval vessel at the design phase for a potential life extension later.

2.4 Human Performance in Engineering and Criteria Evaluation

2.4.1 The Challenge of Human Performance in Engineering

Despite significant progress in including allowance for operational human error into marine design procedures and standards, the marine community has not extensively explored the role of human error in engineering analysis, decision making, and approval assessment itself. Such engineering errors have been shown to contribute to many in-service failures in both marine and other structural systems. Additionally, as engineering analysis methods and performance criteria become more complex the role of human factors in successfully assessing compliance with the required criteria is growing. Thus, in assessing structural design criteria, the questions emerge how should the human engineer's limitation be considered in criteria development? And are there any recommended standards or procedures for accounting for such error?

Other industries have examined the role of analysis errors on business performance, including notable work in the financial industry. The ability of humans to manage complex software systems has also been studied extensively in both aviation and medicine. However, little recent work has appeared on these issues in the marine industry. By contrast, the civil engineering structural community has actively pursued the study of engineering error. Given the similarities between civil and marine steel structures, many of their findings appear applicable and enlightening for the marine community. This section will review both marine and civil studies on human error in engineering.

2.4.2 Past Work

Modern investigations of the human performance of engineers during structural design date to the 1970s and 1980s (Melchers, 1984; Melchers and Harrington, 1983), during the transition to reliability-based LRFD design codes. As various sources of uncertainty in structural loading and resistance were quantified, the performance of human engineers was also examined. Both historical failures and engineer's performance on simple tasks were examined. Overall, it was estimated that roughly 40% of failures stem from errors during the design phase (Melchers, 1984), a figure which appears to have remained remarkably stable with current civil engineering data from Europe (Terwel et al., 2014). Additionally, error rates for individual engineering tasks were shown to be roughly 1% for simple engineering steps such as table lookup, 2% for two-step calculations, 5% for not understanding written documentation. When combined into overall design processes, error rates were shown to be as high as 14% for the design of 2-D portal frames, which are not complex structures (Melchers, 1989, 1984). More recent work has confirmed similar error rates on simple 2-D structures some 30 years later, at least in the civil engineering community (Fröderberg, 2014).

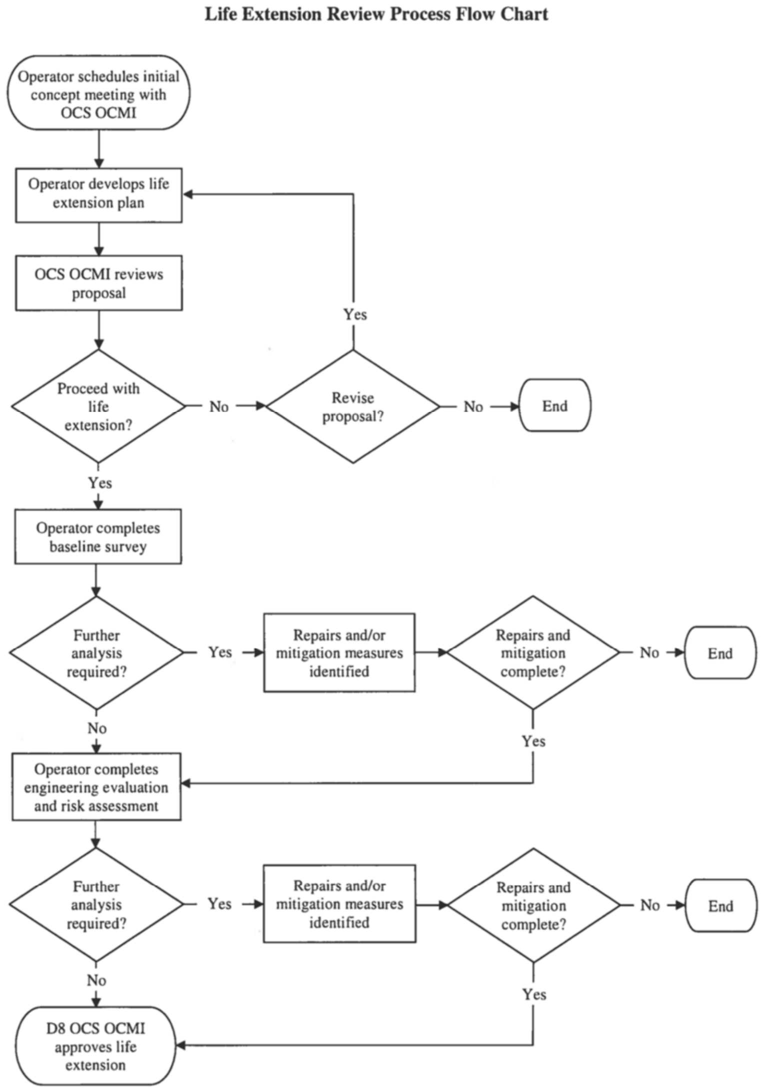

Figure 1: Approval Flowchart for Life Extension on U.S.-Regulated Gulf of Mexico Floating Platforms (Reynolds, 2016)

Shortly after this initial work, a major study of human error in the marine field was published by Bea (1994). For a mix of marine structures for vessel and offshore application, Bea built upon and largely confirmed the work of Melchers and others in the proceeding decade. Engineering human error during design and construction, including both knowledge and communication lapses appears be significant in the marine world. Given the potential magnitude of human engineering errors, and the difficulty in mathematically modeling such errors, the first generation of reliability-based LRFD codes did not include provisions for human error in the partial safety factors used to cover other uncertainties. Instead, the literature at the time (Bea,

1994) focused on quality control and review as the most beneficial approach to minimizing the impact of human error. The late 1980s and early 1990s saw the emergence of Total Quality Management, ISO 9001, and other similar quality-focused approaches which supported the idea that engineering management would be the best method to reduce human error. However, recent post-TQM/ISO 9001 studies in the civil engineering field continue to show roughly the same error rates and error types as these initial studies. Therefore, it is reasonable to ask how successful the quality management principle has been. Such a review will also shed light on the work around human error to further understand how it may impact the design principles and criteria used for marine structures.

2.4.3 Scope of the Current Review

In investigating the issues around the performance of human engineers, recent work in two areas was sought out:

- The occurrence of errors originating from a mismatch between the design codes and numerical models used in marine structural engineering and the engineer's understanding of these codes and models. Since the late 1980s, both the number and complexity of design codes has increased, and the same type of increase occurred for numerical modeling. Thus, the types of errors experienced today may be different or more concerning.
- Errors in communication of model assumptions and meaning between team members, or between the team and approval bodies. As design and approval work continues to rely on large, often globally-dispersed teams, and the design tasks and models used become more complex, the role of communication and team dynamics is expected to grow.

Specifically excluded from this taxonomy is the broader issue of validation and verification of specialized numerical codes. Such V&V approaches have been extensively discussed in the literature. V&V is a distinct problem from that addressed here: that of models created by the engineers in the act of design and approval of a particular vessel or offshore structure. The analysis of human performance of the engineering team appears in its infancy in the marine world. Other domains, such as aviation and medical surgery have performed extensive analysis of both the factors impacting team performance, as well as the development of errors between numerical systems assisting the team and the team members. The remainder of this section will explore ongoing research in different areas relating to human engineering performance. First, the limited work done on the impact of ISO 9001 quality certification will be reviewed, followed by a discussion of mental model discrepancies as a framework for exploring error. Then, the impact of design codes, spreadsheet tools, finite element analysis, and group settings will be reviewed in turn. Finally, conclusions and commentary on the current state-of-the-art will be provided.

2.4.4 Review of Ongoing Research

The ability to formalize quality management to improve company performance and reduce human error continues to be a topic of research. The ISO 9001 certification, built from the quality management ideas explored in the late 1980s and early 1990s has received significant attention. As engineering errors are rarely publically discussed or reported in a central location to allow statistical examination, direct studies of the impact of ISO 9001 on engineering performance are limited. However, recent studies on overall corporate financial performance, presumably positively impacted by reducing human error has been mixed. A recent review of 397 publically-traded firms in the United States, but not exclusively engineering firms, noted a significant positive impact on corporate financial performance following ISO 9001 certification (Aba et al., 2015). However, work in Italy has not confirmed these findings for manufacturing firms in that country (Franceschini et al., 2016; Galetto et al., 2017). Concerns around interpretations of ISO standards include the idea the compliance only certifies that a company has a checking system in place, not auditing that actual checks are carried out correctly (Fröderberg, 2014). Additionally, ISO-required checking systems are internal checks, but recent research on major land-based structural designs in Hong Kong has shown the benefit to using an external audit approach in place of internal checks (Palaneeswaran et al., 2014). In certain sectors of the marine industry, classification societies provide exactly this external review role. Thus, class-approved and non-class approved structures may have significantly different human engineering concerns.

Much of the recent work on human performance in engineering has stepped away from categorizing human errors on small piecemeal tasks of engineering calculations to look at broader issues of how humans work with engineering problems. This tracks with increasing evidence that errors in the overall conception of the problem are significant, perhaps more so, than individual errors in calculation steps. Additionally, such conceptual errors are difficult to catch with self-checking compared to purely mathematical or table-lookup errors. This line of thinking points to the concept of the engineering mental model – the engineers vision of the structure and its environment – as key to understanding the process of engineering analysis.

The growing complexity of structural design codes has emerged as a potential cause of human error during engineering. In many cases, structural mass can be reduced by using more in-depth analysis or requiring consideration of additional potential failure modes. Such improvements are highly worthwhile overall, owing to the improved efficiency of lighter structures, and improved safety from more rigorous checks. With modern computational support, the added calculations in such procedures are not expected to cause additional errors. However, more complex codes may lead to more severe problems in understanding and correctly using the code (Bulleit, 2008) owing to its complexity. Such complexity can also cause the engineer to focus on each component in isolation, and miss the overall system view of the structure leading to incorrect analysis (Björnsson, 2016). Others have suggested that design codes be progressive – starting with simple basic analysis that clearly links the code provisions to underlying structural dynamics, and then allowing more refined analysis as an option when it will lead to reduced structural material or cost (Muttoni and Ruiz, 2012). Such an approach also has the advantage of following the overall design process, where the final design emerges from rough initial concepts. In doing so, the engineer will be forced to start with a strong overall view of the system, and then refine local structural assessments as needed later in the design process.

A range of computer models are also used in the development and assessment of marine structural designs. While perhaps the most pedestrian, the basic spreadsheet is still in widespread use today. At the 2012 ISSC, Committee IV.2 reported on the engineering software in use in marine structural design, and spreadsheets were highlighted as an important and commonly used tool in the structural design and approval process (Pradillon et al., 2012). Spreadsheets allow any engineer or other user to automate and program calculations as they see fit. Unfortunately, this end-user programming has been shown to be difficult to quality control. An entire organization, the European Spreadsheet Risks Interest Group (www.eusprig.org) is now dedicated to tracking such errors. Recent surveys of business software spreadsheets have indicated that almost one out of four spreadsheets with formulas in them contain basic Excel errors, and that emails passing spreadsheets around were ripe for confusion about versioning and control of the documents (Hermans and Murphy-Hill, 2015). Previous work had indicated even higher overall error rates, though not all errors impacted the final results of the spreadsheet as currently used (Powell et al., 2009). Recent work continues to focus on the ideas of the problem of understanding spreadsheets by users who did not develop the spreadsheet, with lack of context for exploring the spreadsheet's formulas and structure cited as a key concern (Kohlhase et al., 2015). The difficulty in understanding context ties into the concept of mental model developed above. Spreadsheets feature normally-hidden formulas that are often written in cell notation instead of problem variables, making them difficult to understand for engineers who did not build them. Procedures and standards for improving spreadsheet and detecting errors are now emerging (Mireault, 2015; *The FAST Standard 02b*, 2016), however, much of this work currently focuses on financial spreadsheets, not engineering calculations.

Beyond spreadsheets, informal discussions have also highlighted the role in which engineer's mental models may diverge from more complex numerical models of structures. For example, users who are not the developers of an in-house analysis code may be confronted with a large number of tunable settings whose impact and role are not clearly captured in the limited code documentation. In this situation, analysts of differing levels of experience with the code may produce very different results (Dr. Paul Hess, Personal Communication October 2017). Lack of transparency in the underlying model is not limited to in-house codes however. Research indicates that complex design codes, commercial software, and group settings can all lead to mismatches between engineer's mental models, often leading to human engineering errors. Recent work in both aviation, marine operations, and medicine has explored this type of problem. In aviation, the term used is "mode error" or "mode confusion" where the crew's mental model of what the automated system on the aircraft are doing departs from the reality (Sarter and Woods, 1995). Similar issues in developing mental models have been reported in marine dynamic positioning operations (Øvergård et al., 2015; Sætrevik et al., 2018). While engineers operate under lower time pressure than aviation or marine operations, there is still reason to believe the mental model – computer model divide is reason for concern. However, there is no evidence yet of researchers using these error frameworks to explore human errors in engineering design.

Finite element analysis is perhaps the most commonly used advanced calculation tool in structural design. Thus, work on the engineer's experience of finite element analysis is a logical place to look for the impact of human errors. Similar to spreadsheets, most FEA codes contain GUIs where mesh, element, and simulation options are buried under complex tree structures, menus, and dialog boxes. Similar to mode errors in automated systems, one wonders if the analyst is always fully aware of what model options are currently active. Indeed, human error in using finite element codes was one of the major reasons for disagreements mentioned in a round-robin study of determining crack trip stress intensity factors in piping systems (Han et al., 2016). This conclusion has been echoed by other authors previously in larger structures (Sgambi, 2005).

Beyond the difficulties in correctly using complex finite element codes, the impact of the complex analysis method on the engineer's focus has also been investigated. The demands of building and completing an FEA model can cause the engineer's focus to immediately be drawn to the lowest levels of structural detail, thus missing larger system effects. This effect was captured in a study by Fröderberg (2015), where the results of 14 Swedish engineers independently designing identical truss systems ended up with solutions whose weights had a coefficient of variation of 28%. These engineers had at least a MSc level of education and averaged 12 years of experience. Particularly, the difficulty in quickly iterating through geometry concepts in finite element software was noted, as the finite element software modeling requirements tended to lock them into their initial concept. Similar concerns of complex software reducing the system-level understanding have been voiced previously (Luth, 2011). The similarity between losing system-level understanding with advanced analysis tools explored here and of losing system-level understanding with complex design codes discussed earlier is notable. Such similarity implies that it is not so much the software's layout or GUI that matters, but how the calculations and modeling required impacts the part of the problem that the engineer focuses on.

Studying interactions with structural codes, spreadsheets, and analysis tools only captures human error originating from a single human engineer operating in isolation. However, most marine structural design is now done in a team setting, with a variety of engineers working on the same project. For more complex projects, it is also likely that these engineers would be geographically dispersed. Such team settings mean that communication of engineering results, and indeed the development of a shared mental model of the structure are also important. While general team dynamics has been widely studied for the past 30 years, structural engineering teams have also recently received research attention. Communication lapses between team members has long been highlighted in civil and marine engineering as a contributor to human mistakes (Atkinson, 1999; Bea, 1994). More recent work on this concept in civil engineering structures has determined that the fragmentation of most design-build engineering sequences contributes to these communication lapses (Love et al., 2012). When a sequential, over-the-wall approach is used with designers, approval bodies, and final builders, even when potential errors are identified it is difficult to "move upstream against the natural flow of the process" (Love et al., 2012) to rectify the problem.

The growing acceptance that the information flow through design teams is central to understanding errors has led to several recent studies to focus on how teams process information, using analogies to social graph models (such as Facebook). A formal model of information flow in engineering teams has recently been proposed (Schneider and Liskin, 2015). This model has been extended to include the influence of social mood on the success of design communication in 34 software engineer teams (Klünder et al., 2016) and to more formally link to social network analysis (Kiesling et al., 2016). Similar efforts to use social network theory to describe the ability to identify and manage design errors in different organizational structures has been explored by At Hattab and Hamzeh (2015). Finally, drawing inspiration from stream-of-variation modeling, Strickland (2015) proposed the Process Failure Estimation Technique to study the composition of marine design teams and the likelihood of errors propagating through design processes. All of these works are at early stages, and the research does not appear to be immediately ready to transition into real-world decision guidance, criteria, or standards. There has been a rapid growth in wider social network analysis techniques recently, and a number of publications that have appeared in this area in the last two years focusing on engineering teams. This situation indicates that studying design team social dynamics is an area of growing interest in the quest to reduce human errors.

In large civil-engineering structural design studies, the design team has also been shown to be a potential source of error correction. Mentoring, supervision, work culture, and thoughtful review of the work of others have all been claimed to reduce error rates in large structural engineering projects in recent studies (Fröderberg, 2014; Love Peter E. D. et al., 2015; Love Peter E. D. and Smith Jim, 2016; Palaneeswaran et al., 2014). Many of these studies are qualitative in nature, based on experience or interviews, however their conclusions are notably consistent. The success of such approaches points to a potential path forward, less structured and formal than ISO 9001, that would allow complex design code and analysis tools to be used while minimizing the types errors discussed above.

2.4.5 Assessment of the State of the Art of Engineering Human Performance Criteria

The role of human error during the engineering design and approval stage of marine structures remains unclear. The last significant marine-focused work is now 25 years old. Recent work, primarily in the land-based civil engineering community, has highlighted several reasons to be concerned about such errors: they represent a significant portion of total errors and in-service failures, there is reason to suspect that more complex regulatory codes and numerical models are impacting how engineers view structural systems, and complex social dynamics in team settings have also been shown to impact information flow and the ability to detect and correct human errors. Related work, primarily in the business community, is showing that ISO 9001 certification alone may not be the best way to reduce human design error, and that even spreadsheet models suffer from many of the same problems noted about design codes and advanced numerical models. Additionally, social network approaches to studying engineering design teams are growing rapidly and may provide a new set of tools to investigate engineering error. Given this situation, it appears that more research into how human engineers interact with complex codes and models in the marine domain, and how human engineers work together in teams in the marine domain, is clearly needed.

2.5 Inland and Coastal Vessels

Vessels which transport cargoes and passengers on rivers and coastal routes play noticeable role in economy of many countries. Usually such vessels do not make international voyages. That is why design of their hulls is defined by Rules of classification societies and national requirements. As practice shows, river and river-sea vessels are classified in classification society which represents the country of planned operation.

For numbers related to Russia, reference is made to Egorov and Egorov (2017), mentioning for dry cargo about 857 motor vessels and 4190 barges, for tankers 652 motor vessels and 692 barges and, finally, 2730 pusher and tug boats and 1336 passenger vessels.

In Ukraine as to Egorov (2012) there are 299 dry-cargo self-propelled vessels and 596 dry-cargo barges, 52 self-propelled tankers and 32 oil barges, 286 tug-pushers and 190 passenger vessels.

The actual age of river-sea vessels at decommissioning is about 45-50 years. Additionally, about 10% of vessels are lost in accidents before this age. Average age of existing vessels is about 40 years. Therefore, in next 5-10 years more than 50% of fleet operated now will be quite objectively decommissioned and volumes of transportations on water transport will reduce.

An overall picture of the dimension of inland water transport (IWT) in Europe can be derived by the recent survey by the Central Commission for the Navigation of the Rhine (CCRN, 2016). There, about 8000 dry-cargo vessels and 1,650 tankers are mentioned, with various sizes. An analysis of the state and age of this fleet is reported in the same paper. In the United States, 2016 statistics include both coastwise and inland vessels, with an overall fleet size of 32,353 barges, 3,215 push-type towboats which are primarily used on river systems (USACE, 2017).

Of course, new river and river-sea vessels are under construction (Egorov et al., 2016a). In accordance with (Egorov et al., 2016a), such vessels include more effective solutions:

- maximal usage of actual way conditions;

- extremely full hull contours which earlier were not applied in world practice (Egorov et al., 2016a);

- expanding of transported cargoes – project cargoes, chemicals, combination of dry cargoes and oil products on one vessel (for example, in one side – oil products, in another – road metal), so called combined vessel, f.e. Seven 5745t DWT vessels of Marine Engineering Bureau RST54 project were built in 2014-2016 in Russia;

- decrease of air draught to pass bridges without requiring bridges to open;

- effect of "rotator" operation scheme when 2-3 barges are working with one pusher;

- usage of pushed barge in combination with a self-propelled vessel.

For example, in 2000-2016 317 new cargo self-propelled vessels have been built in the former Soviet Union. Among them 301 are of coast and river-sea class, 16 are of river class.

It is also necessary to draw attention to the passenger segment. In August 2016 the keel of river-sea high-comfort passenger vessel was laid down in Astrakhan (Egorov et al., 2016b). Delivery is planned in 2019. It is a diesel-electric vessel where three quarters of the cabins have individual balconies, and area of cabins – 19-21 sq.m – conforms to all standards of modern cruise and hotel industry. There are all types of necessary passenger amenities (restaurants, SPA-centers, fitness, bars, etc.). All native leading cruise companies took part in development of project. The vessel completely meets their requirements. The vessel will work at classical river lines, and also make voyages from river ports to marine ports, including the Caspian-sea round voyage and a routing Moscow - Rostov-on-Don - Sevastopol - Sochi.

As for Rules and Regulations, for more than six decades, UNECE Inland Transport Committee (ITC) has promoted the development of international inland water transport at European level. A recent document exploiting the characteristics and advantages of this transport mode is the White Paper on Efficient and Sustainable Inland Water Transport in Europe (UNECE, 2011).

UNECE provides a platform for intergovernmental cooperation to facilitate IWT. An important target of UNECE is the development of a unified normative framework at the European level. This is particularly needed as the IWT suffers, even at a European level, from a historical infrastructural, institutional, legal and also technical fragmentation, due to the presence of local institutions (River Commissions: Danube – DC, Rhine – CCNR, Mosel – MC, Sava – SC) providing requirements for their specific river basins on various overlapping subjects.

For the design stage from technical and safety requirements side main instruments: Resolution №24 – CEVNI: European Code for Inland Waterways; Resolution №61 – Recommendations on Harmonized Europe-Wide Technical Requirements for Inland Navigation Vessels; European Agreement concerning the International Carriage of Dangerous Goods by Inland Waterways (ADN); Resolution №57 – Guidelines and Recommendations for River Information Services; Guidelines for passenger vessels also suited for carrying persons with reduced mobility.

Resolution №61 of UNECE includes 20B chapter which contains special provisions applicable to river-sea navigation vessels. The chapters' rules were based on Russian River Register rules. On this moment Chapter requires updates in positions of coupling devices, sailing areas and some others.

In the February 2017 Fiftieth session of Working Party on the Standardization of Technical and Safe-ty Requirements in Inland Navigation (SC.3/WP.3) of UNECE took place in Geneva (UNECE, 2017). The Marine Engineering Bureau presented information about new built fleet and about conversion experience (main developments are in UNECE document ECE/TRANS/SC.3/WP.3/2017/6). Representatives of European river commissions showed great interest to conversions because of the large number of older vessels in the fleet in Europe. In Russia, such conversions were performed in 2003-2012. A number of regulations and guidance documents have been produced to establish criteria for such reconstruction and re-use: Construction of Inland Navigation Vessels and Combined (River-Sea) Vessels with the Use of Components of Used Vessels (P.003-2003) and Renovation of Inland Navigation Vessels and Combined (River-Sea) Vessels with the Use of Components of Used Vessels (P.041-2014).

Between 2003 and 2012, 89 vessels were built in compliance with P.003-2003, "Construction of Inland Navigation Vessels and Combined (River-Sea) Vessels with the Use of Components of Used Vessels". However, construction re-using existing vessel components ceased in 2012. At this time, the Technical Regulations on the Safety of Inland Waterway Transport Facilities in the Russian Federation entered force. These requirements require the presence of double bottom and double sides for tankers and vessels transporting dangerous cargoes, eliminating the ability to re-use existing vessel components.

CCNR offered in 2015 a European Standard laying down Technical Requirements for Inland Navigation vessels (ES-TRIN, 2015) which is mandatory for EU and CCNR Member States. In future CCNR plans to unite the Rules of Resolution 61 of ENECE, Rhine vessel inspection regulations (RVIR) of CCNR and Directive 2016/1629 of EU on the base of ES-TRIN. In 2017 ES-TRIN will include new provisions for fire-fighting systems, cranes, traditional crafts, navigation and information equipment, elevating wheelhouses, reference updates to EN/ISO Standards and so on.

In the United States, a new regulatory scheme, 46 CFR Subchapter M, was published on 20 June 2016 for inland and coastal towing vessels. This scheme moves the inland and river fleet into a formally inspected status. While much of the discussion during the development and implementation of this rule has focused on the operational impacts and regulations contained in the subchapter, for structural systems is does now formally specify that vessel designs must comply with an approved classification society standard, though class need not be maintained during the operation of the vessel.

3. PRINCIPLES AND CRITERIA FOR USING ON-BOARD MONITORING DATA

3.1 Code and Safety Updating Offline

On 18 January 2007, the 4,419TEU container ship MSC Napoli suffered a catastrophic failure at the engine room bottom and partial hull girder failure at this location, while navigating the English Channel in heavy seas. The investigation made by Marine Accident Investigation Branch (MAIB), UK has identified factors which contributed to the failure. One of the recommendations made by MAIB was to initiate research into the development and use of technological aids for measuring hull stresses on container ships (MAIB, 2008). Six years after that on 17 June 2013, the 8,110TEU container ship MOL COMFORT suffered a collapse in way of her midship bottom and broke in two, while crossing the Indian Ocean. Following this accident, thorough investigation was conducted by Ministry of Land, Infrastructure, Transport and Tourism (MILT), Japan, and ClassNK (ClassNK, 2014; MILT, 2015, 2013). In the investigation report, ClassNK mentioned to consider the utilization of hull monitoring systems to provide useful information for ships referring to the data obtained from the on-board full scale measurement.

Apart from these events during this decade, hull monitoring systems emerged and attracted attention around two decades ago, and several classification societies introduced rules and requirements for the hull monitoring system, including ClassNK, DNVGL, and CCS i-Ship. One of such rules is DNVGL's HMON notation (DNVGL, 2016b). In case of large container ships, HMON requires monitoring of 4 global longitudinal stresses (midship port and starboard, L/4 from midship port or starboard), global transverse stress at transverse deck strip amidships, loading computer systems, ship position, speed/course, speed log, power output and revolutions of propulsor and the wind condition, while recommending monitoring of vertical acceleration at fore part, transverse acceleration in the 0.4L midship area, ship motion in six degrees of freedom, longitudinal stress close to the bottom amidships (port and starboard), double bottom bending, bending/shear stress in pillar bulkheads, lateral loads at bottom near the forward perpendicular and side for slamming impact, gyro compass heading and wave condition. In response to the recent large container ship casualties as mentioned above, IACS (2015b) published new longitudinal strength standards for container ships (UR S11A). UR S11A stipulates that hull girder ultimate strength assessment consider whipping response when assessing the vertical bending moment in all Classification Society procedures. Accordingly, IACS member societies amended their rules, as deemed necessary. For examples, ClassNK (2017) developed an evaluation procedure to assess the hull girder ultimate strength with taking into account of local pressure loads acting on the bottom plating in addition to the whipping contribution. DNVGL (2016c) covers this requirement by introducing a closed-form formula of the partial safety factor for the additional whipping contribution. With respect to hull monitoring, it is stipulated that this contribution of whipping can be mitigated by 30% for ships with the class notation HMON(G). This kind of rational combination of monitoring system and design conditions may open up a new horizon, where the ship master's judgement on safe navigation in rough seas depends on quantitative failure risk or fatigue damage accumulation displayed by the monitoring system, rather than the master's five physical senses and intuition. However, effectiveness of such systems or the relationship between navigational decision making and structural design conditions are not yet clear, and significant research activities are necessary in this area.

Another important benefit expected to be obtained from in-service measurements is improvement of design accuracy by updating design load assumptions using the measured data. Zhu et al. (2017) proposed a new framework to update the load model used in design stage from measured wave load data in service. They proposed a two-level offline lifetime load updating scheme, where corrections to hydrodynamic predictions are established first, and a hierarchical Bayesian models were utilized as learning approaches. This kind of approach is becoming increasingly important, allowing updating under varying operational profiles and wave climates in the future.

3.2 Full-Scale Measurement Campaigns

Full scale measurements of ship hull structures have long been carried out for various kinds of ships in order to confirm structural behavior of ships in actual service at sea. Especially in response to the rapid enlargement of container ships due to the worldwide economic growth and increased seaborne trade, many hull condition monitoring projects on large container ships were conducted during the recent decade.

An early example of such measurements can be seen in Okada et al. (2006), where they carried out measurements of longitudinal bending stresses and deflections of hatch openings for three years on a 6,690TEU Post-Panamax container ship, and showed that in general the measured results were in good agreement with the design assumptions, except that the measured deflections of the cross decks were much smaller than the design assumptions. They also revealed that significant whipping responses were observed, which may increase the fatigue damage twice. Toyoda et al. (2008) made similar full scale measurements on another Post-Panamax container ship. Storhaug et al. (2007) measured stresses onboard a large 294m container ship operating in the North Atlantic, and concluded that the wave induced vibration affects fatigue strength and hull girder ultimate strength and that design considerations of such responses are necessary. Heggelund et al. (2010) assessed measure data on an LNG carrier during a period of about twelve months, and showed that the contribution from vibration to the fatigue damage was as large as 30 – 50% of the total damage, while Koo et al. (2011) showed that the contribution from vibration on an 8,000TEU container ship was about 30%. Heggelund et al. (2011) reported measurement results on an 8,600TEU container ship operating between East Asia and Europe, and confirmed that the fatigue loading of critical details are dominated by the vibrations. Based on measurement campaigns onboard a Panamax and a Post-Panamax container ship, Rathje et al. (2013) obtained damage increase of the factor 2.36 caused by high-frequency vibrational response. However, they also pointed out that the vessels of the fatigue lives of 13~16 years including vibrational fatigue damage have experienced no significant damage, even for ships operating world-wide for more than 20 years, and that the contribution of high-frequency loads in assessing the overall strength of large container ships does not seem to be fully resolved yet. Ki et al. (2015) examined measurement results on a 14,000TEU container ship, and concluded that considerable fatigue damage increase by hydro-elastic behavior could be identified.

In general, all these full-scale measurement campaigns were conducted using one selected ship during several months or years for research purposes. Therefore, due to the limited number of target ships and limited number of measurement locations and sensors, analysis and evaluation of the measured data are as a result confined to, for example, statistical characteristics of longitudinal bending moment, whipping occurrence and so on. To further expand the analysis scope to statistical analysis of the encountered sea state, determination of statistical characteristics of both dynamic and static loadings, and analysis of actual navigational decisions, it is necessary to carry out a systematic and consistent full-scale measurement campaign, obtaining "Big Data" with regard to ship responses, navigational parameters and encountered sea states. To this end, Okada et al. (2017) started a large scale measurement project using ten (10) 14,000 TEU class large container ships, where a hull stress monitoring system and ship information management system are installed onboard all the 10 ships as standard facilities, aiming at effective feedback to rationalize design and maintenance, and also effective support for safe and efficient navigation.

3.3 Decision Support Systems

One of the important measures to support officers onboard to make proper decisions on ship operation in rough seas and increase the operational safety of ships may be a real time onboard measurement system. Nielsen et al. (2009) suggested a procedure to incorporate random variables and associated uncertainties in the calculations of the outcrossing rates that are the basis for risk-based decision support system. They pointed out that for the purpose of decision support, it is necessary to estimate future ship responses within a time scale of the order of 1~3 hours taking into account speed and course changes. Nielsen et al. (2011) further carried out stress monitoring, and proposed a decision support methodology based on extreme structural responses and fatigue damage accumulation.

Deco et al. (2015) used structural health monitoring data to update the prediction of structural performance, proposing a simulation-based technique for Bayesian updating. They solved multi-objective optimization problems and obtained Pareto-optimal sets of navigation route and ship speed, in which the objective functions are the estimated time of arrival, mean total risk, and fuel cost. It is expected that this kind of studies can provide decision makers a strong support to navigate efficiently avoiding the risk exceeding the required target. Dong et al. (2016) further studied multi-criteria based decision making approach, including repair loss associated with flexural failure, fatigue damage accumulation, total travel time and carbon dioxide emissions as the criteria, employing multi-attribute utility theory. They showed that this approach can determine the optimum ship route and ship performance, simultaneously taking into account the decision maker's preferences with regard to the risk-taking and risk-averse attitude for each criterion.

3.4 Onsite Estimation of Ocean Waves

Onsite estimation of the waves which each individual ship is actually encountering is important for various purposes such as proper decision for the ship operation, rationalization of structural design through comparison of assumed loads and actual loads, estimation of hull damage all over the ship under the sea state which the specific ship has encountered, and its application to rationalized maintenance of hull structure. There are many measures to identify encountering waves including visual observation, wave radar, wave forecast and hindcast. Each of them has advantages and disadvantages over other measures, but the method to precisely measure the actual sea state which the ship is encountering is not established yet.

As a promising technique to fulfill this target, usage of measured ship responses as wave sensors (wave buoy analogy) has been studied over several decades. Pros and cons of each estimation method are summarized in Table 2 based on the interpretation of the current literature, where we can recognize that the estimation using ship response is promising once the accurate estimation methodologies are established.

Nielsen (2016) made a comprehensive review and pointed out that the concept of the wavy buoy analogy is not yet widely used in practice, but it has matured to a level that would be applicable for shipboard decision support system. Nielsen (2006) applied various methods to identify on-site wave spectrum from ship responses, and compared a parametric method which assumes the wave spectrum to be composed by parameterized wave spectra and a non-parametric method where the directional wave spectrum is found directly as the values in a completely discretized frequency-directional domain without a priori assumptions on the spectrum. As a result, he concluded that "it is difficult to propose one of the ship response-based methods in favor of the other, since they perform equally well". This was later confirmed through a larger study by Nielsen et al. (2013) on actual sea state estimation using more than 100 hours of response data collected from a 9,400 TEU large container ship in service.

Table 2: Pros and cons of various wave estimation methods

Method	**Accuracy**	**Represent the encountering sea state?**	**Simultaneous post processing and usage of the data**	**Cost**
Visual observation	Not good (Medium for significant wave height and wave period, but impossible to obtain wave spectrum)	Good	Impossible	Good
Wave radar system	Medium	Good	Good	Expensive
Wave hindcast	Good	No good (Estimation grid distance: 50~100km)	Impossible	Good
Estimation using ship responses to waves	Under development (Good results reported in literature, but wave frequencies for which the ship does not respond will be filtered out)	Good	Good	Good

Nielsen et al. (2012) made another comprehensive study on parametric modelling of the directional wave spectra based on sea trial data of a Canadian Navy research ship, and showed that the wave buoy analogy provided slightly better sea state estimates than a wave radar system on average, for the studied data. In this study, the sensitivity of sea state estimates was investigated by using sets of different vessel responses as input for the wave buoy analogy. It was shown that different combinations of motion components significantly influenced sea state estimates of the wave buoy analogy. Therefore, it is very important to select appropriate sets of ship responses, which are most suitable for each specific case. The methodologies of this suitable selection of appropriate combination of ship responses are far from being established, developing such as selection methodology is a challenge for future research in this area.

Pascoal et al. (2008) presented a numerical procedure using a non-parametric formulation which allows for a low constraint on spectral shape estimation. They discussed appropriate smoothing methodology of the spectral shape, which is important because the problem is underdetermined and there are many alternative solutions of the spectra giving a minimum objective function value.

Montazeri et al. (2016) further studied wave estimation by optimizing parameters of directional wave spectra to minimize the difference between the energies of a set of measured ship responses and the corresponding theoretical spectral moments. A partitioning procedure to separate swell and wind seas was applied. In this study, they pointed out that the responses of a large ship with a high inertia filter out the high frequency part of the wave spectrum, leading to poor estimation of higher frequency components, and suggested that it may be beneficial to use wave bending moment, which is more sensitive to the higher frequencies than ship motions. In this regard, Yoshihira et al. (2017) estimated wave spectrum in a numerical tank from the calculated ship responses in artificially generated long-crested head sea irregular waves. As the ship responses, pitch, heave and longitudinal bending stress were used, and as a result, they concluded that the wave estimation based on longitudinal bending stress was the closest to the artificially generated wave spectrum, thus demonstrating the possibility of the effectiveness of longitudinal bending stress as the input for the wave estimation.

Iseki et al. (2015) investigated the short-term variability of ship responses by cross-spectrum analysis. Using long stationary time series during 20 minutes, the transition of amplitudes and relative phase angles of the cross-spectra during 1~6 minutes duration has been investigated by iterative analyses with a few seconds of time shifting, and as a result, they showed that the short-term variability of the relative phase angle was observed and the variability may compromise the accuracy of the wave buoy analogy in effect. In fact, stationary operational conditions with duration of at least 10~15 minutes are considered to be necessary to perform the spectral analysis (Nielsen, 2016), and this direct disadvantage of the frequency domain approaches to be applied to real time sea state estimation on board have recently initiated studies where the direct time domain sea state estimation is sought (Nielsen et al., 2015; Pascoal and Guedes Soares, 2009)

Wave estimation using offshore structures without forward speed is also in progress. Da Silva Bispo et al. (2016) reported wave estimation results from a monitoring campaign on a turret FPSO off the Brazilian coast in comparison with data supplied by a radar system. Mas-Soler et al. (2017) used a semi-submersible platform as a motion-based wave sensor to improve accuracy of the estimation in extreme wave conditions, and showed good agreement with experimental results in a wave basin.

4. PRINCIPLES AND CRITERIA FOR ACCIDENTAL LOADS

Well-validated design principles and criteria for ships and offshore structures are crucial to increasing the safety level of those structures subjected to accidental loads from various causes. The assessment of different types of accidental loads that may cause damage to ship and offshore structures, are reviewed here, such as the loads induced by collision and grounding, slamming, explosion and fire. Details of analytic developments in this area have been covered by several ISSC committees. In the current congress, specialist committee V.1 is examining accidental limit state formulations. In previous work, advances were reported in the recent reports of ISSC committees/specialists committees such as ISSC 2012: I.2, II.2, V.1 and V.7 and ISSC 2015: I.2, II.2, V.1, V.2 and V.5.

4.1 Collision and Grounding

Eleftheria et al. (2016) provided a historical overview of the development of regulations around collision and grounding . They noted that responses to accidents, particularly those with large loss of life, have driven the introduction of new regulations and the strengthening of existing regulations, particularly at the International Maritime Organization (IMO). This has largely been a successful effort, as the rate of accidents has reduced significantly. They state that at the present time, more than 80% of the accidents are related to human factors. Such a high contribution from human factors has led to a focus on active safety measures, targeting the ship's operation. Focusing on active measures can reduce the frequency of accidents. Passive safety measures, which will be the focus of this section, are those related to the ship's design and technology (Eleftheria et al., 2016). These approaches primarily contribute to reducing the consequence of an accident when it does occur. In the structural domain, actions such as simulating collision and grounding to improve the crashworthiness of structures can reduce damage and flooding extents, reducing the consequence of the accident in terms of the ship or platform's stability or residual structural strength.

4.1.1 Collision

Ship and platform collisions can lead to serious vessel safety, environmental pollution, and economic consequences (B. Sun et al., 2015). The current approaches to analyze ship collisions can be generally grouped into five categories: empirical formula method, simplified analytical method, numerical method and experimental method, as well as the recent risk assessment method. Amongst these methods, simplified analytical method and numerical method have been the most widely used methods, while the empirical formula method has a limit on its accuracy due to data limitation. Because of its uncertainty of the scaling factor, the experimental method mainly focuses on the structural dynamics of components or parts of the ship, and this method is very pricy. The risk assessment method combines the probabilistic theory with the structural mechanics, considering the frequency and the consequence of ship collision accident together.

(1) Risk assessment of ship collision

Eleftheria et al. (2016) presented a recent review of the historical record of ship incidents. This work was designed to both support Formal Safety Assessment (FSA) activities, and to look for patterns with ship age and regulations. Their work was in part motivated by reports in the mid-2000s that the safety level in the marine industry was worsening and examined both the frequency of accidents and the corresponding consequences. Eleftheria et al.'s findings indicated that the overall safety level seems relatively constant. They also included a deeper investigation about possible relationships between accident rates and ship's age, but no simple findings could be made, the relationship was more complex than initially thought. This work is notable for the breadth and detail sub-type investigation of the fleet which can inform structural collision and grounding scenarios.

Ship collision risk may be obtained from the historical data, expert opinions and mathematical calculations. However, the past data may be improper and inadequate to predict the likelihood of future occurrences. Meanwhile, the expert opinions may introduce a high degree of subjectivity. For these reasons, mathematical calculations have been widely used to predict the risk of ship collision. Huang et al. (2016) introduced a collision risk assessment method based on Velocity Obstacle (VO). They applied VO to distinguish the dangerous velocities and to judge the collision probability. The ship maneuverability was also considered to find the reachable velocities (RV) in a given time window. With the percentage of dangerous velocities in all RV being defined as the collision risk, the assessment model by Huang et al. (2016) can identify the collision dangers as well as measure the probability of surviving in the encounter situation, regarding to its maneuverability.

The quantitative risk assessment (QRA) technique is a formal and systematic approach to estimate the likelihood and consequences of hazardous events, and to present the results quantitatively as the risk to people or environment. Chai et al. (2017) proposed a QRA model to evaluate the risk of a ship being involved in ship collisions, by taking into account the frequency and consequence of all possible accident scenarios. The proposed QRA model "consists of a collision frequency estimation model, an event tree and consequence estimation models. While the event tree comprises five intermediate events including ship type, ship size, loading condition, hull damage and survivability, two ''generic" mathematic models are developed to estimate the human life loss and oil pollution caused by ship collisions, respectively" (Chai et al., 2017) .

In addition, Spent Nuclear Fuel (SNF) transportation is considered to be a very urgent problem for those plants situated offshore with a shortage of SNF storage space. Christian and Kang (2017) followed the methodology as required by SOLAS 2009 (IMO, 2009) to assess the risks of maritime spent nuclear fuel transportation with a probabilistic approach. In their study, event trees detailing the progression of collisions leading to the damage of the transport casks were constructed. Parallel and crossing collision probabilities were formulated based on the Poisson distribution. The Automatic Identification System (AIS) data were processed with the Hough Transform algorithm to estimate the possible intersections between the shipment route and the marine traffic. Monte Carlo simulations were done to compute collision probabilities and impact energies at each intersection. Possible safety improvement measures through a proper selection of operational transport parameters, including shipment routes, ship's cruise velocity, number of transport casks carried in a shipment, the casks' stowage configuration and loading order on board the ship, are investigated. The proposed methodology is successful in quantifying ship collision and cask damage frequency, and it will be effective in assisting decision making processes to minimize risks in maritime spent nuclear fuel transportation.

The uncertainty analysis is required to be carried out in the Formal Safety Assessment (FSA) as required by IMO. Sun et al. (2018) combined the Monte Carlo random sampling of probability distribution functions with the a-cuts for fuzzy calculus to propagate the uncertainties. In addition, they proposed a method for time window selection to estimate the magnitude of uncertainties. . Sun et al. also present a FSA case-study on cruise ships. The results of this study show that the uncertainty analysis generates a two-dimensional area on the FN diagram for a given degree of confidence, rather than a single FN curve which would result without uncertainty. Sun et al. claim that the area result provides more information to authorities when considering which risk control measure would be effective.

As there are many marine accidents including collisions worldwide, it is necessary but quite difficult to establish all the causes contributing to the accidents. Common classification systems need to be considered to examine all those accidents. Yıldırım et al. (2017) reviewed large amount of marine accidents using the Human Factors Analysis and Classification System (HFACS). It suggested that risk assessment of the effective accident type must be conducted according to the different voyage situation or local conditions. Endrina et al. (2018) conducted a risk analysis study for RoPax ships using the FSA method by IMO and established the collision risk model through an Event Tree.

(2) The mechanism of ship collision

Experimental tests of real-size ships demand heavy financial investment, complicated logistic, intensive labor, and heavy-duty equipment. Hence, most of the collision experiments only deal with large-scale sections of ship structures subjected to impact loads, rather than complete ship structures. Oshiro et al. (2017) described collision tests of scaled ship structures, giving special attention to some similarity complications that are frequent in real tests. For instance, the yielding stress and material strain rate of the model are different from those of the prototype. Since the standard similarity laws are unable to deal with those issues, it is shown how to modify the scaling factors to generate a replica similar to the corresponding prototype. The methodology depicted in this paper can be used as guidance for scaled impact tests of vessels and other types of large structures.

Numerical analysis of ship collision is extremely complex undertaking, which involves developing mathematic models for at least three complicated tasks including deriving procedures for calculation of the probability of ship collisions in a given area, analysis of external dynamics and investigation of internal mechanics. For external dynamics of ship collision, Pedersen and Zhang (1998) developed simplified analytical, closed-form expressions for the energy released for crushing and the impact impulse during ship collisions, by only considering the motions of the ships in the horizontal plane. Their analyses are validated with numerical simulations and good agreement has been achieved. This analytical model is well suited for inclusion in a probabilistic calculation model for analyzing the damage of ship structures due to collisions. Furthermore, Zhang et al. (2017) further validated this analytical model with a large number of experimental results that can be found in literature and reasonable agreement is achieved. In their paper, a simple concept to account for the effective mass of liquids with free surface carried on board of a ship is adopted. In addition, the new modified model could be expanded to take into account the effect of ship roll on the energy released for crushing. The well-known empirical method between the absorbed energy and the damaged volume was proposed by Minorsky (1958) and developed by Pedersen and Zhang (2000). The calculation accuracy was improved by taking the structural arrangement, material properties and damage mode into account. The method was re-examined in Zhang and Pedersen (2017). Good agreement between the simple expression results and experimental results from published papers was obtained. The improved method can be used for the assessment of ship collision damage. However, using the energy based method for the calculation of the structure damage did not provide sufficient details of damage. When predicting the absorbed longitudinal energy, the uncoupled method did not consider the factors like the damage extent. Numerical simulation of a ship collision is an appropriate alternative choice but extremely complex.

It is noted that for most collision analysis, a static approach is used as most incident involved low speed collision. When such methods are applied to relatively high-speed collision, the dynamic effects should be assessed and appropriate design criteria are to be specified.

To reduce the risk of structural impact damage, much attention has been paid to enhancing the understanding of the mechanisms of ship collision and grounding accidents (Luís et al., 2009; Prestileo et al., 2013). For the collision of double hull ships, the rupture of the inner hull should be avoided until all the impact energy is dissipated, to prevent severe economic loss and casualty. Thus, it is crucial to accurately assess the impact resistance of ship double hulls in the preliminary structural design. Liu and Soares (2015) presented a simplified analytical method to examine the crushing resistance of web girders subjected to local static or dynamic in-plane loads, providing preliminary design tools to assess the internal mechanics of ship collisions and thus developing crashworthiness designs of the double-hull structural components.

Prabowo et al. (2017) studied the rebounding phenomenon of a striking ship. They studied the rebound effect on the structural crashworthiness performance of the struck ship. A series of impact scenarios are defined to estimate the behaviour of the struck ship during and after impact by the striking ship. Prabowo et al. summarized these results as crashworthiness criteria.

The study of repeated impacts is of practical significance in many engineering applications. Zhu and Faulkner (1996) firstly conducted study on plates subjected to repeated lateral wedge impacts and applied the method to the design of a semi-submersible hit by supply vessels. Experimental investigation and theoretical work based on the rigid-perfectly plastic method were performed. Both the theoretical solutions and experimental observations demonstrated that no pseudo-shakedown occurs in the studied cases. Simple formulae were first presented to evaluate the dynamic response of repeatedly impacted plates, which can provide engineers and designers with information for the preliminary design of plating against repeated impact loads.

Huang et al. (2000) performed repeated mass impact tests on fully clamped circular plates made from aluminum alloy and square plates made from mild steel. It was observed that the elastic strain energy increases with increase of the transverse displacements for an axially restrained plate. It was pointed out that, the elastic behavior plays an important role and cannot be ignored in the analysis of the pseudo-shakedown of structures. Thus, the maximum elastic energy that structures can absorb can be of great significance for the preliminary design of plating of ships under repeated impact loadings.

Jones (2014) reviewed the research results reported in Zhu and Faulkner (1996), Huang et al. (2000) and Cho et al. (2014). It was pointed out that a plate subjected to repeated identical mass impact loadings does not achieve a pseudo-shakedown state after some inelastic behavior, except in the special state when small enough loadings can be absorbed due to an increase of the elastic range with an increase in the plate deflection.

Thus, through a comparative study between the research results of Zhu and Faulkner (1996), Huang et al. (2000) and Jones (2014), it can be suggested that, different with the structural design under single impact where the rigid-perfectly plastic assumptions can achieve relatively accurate predictions for the structural behaviour, the material elasticity cannot be neglected in the preliminary design of marine structures against repeated impact loads.

For offshore structures installed in cold regions and ice-classed ships, the influence of the repetition of the impact loadings has been investigated in recent years. Cho et al. (2014) performed both experimental and numerical investigations into the effect of repeated impacts on the response of steel beams at room and sub-zero temperatures, for applications to the structural design of polar class vessels subjected to repeated mass impacts from ice floes or similar impact scenarios. Zhu et al. (2015) presented a new ice load-response model to study the structural response of ice-classed ship plates under repeated impacts from drifting ice. It was demonstrated that the repeated ice-load nature shall be considered in the ice-classed ship design. Based on two commonly used design requirements for the specified permanent plastic deformation, the design plate thickness was given based on a plastic design principle. In the plate design example, the design curves and design formulae were both given and the latter one is straightforward and easy to use in Ice Rules for repeated ice impact problems.

(3) Fluid-structure interaction problem in ship collision

To ensure an accurate and reasonable investigation of the causes of marine accidents, full-scale ship collision, grounding, flooding, capsizing, and sinking simulations would be the best approach, which is based on the highly advanced Modeling & Simulation (M&S) system of Fluid-Structure Interaction (FSI) analysis technique, using advanced FSI codes such as LS-DYNA. Lee et al. (2017) presented the findings from full-scale ship collision, grounding, flooding, capsizing, and sinking simulations of marine accidents, and demonstrated the feasibility of this approach for investigating the causes of marine accident.

Yu et al. (2016a) summarized the challenges of solving the full FSI problem during a ship collision. There is a need to keep both complex and non-linear internal structural dynamics and external hydrodynamics together in one simulation. However, Yu et al. make the point that most numerical structural methods are poorly suited to effectively model the surrounding water in a collision. Thus, some sort of interfacing approach is necessary. The Arbitrary Lagrangian Eulerian (ALE) fluid-structure interaction (FSI) method appears to be popular for both ship-ship/ship-ice collisions. This allows coupling of different solver types in the different domains, and hydrodynamics can be incorporated into the collision response, see, for instance, Song et al. (2017).

Although the ALE method is capable of coupling both the external and internal mechanics, such simulation is too time-consuming. Yu et al. (2016a) presented a coupled procedure in ship collisions to predict the detailed structural damage together with reasonable accuracy and little additional computational cost. Yu et al. stated that for the preliminary design stage, "this method is especially useful since the detailed ship hull profile is not needed. The method is capable of efficiently coupling the global ship motions and structural responses with reasonable accuracy and little additional computational cost".

Yu et al. (2016b) firstly established a coupled ship collision analysis model in which the hydrodynamic loads are calculated based on linear potential-flow theory and then are integrated into the nonlinear finite element code LS-DYNA. By this model, a fully coupled six degrees of freedom (6DOF) dynamic simulation of ship collision and grounding accidents can be achieved. The proposed method is capable of predicting both the 6DOF ship motions and structural damage simultaneously with good efficiency and accuracy.

Liang et al. (2017) proposed a new method to simulate the structural dynamic response of ship structure, considering its coupling with water motion in the ship's internal tanks using the structural acceleration as a connection. This study provides a numerical calculation model applicable for the safety assessment of ships carrying liquid in the design stage, which may also have a potential application in the structural design for ships carrying fluids such as the LNG carrier, oil tanker or other vessels in ballast condition.

4.1.2 Grounding

Grounding is one of the most common and destructive maritime accidents. Recently the European Maritime Safety Agency (European Maritime Safety Agency, 2015) has carried out a review of past accidents to passenger ships. The results showed that in the period from 1990 to 2013, there are 126 grounding accidents and 44% of them (56 ships) suffering major damages. The review also indicated that there is an increasing risk from grounding to ship safety. For designing safe ship structures and preventing the unfavorable consequences of ship grounding, much research has been done by using experimental method, non-linear finite element method, simplified analytical method and statistical method and probabilistic method. As a rational design procedure, Amdahl et al. (1995) suggested that the following four items are considered elementary for safe design: scenario definition, global and local structural performance calculation, post-accident evaluation and acceptance criteria. Careful definition of grounding scenarios is crucial to assessing the responses of ship hulls in accident and post-accident. Meanwhile, proper criteria are needed to predict the failure of structures. Using such a design procedure, especially in the preliminary design stage, it is essential that the structural performance of various designs can be quickly checked and compared for a large number of potential accident scenarios.

Seabed obstructions play an important role in determining the extent of grounding damage on ships. According to the seabed topology with reference to bottom size, the seabed obstacles can be grouped into three types: rock, reef and shoal (Alsos and Amdahl, 2007). In addition, the grounding scenarios can be defined according to the damage mechanisms of ship bottom structures, such as stranding and raking and shoal grounding.

(1) Stranding

Stranding is a scenario similar to ship collision, in which, the ship structures are laterally penetrated by indenters. Normally, a stranding grounding does not include forward ship speed, instead the ship settles on the obstacle. Wang et al. (2000) conducted a series of tests to study the behaviour of double hull ships under stranding scenarios, with varying load locations and indenter radius. The results showed that the indenter radius and the load location have very strong influences on the behaviour of a double hull structure. Alsos and Amdahl (2009) carried out quasi-static penetration tests of the stiffened plates to investigate the resistance to penetration of stiffened plates. The results showed that the stiffener has an influence on the fracture strain, residual strength and toughness of the plate.

(2) Raking

Raking is a grounding scenario where a ship strikes a rock-type obstruction while underway with forward speed. It may also be referred to as a powered grounding, as the ship's machinery pushes the vessel onto and along the obstruction. Given the ability to puncture several compartments owing to the forward speed during raking, it can be a severe type of grounding for both vessel flooding and pollution. Therefore, understanding the structures' resistance to raking is an important design task, including during preliminary design.

Thomas and Wierzbicki (1992) proposed a grounding damage prediction model including plate cutting, plate tearing and girder tearing for double hull tankers. Wang et al. (1997) proposed a simple method for damage prediction of ship raking over a rock by assembling four primary failure modes: stretching failure for transverse members, denting, tearing and concertina tearing for bottom plates. Zhang (2002) proposed a semi-empirical formula to estimate the average horizontal grounding force. The formula is based on a parametric study and the longitudinal and transverse members are smeared to the shell plating with an equivalent thickness method. Hong and Amdahl (2008) developed a theoretical model for ship bottom longitudinal girders crushed during a raking scenario. The mean horizontal resistance of ship longitudinal girders was derived by considering the crushing distance and wave angle. Simonsen et al. (2009) proposed a simplified grounding damage prediction method based on full-scale test and the finite element analysis. Abubakar and Dow (2013) also studied the grounding damage with the finite element method. Based on these grounding simulations, it can be concluded that the transverse bulkheads help to increase the average horizontal grounding force level by approximately 15% (Heinvee and Tabri, 2015). By incorporating four load-resisting mechanisms including friction, stretching, bending and fracture, Zeng et al. (2016) proposed an analytical method for the steady state response of plate torn by a rigid cone indenter to assess the crashworthiness of a ship during raking. Sun et al. (2017) presented an analytical mechanical method to predict the bottom structural response. In their study, the bottom plating and transverse floor were assumed to be the major independent structures contributing to the grounding resistance. The aforementioned prediction models and analytical methods are used to elaborate the internal mechanics of ship grounding, with those prediction methods, it is possible to quickly assess the crashworthiness of ships during the structural design phase.

In addition to the simplified analytical method, numerical simulations and empirical formula have also been widely used to analyze the behaviour of ship bottom structures in real ship grounding accidents. Kuroiwa (1996) used the non-linear FEM to simulate a practical accident case in which a single hull oil tanker was torn by a single rock. The grounding force and resulted damage were reported. Pedersen and Zhang (2000) proposed a revised Minorsky method to calculate the absorbed energy of the grounded ships, by taking into account the different damage modes and structural arrangements. Zhu et al. (2002) examined a grounding scenario of multiple rocks based on a cargo ship grounding incident. The results showed that 51% of the initial kinetic energy was absorbed by the four major damages involving continuous rupture and 42% was absorbed by the five major damages involving continuous indentation without rupture.

Based on a set of numerical simulations of tankers and regression analysis, Heinvee and Tabri (2015) presented analytical expressions for a rapid prediction of grounding damage of double hull tankers by omitting the influence of the longitudinal and transverse bulkheads. Later, Heinvee et al. (2016) took into account the influence of the longitudinal and transverse bulkheads in the grounding damage analysis of double hull tankers. The results showed that the longitudinal bulkhead substantially increases the average grounding force and the transverse bulkhead has little influence on the average grounding force. Moreover, to improve the prediction of the onset of the inner bottom failure, a failure criterion for inner bottom was also proposed (Heinvee et al., 2016):

$$\delta = (0.75\frac{a}{B} + 1.17)h_d \tag{1}$$

where, δ is critical penetration depth; h_d denotes the double bottom height; a is the rock size and B is the ship breadth.

(3) Shoal grounding and residual strength

Different from the raking scenario which involve a rocky bottom obstacle tearing a vessel, ships may ground over more blunt obstructions with large contact surfaces such as smooth shoal. In this case, indentation and denting damage rather than tearing damage is likely to occur for the ship bottom structures. Although the bottom may not rupture when the ship moves over a blunt-type sea floor, it may threaten the global hull girder resistance and give rise to even worse consequences such as the hull collapse (L. Hong and J. Amdahl, 2008; Pedersen, 1994). Therefore, in the preliminary design stage or after a grounding accident, it is necessary to predict the residual ultimate strength of the damaged ship.

The requirements of the ultimate longitudinal hull girder strength are usually determined by considering the still-water and wave-induced loads. But the soft grounding accidents resulting in overall failure of the ship hull indicate that the requirements of the ultimate longitudinal hull girder strength should take into account the arising loads during grounding incidents. Pedersen (1994) and Pedersen and Simonsen (1995) discussed this failure mode of ships and developed mathematical models to analyze the responses of a ship grounded on relatively plane sand. The grounding event was divided into two phases, i.e. the initial ideal plastic impact phase and sliding phase, to gain insight into the mechanics of soft grounding scenario. The results showed that the extreme values of grounding-induced sagging shear force aft of amid ship and sagging bending moment were mostly higher than the IACS requirement for the wave-induced shear force and bending moment. The studies are useful for structural strength design and reducing the catastrophic consequence of soft grounding event.

Pedersen (1994) developed a mathematical model and conducted scaled model tests to analyze the responses of a ship grounded on relatively plane sand. The grounding force, sectional shear forces and bending moments were determined. Besides, the results showed that severe shoal grounding may collapse the hull girder.

Hussein and Soares (2009) provided on of the first studies of residual strength under the IACS Common Structural Rules (CSR. They studied the residual strength of three double hull tankers designed according to these rules. They considered different damage scenarios for both side and bottom grounding, while examining different damage sizes to define a lower bound limit of strength which might be used for design. They calculated the residual strength using the Progressive Collapse Method (PCM) and based on the failure modes defined in the new rules.

Luís et al. (2009) used first-order reliability methods (FORM) to conduct a reliability analysis of a damaged double hull tanker. They assumed an accidental grounding centered on the keel, which they state is the worst possible scenario from a strength degradation point of view. The ultimate strength of the damaged tanker in the reliability analysis is calculated by means of a specific structural code. They simulated damage by removing the damaged elements from the model.

Hong and Amdahl (2012) studied the primary deformation modes of the longitudinal girder, the transverse floor and the bottom plating in a shoal grounding accident. Later Yu et al. (2015) investigated the characteristic deformation mechanism of stiffeners on double-bottom longitudinal girders in a shoal grounding accident. Based on the improved Smith's method considering the residual contributions of the damaged structures mentioned above. Sun et al. (2016) proposed a simplified analytical method to predict the ultimate strength of a damaged ship hull girder subjected to shoal grounding.

(4) Regulations on the grounding damages

Comparing to the regulations on the collision damages, less attention has been paid to the risk from grounding. Most regulations just assume that a double bottom with ample height would be enough to provide protection and to ensure safety. For example, the SOLAS 2009 (IMO, 2009) sets a minimum double bottom height of B/20. MARPOL (IMO, 2006) set a minimum double bottom height of B/20 for fuel tanks and of B/15 for cargo tanks. However, the required double bottom may be penetrated in some grounding scenarios. According to the GOALDS statistics (Bulian and Francescutto, 2010), the probability of exceedance of the SOLAS 2009 standard double bottom height is equal to 27.3% (95% confidence interval:[16.1%,41.0%]), while the probability of exceedance of the increased double bottom height, in case of passenger ships with large lower holds, is 14.5% (95% confidence interval:[6.5%,26.7%]). Besides, some grounding accidents show that grounding damage may occur at the side rather than at the bottom of the ship, such as the most recent grounding accident to Costa Concordia in 2012. The High Speed Craft Code (HSC Code) (IMO, 2008) considered this kind of side damage scenario and set stability requirements for this side racking damage. The European Maritime Safety Agency (2015) also studied the side damage due to grounding by reviewing the past grounding accidents. Based on the grounding accidents databases, probabilistic models for bottom damage characteristics and side damage characteristics due to grounding were described. In addition, the distribution functions for the variables describing the location and extent of corresponding damage were reported. Furthermore, with the probabilistic approach, the European Maritime Safety Agency (2015) presented a proposal to assess survivability of passenger ships in damaged condition due to the grounding or contact accident. The probabilistic framework was studied to determine an attained subdivision index for survivability to grounding and contact accidents leading to hull breach and water ingress. In this framework, two factors, named "s-factor" (the probability of survival) and "p-factor" (the probability of flooding some compartments), were adopted.

4.1.3 Failure criteria

In the metal forming industry, the Forming Limit Diagram (FLD) was studied extensively since the early 50's. Zhu and Atkins (1998) proposed failure criteria using two types of diagram, ‘necking’ Forming Limit Diagram (FLD) and ‘fracture’ Forming Limit Diagram (FFLD), to predict the necking and fracture of ship structures under the impact of collision and grounding. There is extensive work on the grounding and failure prediction as a result of Joint Industry Project on Tanker Safety let by MIT between 1993 and 1999. Using the concept of FLD, real grounding incidents were assessed by Zhu et al. (2002). However, there are many factors affecting the forming limit of metal materials, such as strength level, strain-hardening exponent, strain-rate sensitivity factor, material imperfection, plastic anisotropy and pre-strain. For these reasons, Alsos et al. (2008) proposed the BWH instability criterion by combining the Hill’s local necking analysis (Hill, 1952) with the Bressan and Williams (1983) shear stress criterion to analyze sheet metal instability. The BWH instability criterion describes the FLD in the stress space and determines the onset of local necking of structures. Jie et al. (2009) studied FLD by taking into account the strain rate sensitivity of the material and proposed a formulation for ε_{1f}. Based on the work of Jie et al. (2009), Abubakar and Dow (2013) used the FLD to predict the maximum deformation of the ship structures before necking. By considering the limitation of the strain-based FLD which is only useful on the case of proportional loading, Stoughton and Yoon (2012) derived a stress-based forming limit criterion from the strain-based FLD. The results showed that the stress-based FLD was independent of loading history. For this reason, it could be more accurate to predict the damage of ship structures under grounding accidents which suffer complex loading history. Hoogeland and Vredeveldt (2017) carried out a series of full thickness material failure tests with maritime plates to study the full thickness effect on the FLD. The results showed that the FLD based on Swift-Hill theory (Hill, 1952; Swift, 1952) had a conservative value and the effect of the multi-axiality needed to be considered in the failure criteria. This was also addressed by Bao and Wierzbicki (2004). Liu et al. (2017) proposed an expression to estimate the critical failure strain of coarse meshed ship structures struck by an indenter with hemispherical shape.

During collision events of marine structures, more complex variables such as loading or deformation histories, strain gradients, out-of-plane loading and stress concentrators at plate intersections would have strong influences on the plate failure. Calle et al. (2017) conducted experimental tests on purpose-designed samples, which particularly explained the performance of the failure criteria under different triaxiality ranges induced by the stress concentrators and high strain gradients.

Storheim et al. (2015) assessed “some of the current state-of-the-art fracture criteria that are applicable to coarsely meshed shell structures through comparison with various indentation experiments and a full-scale collision event”. Storheim et al. investigated the robustness of each criterion applied in a design situation. The work particularly focused on the extent each criterion would give reasonable results when applied over wide range of problem. This assessment was made while restricting calibration to only data from a uniaxial tensile test.

In addition, some other failure criteria were proposed. Germanischer Lloyd (Scharrer et al., 2002) suggested a through thickness strain criterion called GLF. Peschmann (2001) proposed a maximum plastic strain criterion called PES. In addition, Törnqvist (2003) developed the RTCL damage criterion by combining the modified Cockcroft–Latham–Oh damage criterion (Cockcroft and Latham, 1968) with the Rice–Tracey damage criterion (Rice and Tracey, 1969). Ehlers et al. (2008) used the three failure criteria to model the ship collision. The results showed that the force penetration curves were influenced by mesh size. Alsos et al. (2009) adopted the finite element method with the RTCL damage criterion and the BWH instability criterion respectively to simulate the penetration tests of the stiffened plates (Alsos and Amdahl, 2009). The numerical results showed good performance of the two failure criteria.

4.2 Slamming

Von Karman (1929) started the research into slamming by studying the maximum pressure acting on a seaplane float during landing by the application of momentum theorem. Based on the kinematic description of the impact dynamics, Ochi and Motter (1973) established a method to predict the necessary information on slamming characteristics and hull responses of a ship at an early design stage, which is known as the Ochi Oriented Criterion. However, this criterion does not take the slamming cluster, stern slamming and bow-flare slamming into account, which may lead to wrong conclusions (Dessi, 2014). Hence, probabilistic models for the prediction of extreme stress and fatigue damage are needed for ships in slamming conditions. A common model assumes that the wave-induced stress is considered to be a stationary Gaussian process, while both the shipping and combined stress processes are non-stationary (Jiao, 1996). Kapsenberg and Thornhill (2010) proposed an approximation method based on momentum theory by which the statistical properties of the impact loads from slamming could be derived. Based on the partial safety-factor-based design criterion, Paik et al. (2004) developed strength criteria of ship structures against impact pressure loads. Realistic characteristics of slamming pressure actions were addressed in terms of the pressure-time history involving the rise time, peak pressure, duration time and type of pressure decay. Considering bow flare slamming, Zhu (2007) presented the common structural damage patterns and damage statistics and typical cases caused by slamming. A flow-chart of slamming impact pressure and strength assessment was presented and a typical example of containership is illustrated to perform the bow-flare slamming impact pressure calculation. In design against bow flare slamming, the local details should not be overlooked, especially at the connection. In addition, some suggestions for design criteria of local details were proposed. The reduction factor of effective plastic Section Modulus for tilted web plate was given. The ISSC 2012 Dynamic Response committee performed a benchmark study of slamming and whipping (Parunov, 2012). The goal of this benchmark study was twofold. On the one hand, the degree of variation in estimation by different methods and organizations was revealed. On the other hand, the absolute error made in the analyses was investigated by comparison with the measured responses from model tests. Drummen et al. (2009) used the model test results of a flexible segmented backbone model of a ferry to investigate the absolute error. Yang (2017) proposed a semi-empirical formula to calculate the slamming pressure due to plunging wave breaking on a sloping sea dike. Sun and Wu (2013) and Sun et al. (2015) have done symmetrical studies into the hydrodynamic problem of oblique water entry by the three-dimensional incompressible velocity potential theory with the fully nonlinear boundary conditions on the moving free surface and body surface boundary. This work gave information on the pressure distribution on the wetted solid surface.

In both slamming research and ship design pressure for slamming, the drop test has been widely used, and design curves are obtained based on the pressure coefficients and associated motion predictions (Chuang, 1970; Hagiwara and Yuhara, 1975; Hayman et al., 1991; Zhao et al., 1996; Zhu and Faulkner, 1995). A series of drop-test experiments was performed by Swidan et al. (2016) to "investigate the hydrodynamic loads experienced by a generic wave-piercer catamaran hull form during water impacts. The experiments, which focus on the characterization of the unsteady slamming loads on an arched wet deck, were conducted using a servo-hydraulic slam testing system that allows the model to enter the water at a range of constant speeds up to 10 m/s. A strong relationship between water-entry velocity and slamming force was found and an empirical relationship is proposed to estimate the magnitude of the slamming force as a function of the impact velocity". This relationship is of great importance for the catamaran design to provide an estimation of the slamming force for a broader range of relative impact velocities. Sruthi and Sriram (2017) studied the slamming forces on a jacket using the improved methodology and experiment method. In their study, a slamming coefficient was proposed for the jacket structures. The method can also be used for estimating the impact loads on complex structures. Ringsberg et al. (2017) demonstrated the practical use of "quasi-response" prediction methods for the assessment of slamming loads on modern free fall lifeboats. Drop test experiment of lifeboats were conducted and presented.

Faltinsen (2000) and Faltinsen et al. (2004) pointed out that slamming should be considered in the framework of structural dynamics response and integrated with the global flow analysis around a ship or ocean structure or with violent fluid motion inside a tank. Thomas et al. (2003) investigated the whipping response of the structure, with the principal structural response frequencies being identified through spectral analysis. Thomas et al. (2006) studied the influence of slamming and whipping on the fatigue life of a large high-speed catamaran. Dessi and Ciappi (2013) investigated the dependence of the whipping response on the impact velocity. However, the accident with the container ship MSC Napoli showed that slamming and slamming-induced whipping were not yet soundly incorporated in the rules of Classification Societies. For this reason, a whipping oriented criterion based on the analysis of the peak of the induced high-frequency VBM response occurring closely after a water-impact was proposed (Dessi, 2014). Magoga et al. (2017) presented an investigation into various methods for identifying slams for structural response analysis. The stress criterion, stress rate criterion and a slam criterion based on the fatigue damage incurred in a structural item were studied in the paper. Hassoon et al. (2017) simulated the behaviour of composite wedges under slamming impact with the presence of damage by employing the finite element method. To investigate the situation, the hydro-elastic influence was analyzed as both a kinematic effect due to deflection of the composite panel and a dynamic effect caused by the interaction between the water and the structure.

As to the slamming impact calculation, Das and Batra (2011) simulated the slamming impact of rigid and deformable hull bottom panels by using the coupled Lagrangian and Eulerian formulation in the commercial software LS-DYNA. Veen and Gourlay (2012) applied the Smoothed Particle Hydrodynamics (SPH) algorithm to two-dimensional hull impact problems in order to simulate the ship slamming. Simulations are made for cones (or other shaped solid objects) of various deadrise angles and different oblique entries, and detailed results have been presented in terms of the free surface shape, pressure distribution on the wetted solid surface, and so on. Sun and Wu (2014) investigated the hydrodynamic problem of a three-dimensional (3D) water column impacting on a solid wall through the boundary element method (BEM). Lv and Grenestedt (2015) modelled the slamming pressure as a high-intensity peak followed by a lower constant pressure traveling at constant speed along the beam. Kim et al. (2015) proposed a numerical method utilizing a 3-D Rankin panel method, 1-D/3-D finite element methods, and a 2-D generalized Wagner model. Wang and Soares (2016) calculated the slamming occurrence probability and slamming loads on a ship hull in irregular waves by using the Arbitrary-Lagrangian Eulerian(ALE) algorithm. Datta and Siddiqui (2016) presented a theoretical hydro-elastic analysis of an axially loaded uniform Timoshenko beam, with intermediate end fixities, undergoing hydrodynamic impact-induced bottom slamming. Marrone et al. (2017) studied slamming loads on LNG tank insulation panels by using an enhanced Smoothed Particle Hydrodynamics (SPH) model. Experimental data involving wet drop tests of both flat and corrugated panels have been performed and the pressures during the impact have been measured at several points along the panel surface.

4.3 Explosion and Fire

4.3.1 Principles and criteria for structures under blast loading

The design for ships and offshore structures subjected to explosion loading has been concerned by each Classification Society since World War II. Many relevant principles and criteria have been formulated, among which the Quantitative Risk Analysis (QRA), Probabilistic risk assessment and P-I diagram method are widely used. With the development of the offshore oil and gas exploitation and transportation industries, designs method for special categories of ships such as LNG, FPSO and FPDSO, considering explosion loading, has been studied by many researchers. The principles and criteria for these ships under explosion loading are more stringent than other ships due to their higher risk.

(1) Explosion load

Generally, the explosion load can be divided into two scenarios: net reaction force and surface load. For ships and offshore structures, each kind of explosion load might be further divided into static pressure, dynamic pressure, reflected pressure and overpressure (Lloyd's Register, 2015). At present, the explosion loading is usually assumed to be a uniform pressure pulse with rectangular shape, triangle shape, or exponent shape. The impulsive loading is employed when the loading duration is ultra-short. The most famous assumed pressure is the triangle pulse loading. Over the past decades, many studies have been devoted to investigating the effect of pulse shape. The earliest study on the effect of pulse shape can be traced back to Symonds (1953), who found that the final deflection of a free beam subjected to a concentrated force pulse only depends on the total impulse and peak load of the pulse. Hodge (1956) remarked that this conclusion was valid only for loading intensities far beyond the yield load; otherwise this simplification may result in large errors.

Based on a large number of experimental research and theoretical analysis work, many scholars summarized empirical formulas for the calculation of the parameters of the blast wave in the ideal air and gave their reasonable scope of application. In the calculation of the peak value of the explosion pressure, Brode (1959) used the finite difference method to solve the Lagrange equation of motion, and obtained the empirical formula for the peak overpressure of the blast wave in an ideal gas. Through a large number of experiments, the expression of the peak value of shock wave overpressure was obtained by Henrych and Abrahamson (1979). Wu and Hao (2005) proposed an empirical formula for calculating the overpressure peak for structural response analysis of surface explosions. The results from early empirical formulae were generally in the middle or lower value, thus there was a risk of underestimating the shock wave. Compared with the empirical formula, the numerical simulation results tended to be low. Wu and Gao (2014) proposed a method to correct the results of numerical simulation by empirical formulae. Those empirical formulae have a small gap in the far field, but the difference between the results in the near field is large. Therefore, the calculation of near field explosion is best based on experimental results.

Youngdahl (1971, 1970) proposed two correlation parameters to eliminate pulse shape effects. In his studies, the dynamic response of a structure under a general loading pulse can be approximated by using a rectangular pulse impulse with an effective load and pulse duration. In addition, an empirical estimation of the structural response duration was suggested. A triangular shaped pressure loading pulse was studied by Jones (1973) and the results implied that a rectangular plate remained rigid for certain loading. The applicability of Youngdahl's approximation to various structures under pulse loading was verified by Zhu et al. (1986).

Zhao et al. (1995, 1994) firstly discovered the "saturated impulses" in the large plastic dynamic response of the structure under moderate-intensity pulsed loading, and made a reasonable explanation of this phenomenon from the perspective of rigid plasticity theory. Zhu and Yu (1997) proposed the elastic-plastic "saturated impulses" of the square plates and the "saturation time" of the structure subjected to the pulsed loading. Besides, based on the elasto-plastic analysis method, the authors proposed the "maximum deformation" and "permanent deformation" of the two “saturated impulse". A theoretical model for rigid-plastic responses of common structural members was established by using the bound theorems, as exhibited by Li and Jones (2016). In addition, it also reveals that Youngdahl’s empirical estimation for the structural response duration generally gives a lower bound of the actual response duration. More recently, Ren et al. (2014) examined the applicability of the foundation equivalent method proposed by Youngdahl for a tensor skin and found that this method is applicable not only to stable structures, but also to geometrically unstable structure such as tensor skin. The scaling effect of using a fixed square plate under a rectangular pressure pulse as a typical example of saturation has been studied (Zhu et al., 2017b). Zhu et al. (2017a) studied the effect of the pulse shape of linearly decaying pressure pulse, and proposed an equivalent method based on saturation impulse. The comparison with non-linear FE results showed the proposed method made a major improvement on Youngdahl's by considering the saturation of structures. In the design of structural components involving plastic deformation, the pressure Linear Decaying and Exponentially Decaying pulses can be treated as an equivalent Rectangular Pulse. This will significantly simplify the plate design calculation involving plastic deformations when design acceptance criteria are given. More recently, Bai et al. (2017a) studied the boundary condition effect for the saturated impulse using both rigid-plastic model and elastic-plastic model. In his study, the elastic-plastic numerical predictions showed good agreement with the experimental results in terms of both the permanent deflection and transient deformation profiles given by Zhu (1996). In 2017, Bai et al. (2017b) further studied the saturated impulse for square plate under Linearly Rising Exponentially Decaying (LRED) considering transient plastic hinge lines.

(2) Structure response analysis

Each classification society formulates the accidental limit state (ALS) for structures under accidental loading. For explosion loading, the following ALS should be considered where relevant, which is taken from NORSOK Standard Z-013, Edition 3:

a. Global structural collapse;
b. Rupture or unacceptable deflection of an explosion barrier, including unacceptable damage to passive fire protection of the barrier and cable or pipe penetrations;
c. Damage to equipment or piping resulting in unacceptable escalation of events, including damage due to deflection or damage of supporting structure;
d. Unacceptable damage to safety critical equipment or systems which need to function after the explosion.

Generally, the response of structural components can conveniently be classified into three categories according to the duration t_d of the explosion pressure pulse relative to the fundamental period of vibration T of the component: Impulsive domain ($t_d/T< 1/3$); Dynamic domain, ($1/3<t_d/T< 10$); and Quasi-static domain, ($t_d/T> 10$).

In principle, the probabilistic explosion load distribution obtained based on the QRA or probabilistic risk assessment should be presented as a frequency distribution of overpressure and impulse, i.e., Pressure-Impulse diagram (P-I diagram). P-I diagram uses have been widely documented, see for example Abrahamson and Lindberg (1976), Morton (1966), Smith and Hetherington (1994), Li and Meng for a hitorical overview of their use on structural and injury critiera (2002).

(3) Leakage and ignition

The loss of containment of LNG or LPG can result in a range of scenarios which could cause serious explosion damage. However, it is basically limited to liquid jet, two phase jet and an evaporating pool, depending on the storage conditions of the liquid and the ambient conditions. Therefore, jets, liquid, pool formation, pool spread and evaporation are the non-negligible scenarios. Lloyd's Register noted that the research for these aspects of LNG spills is thinner than for vapor dispersion models (Lloyd's Register, 2015). Lloyd's notes that the UK HSE has issued a state-of-the-art review of LNG source term modeling (Webber et al., 2010). At the current time, this reference appears to be the most up-to-date source model evaluation. .

Immediate spontaneous ignition is considered to occur so quickly after the leak has started that the scenario results in a fire (since no gas cloud has been accumulated). It should be documented that ignition within a few seconds after the leak has started will not result in significant explosion loads unless such early scenarios are included in the explosion analysis.

(4) Numerical simulation method

Along with the development of computer technology and numerical analysis theory, the Direct Load Measurement (DLM) based on the Finite Element Modeling (FEM) is applied by many Classification Societies.

The probabilistic procedure requires a large set of different release and explosions scenarios to be analyzed. NORSOK Z-013 and Lloyd's Register note that symmetry considerations, reasoning and simplifications based on sound physics may be used to reduce the number of scenarios for consideration. Simplified relations between input parameters and results from the CFD simulations can be used for extrapolating results from both gas dispersion and explosion simulations, provided that their validity and limitations are documented. As a general principle, any uncertainty in such simplifications should be compensated by added conservatism (Lloyd's Register, 2015).

The accuracy of the DLM method will accordingly be dependent on the size of the control volume of the grid used in the CFD simulations relative to the object size. Many efforts have been made to investigate the validation of numerical simulation method, and the topic for numerical simulation of explosion has been well discussed in many international conferences such as ISOPE and OMAE.

However, for load receptors far away from the gas clouds where CFD simulations may be too time-consuming or expensive, more simplified methods for calculating far field blasts can be applied. In this case, the accuracy and/or conservatism of the results should be addressed.

4.3.2 Principles and criteria for fire induced hazards

The fire response of structures is traditionally studied by assuming that the heat-flow problem is separable from the structural analysis. However, when changes in geometric characteristics associated with structural distress change the heat-flow problem, the interaction between heat flow and structural response can be handled by iterative process.

To fill the gap between the simple calculation method and the finite element method, an approach based on the elastic and plastic methods for fire resistance analysis is developed (Wong, 2001). FDS, which is a CFD model for fire-driven fluid flow, can numerically solve a set of Navier-Stokes equations appropriate for low-speed, thermally-driven flow with an emphasis on smoke and heat transport from fires (Mcgrattan et al., 2010).

Large offshore topsides are often steel beam and truss structures, and some work has been done in similar areas. Sun et al. (2012a, 2012b) examined two-dimensional steel framed structures under fire loading with different fire locations. The analysis used both static and dynamic models depending on the stability of the structure. Naser and Kodur (2016) presented critical factors that influence the onset of local buckling in steel beams when exposed to fire conditions. A three-dimensional nonlinear finite element model capable of accounting for critical factors that influence local instability in fire-exposed steel beams is developed. Luongo and Contento (2015) resolved the nonlinear elastic problem for planar frames made of rectilinear beams subjected to thermal loadings.

Research on the properties of steel structures under the combined action of fire and explosion loads is relatively less. However, the response analysis of steel structures under the combined action of fire and explosion loads have become more important after the “9/11”event in the United States (Tan et al., 2017).

With regard to the nonlinear response of steel frame under fire and explosion loads, Song et al. (2000) and Izzuddin et al. (2000) proposed an adaptive numerical analysis method to evaluate the influence of blast loading on the fire resistance capability of steel structures. Mirmomeni et al. (2015) implemented a comprehensive test program to investigate the post-impact fire properties of Grade 350 steel under well-defined conditions. The test results indicate that the effects of these combined actions are profoundly different from those in which the structure is individually subjected to either high strain rate or thermal loading. Xi et al. (2014) adopted the governing equations in the form of finite difference to describe the response of steel beams under the combined effects of fire and impulsive loads.

Liew and Chen (2004) and Liew (2008) adopted the mixed element method to analyze the steel frame that was locally impacted by blast loading and caused the fire. The response behavior of steel structures under blast and fire loadings were investigated, and the influence of blast loading on the fire resistance capability of multistory steel frames was elaborated.

The sequence of fire and explosion loads applied on the steel structures was rarely considered in previous studies. Two scenarios that apply fire and explosion loads in different orders all have strong engineering backgrounds. A substantial amount of research results has recently emerged for the scenario in which the explosion load is applied followed by a fire. However, related research results for the scenario in which explosion load is applied during a fire are currently rare (Tan et al., 2017). As indicated in the study of Xi et al. (2014), the strain rate constitutive model related to the temperature should be considered in this situation. However, relevant experimental data are currently generally lacking. Two scenarios are discussed in this study. In this study, the blast resistance capability of steel structures during a fire is represented by the peak amplitude of the pulse load–impulse (P–I) diagram, while the fire resistance performance of steel structures after the action of an explosion load is represented by the Tcr–I diagram.

Tan et al. (2017) has studied the pulse shape effects on the fire and blast resistance capabilities of steel beams. The peak amplitude of the pulse load–impulse curve and the critical temperature–impulse curve is proposed to distinguish safe and unsafe areas. Two scenarios that apply fire and explosion loads in different orders are considered. Numerical analysis results show that the blast resistance capability of steel beams sequentially decreases under the action of exponential, triangular, and rectangular pulse loads; the effects of rectangular, triangular, and exponential explosion pulse loads on the fire resistance performance of steel beams consecutively decrease; and the pulse shape effects on the fire resistance capability of steel beam decreases with the increase in dynamic load ratio.

5. PRINCIPLES AND CRITERIA FOR ARCTIC OPERATION

5.1 Arctic Operational Environment

With melting ice caps covering the Arctic areas, the Northern Sea route connecting the Far East and Europe becomes available for the navigation of commercial ships during the summer time. Ensuring an appropriate level of reliability and acceptable performance for such marine structures in the Arctic requires the consideration of risk and reliability in their structural design. Harsh environmental features such as geographic remoteness, ice-covered areas, ice loading, icing, floating ice, winterization, and hydrodynamic interactions is part of important design aspects for those structures. For instance, floating ice such as icebergs can damage offshore and sub-sea structures and sometimes this yields serious consequences to the Arctic environment. Meanwhile, field data collected from Arctic voyages can be served as fundamental information to further increase the design capabilities of marine structures in the Arctic. As an example, the icebreaking research vessel ARAON voyaged to the Chukchi and Beaufort seas during the summer season, and performed ice field trials (Lee et al., 2014), see Figure 2.

Figure 2: ARAON in the Arctic Sea (Lee et al., 2014)

In total four ice field trials are conducted to understand the ship performance under the Arctic operational environment. Various ice properties like ice load and thickness, and navigational information for the ship such as speed, engine power and hull strength data from strain gauges are gathered as well as air temperature, wind speed and the heading of the ship. This section reviews recent work for load prediction and criteria development in the Arctic, ISSC specialist committee V.6 report on the Arctic Technology provides a wider overview of Arctic development.

5.2 Ice Load Prediction

Prediction of the ice load is an important design factor to secure the reliable structures of polar ships that navigate in ice-covered waters because the ice load is the most dominant load acting on the ships. In general, the magnitude of ice-induced load is greater than that of wave-induced load including slamming loads. Ice load components can be categorized as global ice load and local ice load. The former is usually results hull girder bending moments and the latter is often the pressure acting on local hull structure. Ice type, ice thickness, ice failure modes, ice-hull structure interaction, and ship speed are parameters that influence design pressure from the ice. In understanding the responses between the ice load and hull structure, the time history of the ice load on hull structure needs to be identified. Therefore, determination of the accurate ice load acting on the ships requires a good understanding on the mechanism of interaction between the ice load and the ships to enhance the safety level of the ships in the Arctic. Research on the mechanical properties of the ice has become increasingly important. It is understood that the ice has stochastic material properties because various natural parameters affect its mechanical and physical properties. Furthermore, the brittle feature of the ice adds complexity to the ice-hull structure interaction. At present, there are discrepancies in dealing with the ice load between rule-based design approaches and ice field test measurement approaches, and existing numerical programs cannot satisfactorily simulate the mechanical properties of the ice yet.

Research efforts made so far to improve the ice load prediction capabilities generally fall into numerical, experimental and ice field test categories, and some representative work of in each category is introduced in the following.

For the modelling of the ice behaviour, a constitutive relation of ice with high strain rates was proposed, and this approach develops a numerical integration algorithm based on a plasticity failure criterion (Pernas-Sánchez et al., 2012). For the ice subjected to a multiaxial state of stress, a continuum damage model for its temperature dependent creep response is proposed. In this model, a thermo-viscoelastic constitutive law for the ice creep, and a local orthotropic damage accumulation law for tension, compression and shear stresses are considered (Duddu and Waisman, 2012). In the ice impact load case, a strain rate sensitive ice material model is developed by considering physics and phenomena governing spherical ice impact. Predicted ice failure progression from this model shows a good agreement with the ice crack propagation observed from the ice impact test (Tippmann et al., 2013). Structural response of a stiffened panel under the ice load is obtained from finite element method (FEM) and rule-based method, and they are compared for the estimation of design load (Erceg et al., 2015). FEM alone or combined finite element and discrete element methods (FEM-DEM) based simulation approaches are also used to predict the ice load. Two-dimensional FEM-DEM simulation approach is demonstrated for predicting the maximum ice load from the ice-hull structure interaction. Based on 110 simulations with two different plastic limit values, the statistics of the ice load from the simulation is studied, and this approach is suggested for the improvement of the ice load prediction (Ranta et al., 2015). Discrete element-based models have some advantages over continuum-based models, because the ice fracture propagation is discrete in nature. Thus, DEM is applied to simulate the global resistance acting on the hull structure in level ice under different ice thickness and ship speed. In this approach, the breaking process of ice cover and the size distribution of broken ice floes can be obtained, and the ice load in each contact pair is determined through the contact detection between ice particle element and hull element in the simulation. Field data are employed to check the accuracy of the DEM numerical approach. The ice force acting on the icebreaker by a repetitive ice-ship contact depends on the size of ice floe and ice concentration that affect ice failure mode. Numerical models for the simulation of ice floes' distribution when icebreaker is advancing into ice-covered water with pack ice have been developed to calculate the ice load. In these models the motion of ice floes due to collisions with a vessel is expressed by rigid body equations (Sawamura and Kioka, 2016).

Full scale experiments involving the ice-hull structure interaction are conducted in which significant deformation is observed. Stiffened panels are considered to represent the hull structure and laboratory made ice blocks are loaded on the panels to observe large scale plastic deformation (Manuel et al., 2015). Non-linear FE analysis of the panels is performed, and a comparison between the experiment and simulation is carried out. This approach demonstrates a practical way of estimating the local ice load on the hull structure. High velocity impact of ice spheres is also experimented to estimate the ice load in dynamic nature, and experimental procedures are developed (Pernas-Sánchez et al., 2015).

Ice field test programs are conducted to predict the actual ice load acting on the ships operating in the Arctic. Ships navigating in ice-covered water should comply with route specific ice-induced load. Full scale pressure distributions are obtained from the ice field test by Japanese Ocean Industries Association (JOIA) to investigate the effect of spatially localised load on the local hull structure such as a grillage. Similarly, the characteristics of the local ice load and ice load signal acting on the side shell in the bow section of ARAON is investigated through the ice field test (Lee et al., 2016, 2014). The local ice load signal refers to fluid impact pressure and it is different from the ice load in terms of physical aspects. The shape characteristics of the load signal shows similar trend in the signal characteristics, such as peak and decaying shape. The local ice load is obtained from 6 degrees of freedom (DOF) internal measurement system and FE analysis. The measurement system treats ARAON as a rigid body and measures whole ship motion and the global ice load from the full-scale ice sea trial data. As a part of results, the pressure-area curves are developed as shown in Figure 3.

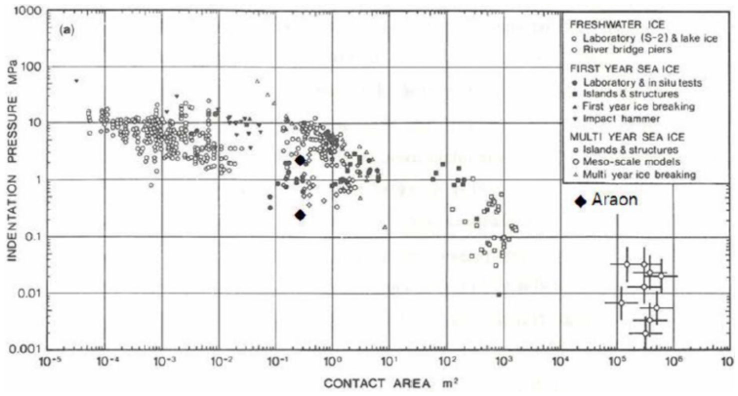

Figure 3: Pressure levels measured on ARAON in comparison with existing pressure-area curve (Lee et al., 2014).

5.3 Design Approaches for Ice Loaded Hull Structures with Application to Structural Design

Erceg et al. investigated structural responses of a stiffened plated structure subjected to full-scale ice pressure distributions obtained from field measurements. Within rule-based design method, Finnish-Swedish Ice Class Rules (FSICR), and probabilistic design method approaches for the ships in the Arctic, the plate responses are analysed using LS-Dyna and ANSYS finite element model solutions. From the two different design method approaches for the plated structure, the higher von Mises stress values are obtained from the full-scale ice pressure distributions than both FSICR and the probabilistic approaches (Erceg et al., 2015). Ice ridge, iceberg and ice islands are examples of floating ices in the Arctic. Among them, an iceberg has the highest impact and chance of interaction with the ships and subsea facilities in the Arctic. Kim et al. (2017) focus on iceberg, and investigate the factors related to the interaction between iceberg and the subsea structure such as areal density, iceberg drift arising from wind, wave, current, uncertain iceberg shape and subsea structure types.

Based on the dynamic response of the hull structure under impact in which the deformation of the impacting object is not considered, the structural analysis of plated structure subjected to repeated ice load has been investigated by Zhu et al and others. From this ice-plated structure interaction analysis, design curves and formulae are derived for the structural design of the ice classed ships using the design criterion based on allowable permanent deformation (Zhu et al., 2015). Damage resistance of laminated composite structures due to hail ice impact is experimented by Rhymer et al. (2012). This impact case may create internal damage to the laminate that is not visually detectable and is therefore a damage tolerance concern. A laminate manufactured from carbon and epoxy materials are considered and it is subjected to high velocity ice sphere, i.e., simulated hail ice. Gagnon and Wang (2012) conduct the numerical simulation of collision between a loaded tanker and an iceberg using LS-Dyna. In the simulation, hydrodynamics and validated crushable foam ice model are taken into account. Using the same simulation program, LS-Dyna, the structural analysis of an arctic LNG carrier is performed by Gagnon et al. (2017). Different iceberg masses, iceberg shapes and water condition are considered in the modelling and it is validated using the data from growler impact test in National Research Council Canada's ice tank facility and full-scale measurements. Wet and dry case simulations are developed to calculate the hull deflections, and it is noted that wet case simulation provides more realistic results, see Figure 4.

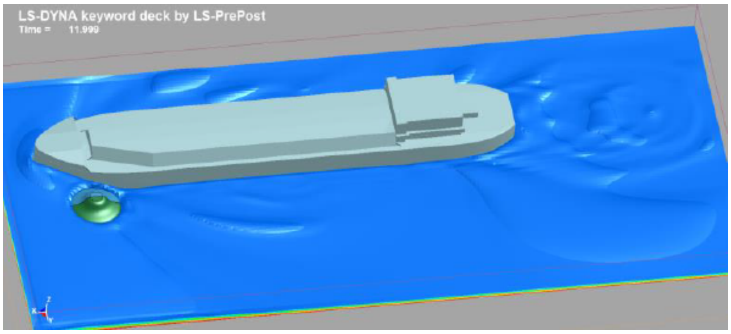

Figure 4: Ship-ice collision modelling using LS-Dyna (Gagnon et al., 2017)

Flow of ice around both fixed and floating offshore structures of different shapes can be predicted by using a multi-model approach. Through this simulation-based approach in the design of the arctic offshore structures, ensuring of no excessive pile-up and encroachment on the topside facilities, and prediction of the load on the structures consistent with the relevant design codes and standards can be investigated. The simulator program based on a multi-model approach is developed by Dudal et al. (2015). This simulator is capable of simulating ice flow and calculating the load on conical or sloping walled structures where ice sheet fracture is dominated by bending (see, Figure 5). Thus, it predicts the ice behaviour and load applied on offshore structures accounting for water current and interaction among the structures, ice sheet, ice floe, ice blocks and the seabed.

Figure 5: Modelling of underwater ice flow (Dudal et al., 2015)

Pang et al. (2015) presents a comprehensive survey of the literature on the cohesive element method (CEM) applied to the ice-hull structure interaction. CEM is a kind of blending between FEM and DEM that improves the drawbacks on both FEM and DEM solutions. CEM can model the full-scale ice sheets undergoing continuous crushing without violating the conservative laws. It is noted that the structure becomes softened with increasing cohesive element density, and for this case, a scaling law needs to be considered for cohesive element properties such as different mesh sizes. A three-dimensional DEM bonded particle model is used to simulate the ice. In such an approach, blocks of the ice are not modelled by a single particle instead the blocks are modelled by a collection of bonded particles that can break into smaller blocks as bonds fail (Morgan, 2016). It enables the simulation to have a better understanding on the fracture process and rubble behaviour of the ice.

It is critical to understand the salient failure modes of ice features for the structural design of icebreakers. Lu et al. (2015) defined that "The dominant failure modes are influenced by the structural properties, interaction process, and characteristics of the ice features. For an ice feature of finite size with relatively small lateral confinement, splitting failure has been frequently observed during ice-structure interactions". Lu et al. (2015) proposed a conservative classification of ice floes out-of-plane failures under an edge load. Besides, the ice fracture processes are highly influenced by variability associated with flaw structure and contact conditions, Taylor and Jordaan (2015) develops a probabilistic fracture mechanics model to model the localized fracture events for ice specimens with ice edge taper angles ranging from 0 to 45 degrees. The crack instability criteria are formulated for compressive and tensile stresses. Hendrikse and Metrikine (2015) propose a new mechanism to explain ice-induced vibrations. They propose a model where the variations in ice-contact area impact the ice load magnitude, and that these variations drive the ice induced vibrations. They propose a numerical model built around the dominate aspects of this mechanism. This model is claimed to predict all regimes of ice induced vibrations of compliant structures as well as being able to reproduce the aperiodic characteristics of ice loading on rigid structures.

Risk and reliability aspects need to be incorporated in the design of arctic offshore structures to secure acceptable performance. Thomas (2015) develops the ultimate and accidental limit states with respect to the risk and reliability of the offshore structures. It is demonstrated that all risk events, including those from very rare environmental events beyond abnormal level, need to be characterized in order to assess risks and ensure appropriate planning, documentation and management. Ayele and Barabady (2017) propose a simplified risk-based offshore structure design methodology with respect to the Arctic environment. They consider risk factors like choice of material, equipment, support strategies, physical environment, human factors and HSE (Health, Safety, and Environment), which are additional risk factors beyond the traditional risk factors. All these risk factors are taken into account because of the stringent requirements in terms of emissions to the atmosphere and discharge to the sea as well as design procedures with respect to risk reduction measures such as prevention of risk incidents, control of risk incidents, and mitigation measures. A proposed risk-based arctic offshore structure design methodology from the literature is shown in Figure 6.

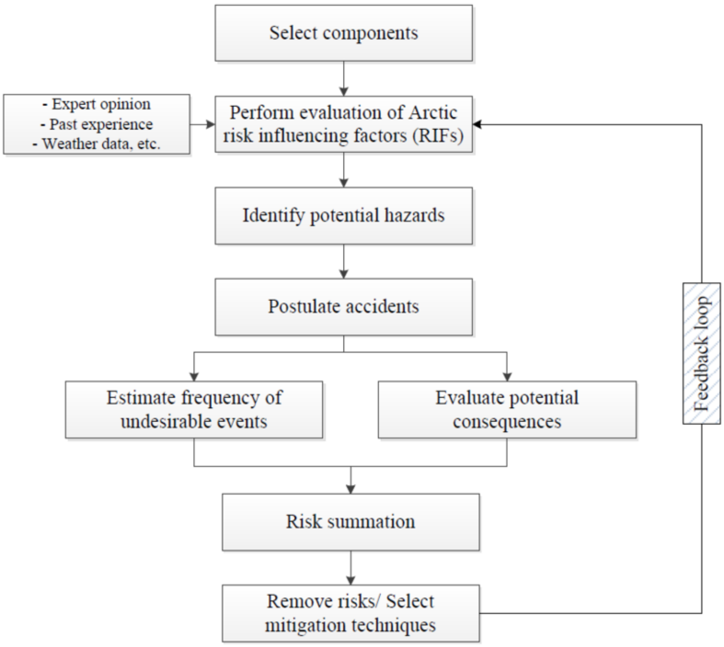

Figure 6: A simplified risk-based offshore structures design methodology for Arctic operating conditions (Ayele and Barababy, 2017)

Ki et al. report on full-scale impact test of a newly built arctic LNG carrier according to ARC 7 class of the Russian Maritime Register of Shipping (RMRS). This has performed to check the acceptance of hull structures and weld strength with respect to impact load. 7 tons of steel with controlled dropping height is used to experimentally simulate the impact load equivalent to encountered ice load. Iterative drop object analysis result is used to determine the drop height, and the ice load for ARC 7 requirement is calculated using direct ice load calculation method. The nonlinear analysis is performed to check the hull and Cargo Containment System (CCS) strength with respect to the calculated ice load (Ki et al., 2017).

5.4 Assessment of Ice Class Rules

Development of the harmonized ice class rules for the ships in the Arctic by International Association of Classification Societies (IACS) reduces the large variety of different ice class rules resulting in an easier selection process for an adequate ice class rules meeting the functional requirements assigned for the ships. Riska (2013) analyzed the design point that is the limit state together with the frequency the limit state is reached at different ice class rules. The analysis is based mostly on the ice load from first year ice but also ice regimes where the multi-year ice occurs. The comparison is done by using two example ships (8,000 DWT chemical carrier and 20,000 DWT bulk carrier) and scantling is obtained from different ice class rules. Both FSICR and IACS polar rules are used (Riska and Kämäräinen, 2012). The design equations for ice loads from IACS rules are examined through the relation among ice load, iceberg's buttock angle and velocity (Choi et al., 2012). Also several ice class rules such as American Bureau of Shipping (ABS), DNV- GL, RMRS and FSICR are referenced, and new design formula is proposed based on the intensive investigation of referenced various rule-based formulae and experimental results. Based on laboratory impact test and modification of DNV-GL ice class rules and IACS Polar class rules, the authors suggest design equations for impact ice load.

The objective of International Organisation for Standardisation (ISO) 19906 is to ensure that complete structures including substructures, topside structures, floating production vessel hulls, foundations and mooring systems in arctic and cold regions are provided with an appropriate level of reliability with respect to personnel safety, environmental protection and asset value. ISO 19906 demonstrates an improvement from the traditional approach to the design of offshore structures which are largely derived from steel jackets and lattice tower structures. Nowadays ISO 19906 is used in all countries with arctic interests for assessment of ice scenarios and ice actions, for design of structures in ice environments and for the ice-structure interaction (Muggeridge et al., 2017). In ISO 19906, the limit state design covers design situations arising from extreme operation, abnormal, and accidental events so that the desired structural reliability is verified for the relevant limit states (Thomas, 2017). If the ultimate limit state (ULS) is considered on the extreme and abnormal design situations, ISO 19906 provides requirements, recommendations and guidance for the design of offshore structures in the Arctic and cold regions.

FSICR have their origin in the rules first put forth in 1890. Since that time, the rules have evolved and, at present, FSICR can be considered as an industrial standard for designing ships for first-year ice environment. Decades of experience including numerous damage surveys and full-scale measurements make FSICR as the rules being incorporated in most major classification societies, though new research findings have also influenced the rule development (Riska, 2013; Riska and Kämäräinen, 2011).

Kim et al. (2015) investigate differences in the ice load and plate thickness requirement between IACS and RMRS rules. To understand the background and limitations of those rules, assumptions made for design formulations and ice class factors are reviewed. It is noted that the ice load from IACS is based on an oblique collision with a large ice floe having a 150 degree front angle. This ice load acting on the hull structures is acquired from an average pressure that is uniformly distributed over a rectangular load patch area which depends on ice category, hull angles and ship displacement. In case of RMRS, the ice load is obtained from maximum pressure in the ice-hull structure contact area. The main difference between two approaches is that IACS utilizes Sanderson's pressure-area relationship, in which the average pressure decreases with increasing nominal contact area whereas the RMRS approach assumes an intermediate crushed layer and uses the Navier-Stokes equations to determine ice-pressure distributions over the nominal contact area. Both IACS and RMRS have almost the same rule principles, and they provide very close results: IACS and RMRS rules assume the ice pressure and the load height as a function of ice geometry, ice mechanical characteristics and parameters of the vessel. The design of plates and stiffeners in Arctic vessels is performed considering a combination of experience, empirical data and structural analysis. Especially design factors driving the shell plating for the ships are based on two assumptions, namely the ice load calculation and structural resistance calculation.

6. CONCLUSIONS

During the current mandate period the committee found encouraging developments in structural design philosophy and criteria. Based on the extensive prior coverage of goal-based standards and sustainability in design from this committee, it is gratifying to see the implementation of these approaches at IMO and other national regulators now appearing. The review of IACS CSR to GBS marks a major milestone in the adaption of this philosophy, and the continued use of formal safety assessments and other design approaches discussed in prior IV.1 reports is also encouraging. It is possible that the next ISSC IV.1 committee will be able to start to summarize lessons learned from these large-scale applications of the goal and sustainability-based design principles.

It is also clear that in-service monitoring data is becoming a major factor in both structural design and life extension. The ability, or perhaps in future, need, to revisit structural adequacy based on in-service monitoring results represents a potential shift in design philosophy. To date, such philosophy focuses more on improving design-stage rules and regulations without considering reassessment. As reviewed in this report, life extension approaches are often categorized depending on the type of through-life data available. With the rapid growth of aging wind farms and the continue aging of oil platforms, in-service monitoring for fixed structures is likely to continue to increase. The detailed review of ship-based in-service monitoring shows that this problem is hard, and not yet fully resolved despite a clear demand signal from recent containership mishaps. While much development is clearly apparent from the literature reviewed, and the notable instrumentation campaigns underway, a clear tie to updating goal or sustainability criteria is not yet present. How the results of such studies will influence both design and operational-phase criteria must still be explored.

A more wide-ranging study of accidental loads and polar criteria was also presented. The direct analysis of accidental loads during design is a precursor to effective regulation of the performance of marine structures in accidental limit states. Collision, grounding, fire, and explosion load estimating approaches were all reviewed. Polar operations continue to grow, and our review of polar loading and design codes highlights similar needs, if not technology, to more conventional operations. Risk-based approaches are favored given the unique nature of the polar regions and the relative lack of operational experience compared to more temperate climates. Likewise, rule comparison and harmonization appear to be growing concern for researchers, with several publications exploring such aspects during the mandate period.

Inland and coastal vessel developments were also reviewed, with numerous criteria updates noted. The unique challenges of the inland waterways provide a contrast to ocean service criteria. However, it is not yet clear to what extent sustainability and goal-based implementations are being attempted in this industry. Here, the lack of a venue such as IMO leads to an even more fragmented and hard-to-track regulatory approach. Our shorter review of human error in assessing criteria found the marine industry little changed since the last major work in this space 20 years ago. However, related human-structural engineering problems in the civil engineering domain have been more recently explored, highlighting potential dangers of increasinglycomputerized engineering approaches. More investigation into the role of the human engineer in implementing ever-more-complex design criteria assessments seems warranted at this point.

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