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COMMITTEE V.6
ARCTIC TECHNOLOGY

COMMITTEE MANDATE

Concern for development of technology of particular relevance for the safety of ships and offshore structures in Arctic regions and ice-covered waters. This includes the assessment of methods for calculating loads from sea ice and icebergs, and mitigation of their effects. On this basis, principles and methods for the safety design of ships and fixed and floating structures shall be considered. Recommendations shall also be made regarding priorities for research programmes and efficient implementation of new knowledge and tools.

AUTHORS/COMMITTEE MEMBERS

Chairman: S. Ehlers
A. Polojärvi
A. Vredeveldt
B. Quinton
E. Kim
F. Ralph
J. Sirkar
P.O. Moslet
T. Fukui
W. Kuehnlein
Z. Wan

KEYWORDS

Arctic Ships, Polar Class, probabilistic design, mission-based design, limit states design, ice mechanics, iceberg, sea ice, Arctic Sea transportation, Northern Sea Route, North West Passage, Polaris, IMO

CONTENTS

1. INTRODUCTION

The abundance of commercial opportunity that exists in the arctic as well as observed changes in environmental conditions, we can expect substantial increase in offshore and marine transportation activity in the Arctic. A definition of Arctic regions is given in the preceding ISSC committee report on Arctic Technology V.6 (2015). Consequently, ships and offshore structures must be designed to comply with comply with regional conditions and design requirements. To ensure ships and offshore structures are safe, clear guidance is needed, which may include the definition of target reliability levels and corresponding structural failure modes and limit states. Guidance from other disciplines may be considered, such as aviation or nuclear engineering, but it must be ensured that guidelines are clear and not misleading to society. In the Arctic, ships and offshore structures should be a safe haven in the event of accidental actions. Aborting the ship or offshore structure should be avoided even if it is plausible to escape from the hazard (i.e. with the exception for example of a fire), because the persons placed in life boats will face severe environmental conditions. In conclusion, accidents in Arctic regions require a different mind-set, because the environment to evacuate into may be much more dangerous then to stay on the ship or offshore structure.

A general observation to be drawn from operations of ships and offshore structures is that heavy reinforcement is generally safer. In the case of offshore structures it may be lower life-cycle costs to design the hull to withstand ice impact rather than to include a disconnect option or to do repairs after incidents with ice. In case of ships, excessive strengthening is typically in conflict with the requirement to minimize initial expenditure. On the other hand, the maritime world links ice conditions to ice classes and insurance as well as ice breaker service following a cost/benefit-approach. The latter typically contains higher damage acceptance in ice class rules for ships, than what is often experienced for offshore structures.

The IACS Polar Code seeks to contribute to the safety of ships, yet it does not quantify safety in terms of reliability target (for instance in the terms of impacts per year or an annual failure rate). The introduced POLARIS system checks if the vessel journey is to be made safely and follows the concept of the Arctic Shipping Pollution Prevention Regulations (ASPPR), even though the background of the contained multipliers are not well defined and thus subjected to uncertainty when used. Another aspect not addressed sufficiently for ships and offshore structures is the design ice load prediction resulting from ice rubble. For the latter the simulations may serve as a fine purpose while complex phenomena can be analyzed also with the help of ice model tests.

In order to design and operate ships in the Arctic, an international legislative framework has to be followed. The main bodies of this framework are the United Nations Convention on the Laws of the Seas (UNCLOS), the International Maritime Organization (IMO), the maritime states, Recognized Organizations (ROs), and the International Association of Classification Societies (IACS) (DNV, 2012). In addition, there is the International Labour Organization (ILO, 2014). The enforcement of mandatory requirements of the IMO conventions depends upon the individual IMO members, which include most maritime states. The member state acts both as flag state and port state. A flag state has the authority and responsibility to enforce regulations over vessels registered under its flag. Since all ships have to meet the international requirements set by the IMO, flag states need to integrate their own statutory requirements with the requirements set by the IMO. "When a Government accepts an IMO Convention it agrees to make it a part of its own national law and to enforce it just like any other law". As a result, any IMO member (i.e. maritime state) has the authority to carry out so-called Port State Controls (PSC) to ensure that the condition and equipment of ships visiting their ports comply with the IMO standards). This complex framework regulates the design and operation of ships in general, which is further described by Bergström (2017) and in Figure 1.

The International Maritime Organization (IMO) Polar Code, being in force since January 2017, seeks to contribute to the safety of ships in the ice covered waters of the Arctic Sea (See Section 2.1.1). the International Association of Classification Societies (IACS) provides the "Unified Requirements (UR) for Polar Ships", which standardized global ice classification specifications in seven polar classes.

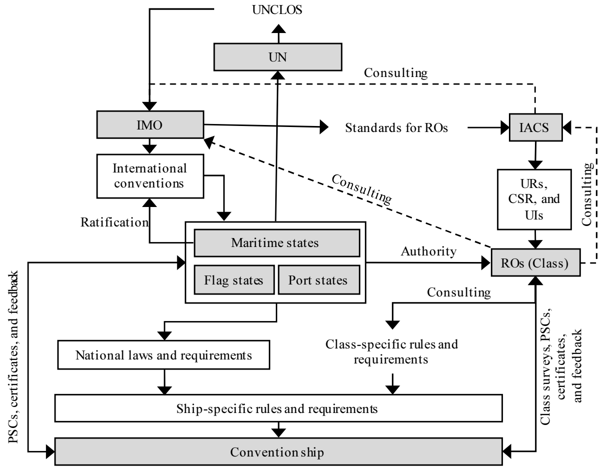

Figure 1: The current legislative framework for arctic ships (based on Bergström 2017)

Concerning offshore structures one challenge is to address the aspects involving disconnection versus stationary offshore structures with and without ice management. As outlined in ISO 19906, an offshore structure can be categorized in the following way:

- active: move-off capability, physical ice management capability;
- semi-active: move-off capability, no physical ice management capability;
- semi-passive: no move-off capability, physical ice management capability;
- passive: no move-off capability, no physical ice management capability.

For structures categorized as passive, the design approach is rather straight-forward. Other categories can make cost-benefit analysis to see how much shall be spent for a certain operational measure. For fixed structures in ice the load is defined through the probability of exceedance levels for ULS and ALS in ISO of 10^{-2} and 10^{-4}. These loads can be established using probabilistic models including all uncertainties of the parameters. Here, the target reliability levels based on analysis of failures have some level of human error integrated. However, to model human error in loads, without adjustment of target reliability levels will be overly conservative.

A robust operational philosophy is needed including an economic feasibility study. To have success in realizing new projects in Arctic or ice covered areas, these projects need to consider besides operational and technical also social, physiological and political aspects. This means prior such a project should be defined, all aspects need be heard, collected and included in the development of the project.

Further, given the limited availability of operational data, uncertainties limit the ability to exercise robust models and design in the following areas: sea spray icing; ice and iceberg forecasting; quantification of loads for floating structures in ice from managed and broken ice; ice in waves causing loads above and below the ice belt (relevant for marginal ice zone); and air temperature requirements. For example, wind and low temperature does not occur at the same time, thus the return period for each event is different and a 100-year maximum cannot occur for both at the same time. Consideration for modeling human error in combination with this vast amount of contributing factors will be rather challenging. Further, attempts to address this issue must however be carried out very carefully ensuring consistency with estimates of design risk, and calibration of safety targets based on analysis of accidental data.

In conclusion, the objective of this committee report is to present the current state of the art in rules and regulations to be considered when designing ships and offshore structures for ice loads. The background and motivation of the presented rules will be presented to ensure their use in line with the design conditions and assumptions. In order to progress beyond the current rules, the report presents a mission-based approach to identify the design ice load and scantlings corresponding to target ice conditions and reliability targets. Allowing for a link back to the current ice classes will ensure a straightforward applicability of the proposed approach in terms of well-known measures. Furthermore, the mission-based approach will serve as decision support tool towards the most suitable ice capability of the ship of offshore structure by also addressing the uncertainties involved in the obstacles involved.

2. DESIGN METHODS FOR MARINE STRUCTURES

The design of marine structures need to consider in addition to operational and technical issues also social, physiological and political aspects (Kuehnlein 2016). Furthermore, ambitious and challenging offshore installations in harsh environments must be designed and optimized from an operational point of view taking into consideration the full range of determining factors, such as environmental sensitivity, operational aspects, technical possibilities, investment requirements, lifecycle and operational costs. Each project should be approached with a tailor-made solution, as it is not possible to copy one project from one location to another location, even if the defining parameters are quite similar. But of course, such an existing project might be a good start for developing a new tailor-made project solution. The design should be developed by an integrated team which consists at least of psychologists, sociologists, politicians, lawyers, operators, mariners, engineers and managers. Concerning the technical aspects of the project, the following aspects should be evaluated:

- Environmental conditions;
- Environmental protection and cleanup premises;
- Year around operations;
- Year around evacuation;
- Long periods without supply;
- Extreme ice loads;
- Ice management;
- Dynamic Positioning;
- Disconnectable solution versus non disconnectable solution in ice; and
- Minimized discharge (cuttings, solids, liquids, emissions, …).

Overall, the following multi-disciplinary aspects should be considered:

- 1st nations engagement: how they are involved in the project and how their fears and concerns are mitigated?
- What kind of psychological /social and physical environment will exist and/or has to be created in order to have efficient and satisfied people working there?
- What kind of legal and political environment will exist and/or has to be created in order to have an efficient and satisfying project performance?
- What environmental and environmental protection aspects could/should/need to be considered and maintained?

- What is the main purpose of the project and how can it be achieved?
- What operational aspects have to be considered and how can these be achieved?
- What technical challenges is the project facing and will the right technology be in place to overcome these?
- What are the risks of the project and does the chosen concept minimize these (ALARP)?

2.1 Rules for ships

The choice of a certain ice class depends on a variety of factors and is different for different stakeholders. While heavily reinforced ships generally work well in ice, they may not be economical for the majority of operations (von Bock und Polach *et al*., 2014, Bergström 2017). Possible motivations include the following:

- the need for a certain performance target certain ice condition,
- the need for a certain ice class certificate to operate in a specific geographical location,
- benefit of a higher ice class compared to the rest of the regional fleet comparing increased capital costs with otherwise increased operational costs.

While the first point requires a thorough analysis of all contributing aspects, partially covered in this report, the following points are mostly driven by economic measures, which are not covered in this report.

In general, it is important to understand the underlying assumptions in the specific rules, e.g. the Baltic Ice classes require open channels or icebreaker support and the ships are not supposed to ram ice, while the amount of acceptable rams with an ice edge increase exponentially to the highest IACS Polar Class, namely PC1. Furthermore, each ice class is created around a target ice condition and while the latter cannot be accurately monitored even when operating in it, the possibility to operate the vessel outside the design ice condition is given and thereby damages are possible. In terms of the FSICR rules, the possibility of damaging the vessels structure due to overloading from ice is apparent, because the return period of the design ice load is typically below 10 days. The IACS Polar Code seeks to contribute to this aspect of safety of ships operating in ice, but so far it does not quantify safety in terms of annual exposure and reliability targets (the only reference to probability is an assumption that at least one impact occurs each year).

2.1.1 IMO Polar Code

The Maritime Safety Committee of the International Maritime Organization (IMO) adopted the International Code for Ships Operating in Polar Waters (the Polar Code) in November 2014 and the Marine Environment Protection Committee adopted the Polar Code in May 2015. The Polar Code entered into force in January 2017. The requirements of the Polar Code are intended to address the particular hazards associated with operations in the Polar regions. The structural requirements are associated with the design capabilities based on the expected ice conditions – and are based on the Unified Requirements of IACS, Polar Classes 1 through 7. Most major classification societies have provided detailed guidance on the implementation of the Polar Code (See www.lr.org and www.eagle.org for examples). The Polar Code contains specific provisions for ship structure, subdivision, stability, equipment for life-saving, navigation, and communications, as well as crew training, and environmental protection for ships in the Arctic (N of 60ºN) and Antarctic (S of 60ºS). These provisions are in addition to the following IMO Conventions: Safety of Life at Sea (SOLAS), Prevention of Pollution from Ships (MARPOL), and Standards for Training, Certification, and Watch-keeping (STCW).

2.1.2 IACS Polar Class Rules

A preliminary review of the IACS Polar Class rules was carried out by Ralph (2017) including background derivations of fundamental equations (ARMARK and MUN 1998). A brief summary is included here.

Global impact forces are estimated using a closed form kinetic energy collision model where kinetic energy from a ship collision with ice is dissipated by crushing and inertial response of the vessel. A resultant equation for maximum normal force for a given interaction area (e.g. bow or shoulder) is given as

$$F_{N\,MAX} = P_0^{\frac{1}{3+2e_x}} \cdot f_a^{\frac{1+e_x}{3+2e_x}} \left((3+2e_x)\frac{1}{2}\frac{M}{C_0} \cdot V_n^{\,2} \right)^{\frac{2+2e_x}{3+2e_x}}$$

where

- P_0 is a class parameter scaling ice pressures;
- *fa* is an interaction shape parameter;
- e_x is the ice failure exponent;
- *M* is the vessel mass;
- C_0 is the Popov mass reduction coefficient accounting for vessel and ice rotation during a collision (See Appendix A); and
- *Vn* is the impact speed normal to the hull.

Many of these factors are given in Table 1 below although justification or calibration of the parameters are not provided.

Table 1. Class factors in IACS rules and governing parameters.

Polar Class	Crushing Failure Class Factor	Load Patch dimension Class Factor	Flex Failure Class Factor	Displ Class Factor	Long'l Strength Class Factor	Impact Speed (m/s)	Ice Strength (MPa)	Ice Thickness (m)	Flex Strength (MPa)
	CF_C	CF_D	CF_F	CF_{DIS}	CF_L	Vs	P_0	h_{ice}	flex
1	17.69	2.01	68.6	250	7.46	5.68	6.02	7.000	1.400
2	9.89	1.75	46.8	210	5.46	3.99	4.21	6.000	1.300
3	6.06	1.53	21.17	180	4.17	3.00	2.99	4.200	1.200
4	4.5	1.42	13.48	130	3.15	2.51	2.47	3.500	1.100
5	3.1	1.31	9	70	2.5	1.99	2.00	3.000	1.000
6	2.4	1.17	5.49	40	2.37	1.77	1.50	2.800	0.700
7	1.8	1.11	4.06	22	1.81	1.50	1.25	2.500	0.650

The interaction scenario considered in the rules is a shoulder collision (Daley 1999). Icebreaker design is not specifically considered. The force transmitted into the hull is limited by a flexure failure calculation based on some prescribed classed based flexure strength parameter and ice thickness (which is not yet measurable on transit through an ice prone region).

Given the global impact force is transferred into the structure through localized contact areas resulting from fracture and spalling processes, the nominal contact area is adjusted to estimate a semi-local contact area and corresponding pressure using a two dimensional (2D) brittle flaking model (Daley 1992). The resultant proportion of local area to global - was on average estimated to be on the order of 25-30%. Forces through this reduced semi-local area result in higher pressures that are very high compared with other codes.

Further localization is considered recognizing that pressures on smaller areas can significantly increase. Local pressures on plating between main frames are scaled higher using peak pressure factors. The final local pressure and contact area used for plating design is based on some reduced height of the contact ice feature, and frame span.

To initially estimate the global contact area, a global pressure area model consistent with $P = Cp\ A^{-Dp}$ (written as $P = P_0 A^{-ex}$) is used except that the Polar Class rules only model a minimal scale effect with $e_x = -0.1$ unlike experimental results demonstrating a scale effect proportional to e_x (or Dp) = -0.4 (Riska 1987; Joensuu and Riska, 1989; Riska 1991; Jordaan *et al*. 2005). Interestingly if, one were to program the rule based equations and substitute $e_x = -0.4$, the trend in design is no longer correct: local pressures and plating thickness for lower exponents (e.g. $e_x = -0.5$) reduce for increasing vessel displacement. Although these reference global scale effects, for illustration, local design pressures from ship ram data follow a scale effect consistent with $A^{-0.7}$ as illustrated in Jordaan *et al*. (2007); Taylor *et al.* (2010); Masterson and Frederking 1993; Masterson et al. 1997; Palmer et al.,2009).

The final design equation for semi-local contact area models a pressure area effect with pressure increasing with increasing contact area and a scale effect proportional to $A^{+0.3}$. The intent of this empirical equation is to model the effect that higher penetrations and global contact area will result from higher energy collisions from larger moving faster ships which leads to increasing pressures locally. Contrary to Frederking (1998, 1999), Daley (2004) suggests that justification for this trend in the background literature to the Polar Class Rules is that there is no reason for traditional pressure area scale effects to exist and that with confinement, fracturing processes will be limited. But fracturing processes exist at all scales. The occurrence and behavior of HPZs either lead to very large stress localization that enhances fracture events or they undergo microstructure damage that softens the ice at the structure interface. In probabilistic extremal analysis, this design trend is entirely consistent with exposure modeling (i.e. faster larger ships will penetrate further increasing pressures locally). The resultant design trend in polar class rules is reasonable - increased pressures for larger vessels moving faster, the background ice mechanics needs improvement. We must be very careful to not confuse empirical equations of best practice with theory.

Preliminary Comparison with Exposure Based Calculations

As part of earlier work to review the Arctic Shipping Pollution Prevention Regulations (ASPPR) proposals, an extremal probabilistic design methodology was used to estimate exposure based ship ice ram design global forces and local pressures on the scantlings. The number of expected annual collisions with ice is key to modelling exposure among different class vessels (i.e. for benchmarking exercises, the annual number of expected interaction with CAC1, CAC2, CAC3 and CAC4 vessels was assumed to be 10000, 1000, 100 and 10 rams respectively). A ship ram software called FMAX (a dynamic time step ship ice structure interaction software) was developed during the ASPPR proposals review to model a "parent" distribution of impact forces for any ram, a model calibrated with full scale measurement of ship ram forces from Kigoriak, MV Arctic, Polar Sea, Manhattan and Oden trials (Carter et al. 1996). Using extremal analysis, estimates of the maximum force out of n rams in a year for a given vessel having a particular Arctic class can be estimated. Estimated design forces based on annual target exceedence probability were compared with deterministic design formulations in the Code to verify the design recommendations. Similarly, the methodology in ISO 19906 for local glacial ice design (ISO 19906, 2010) was used for designing the shuttle tankers for the White Rose development, traversing iceberg prone regions (Ralph et al., 2006). An exposure based first principle approach was developed to estimate local pressures on the hull(s) and an equivalent ship class selected (i.e. highest Baltic Class with extra ice shielding or belt around the bilge to consider deeper icebergs). Probabilistic methods were used to arrive at a suitable class as well as to verify the design adequacy. A parallel activity was to identify an equivalent ship class to assist the ship builder (see also Ralph and Jordaan 2013).

Using the extremal probabilistic approach outlined for the Arctic Shipping Pollution Prevention Regulations (ASPPR) work (ASPPR 1995, Carter et al. 1991 & 1996, Fuglem et al. 1996), the resultant recommendation for design pressures in the Polar Class rules and particularly the class coefficients that govern design pressures were reviewed by Ralph (2017). Consistent with the ASPPR proposals review, exposure levels were mapped to each of the highest Polar Classes (e.g. Polar Class 1 at 10,000 rams per year; Polar Class 2 at 1000 rams per year; Polar Class 3 at 100 rams per year; Polar Class 4 at 10 rams per year; Polar Class 5 at 1 ram per year). Local pressures were estimated based on probabilistic methods and compared with rule based design recommendations. As shown in Figure 2 and, preliminary results show that plating design pressures are reasonable (See also Tõns et al. 2015 and Erceg et al. 2015). Some lower classes with a potential risk of interaction with multiyear or glacial ice may consider possible increase in coefficients. A full comprehensive exposure based analysis of all classes is recommended particularly where a region is prone to multiyear ice.

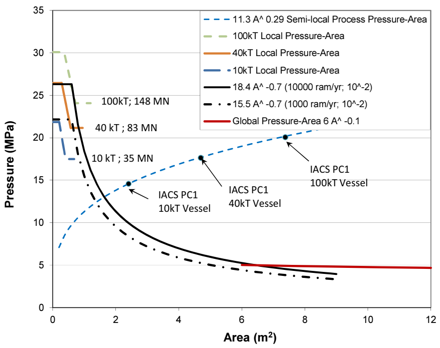

Figure 2: For shoulder impact model with contact 5 m from stem, comparison of ISO 10^{-2} exceedence, 10,000 ram local pressures on a 40 kTonne vessel with IACS Polar Class 1 local pressure-area predictions for 10, 40 and 100 kTonne vessels

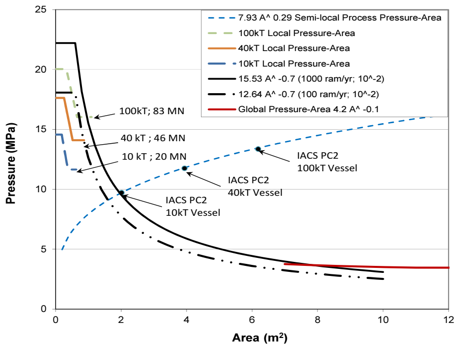

Figure 3: For shoulder geometry with contact reference 5 m from stem, comparison of ISO 10^{-2} exceedence, 1000 ram local 'bow' pressures on a 40 ktonne vessel with IACS Polar Class 2 local pressure-area predictions for 10, 40 and 100 kTonne vessels

Consideration for Probabilistic Design

As suggested above, once a Polar Class is selected, the development of scantlings following the empirical equations outlined in the rules is straight forward. Selection of the appropriate class based on exposure of the vessel to ice conditions is seen as an area for improvement. By exposure we mean consideration for the annual occurrence of ice conditions in the region of interest, potential impacts based on annual transects through the region, routing through the region, and application of risk mitigation measures (detection and avoidance). A probabilistic methodology for design of ships based on the principles of safety and consequences will allow the designer to estimate design pressures than can be compared with class pressures from exercising the rules. This way the sensitivity to increasing or decreasing a class and adding or reducing risk can be incorporated in the decision process. A higher classed stronger vessel will cost more, but have reduced risk of downtime. A weaker vessel will cost less, but with increased risk of delay or downtime. Hence the designer has a deeper understanding of risk supporting his final decision and opportunity to model operational risk mitigation in the design (i.e. detection and avoidance). He may need to justify the installation of a special ice detection radar, performance of which can be modeled in probabilistic methodology. As noted earlier, human performance may also be considered but not before an appropriate recalibration of performance targets has been carried out.

Consideration for Icebreaker Design and Concentric Bow Impacts
The design approach of future versions of the Polar Class rules should allow for the assumption that the captains will avoid ice impact, as well as specific consideration for concentric bow geometry, as opposed to shoulder only impacts. Interaction geometry and models for different alternative scenarios are formulated in Daley (1999). It is not entirely clear, however, that concentric bow impacts should be ignored even for conventional ship design. While glancing impacts with blunt hull geometry may have steep force penetration curves, shoulder impacts have a reduced Popov equivalent mass that reduces impact force as eccentric impacts result in subsequent yaw motion. further, the level of load resulting from shoulder impacts is based on an assumed ice angle of 150°. Loads are rather sensitive to this geometric interaction angle.

While the premise for this is that ship owners and captains will be motivated to avoid ice and any impacts from a manoeuvring attempt, multi-year ice embedded in level ice is largely undetectable and impact can occur anywhere across the whole bow. As a result, a designer would benefit from considering both. It is also noted that ramming events should not be assumed to only occur with an icebreaker during ice management or escort operations. Experience on bulk carriers (e.g. the MV Arctic and captain experience) demonstrates that there are times when delay in shipment of goods is not desirable, nor may the risk of getting stuck, and ramming be required to transect particular regions of ice.

2.1.3 IMO POLARIS

The IMO Polar Code requires the carriage of a valid Polar Ship Certificate that (among other items) establishes operational limitations, including limitations related to ship structural capabilities. IMO has developed general guidance (IMOb, 2016) on methodologies for operational limitations and capabilities in ice. The general guidance is that for developing any methodology, it should take into account hull structural capability, ice regimes, independent or escorted operations, and ice decay.

One methodology, considered acceptable to IMO, is the POLARIS (Polar Operational Limit Assessment Risk Indexing System), which has been developed incorporating experience and best practices from Canada, Russia, Finland and Sweden. POLARIS provides a risk assessment tool to evaluate the risk of operations for a given ship design in different ice conditions. The use of POLARIS is not mandatory – it is provided as one acceptable methodology to determine operational limitations. For detailed descriptions related to POLARIS, the reader is referred to www.eagle.org.

2.1.4 RMRS Rules

The Russian Maritime Register of Shipping or RMRS (listed in the bottom of figure) provides services for the classification of ships and offshore structures, including verification of their compliance with the applicable national and international standards. The regulatory framework of RMRS consists of rules, guidelines and other technical documentation and covers all types of modern ships and marine structures, including those suitable for operation in cold climate and in the Arctic. At present, full text electronic documents such as Rules for the Classification, Construction and Equipment of Mobile Offshore Drilling Units and Fixed Offshore Platforms, Rules for the Classification and Construction of Sea-Going Ships, Operating Experience of Ice Strengthened Tankers, among others are made available on the RMRS webpage in Russian and some are in English.

The focus is on hull scantling design in accordance with RMRS (2015). The standard approaches to limit states in RMRS ice class rules take either the yield point (elastic design) as the design limit state for the Baltic ice classes or the formation of a plastic mechanism (rigid-plastic design) as the design limit state for the Polar and RMRS ice classes.

The rules for RMRS ice class and Polar classes share much in common. For Polar classes the detailed derivation of the design loads can be found in the literature, along with the list of assumptions linking the ice class to physical values; see Daley (2000) for details. In contrast to Polar classes, the design formulae for RMRS ice classes can be difficult to understand because the explicit relationships between the physical parameters and class factors are not available in the open literature.

The ice class factors are selected to give values that are consistent with the range of desired ice class requirements for strength (i.e., PC1 should require plate and framing dimensions consistent with the hugest Arctic ice class in service). However, according to the discussion in Quinton et al. (2012), the real problem lies in the side shell pressures specified for PC1 and PC2. All evidence from various kinds of tests supports the thesis that these pressures are not reasonable but are excessively and unjustifiably high. Thus a real problem is created for higher class icebreaking ship hull design.

The Finnish-Swedish Ice Class (FSICR), IACS Polar Class (PC) and the Russian Ice Class (RMRS) rules, accept that some plastic deformation occurs during the ships' lifetime. The amount of plastic deformation (i.e. limit state) and the expected number of times it may be exceeded (exposure) is however not clearly defined, see also Kujala and Ehlers (2013) and Kämärainen and Riska (2012). Nevertheless, the critical deformation limit that requires repair can be found in the RMRS Instructions for Determination of the Technical Condition, Renovation and Repair of the Hulls of Sea-Going Ships (refer to Appendix 2 of the Rules for the Classification Surveys of Ships).

We are still a long way from being able to formulate ship rues strictly from theory. The Daley model and the Kurdyumov–Kheisin model for calculating ice crushing pressure lack some physical realism, thus making their use difficult outside the application range of the rules. For instance, as there is very little information in ISO 19906 around production floaters in sea ice, some parties may consider that designing vessels to ice class may be sufficient (see 13.5.1 in the ISO 19906). For detailed discussion on this topic refer to Kim and Amdahl (2016).

2.2 Rules for offshore structures

The section discussing the ISO standards 19900 series will be subjected to changes as the ISO19906 is currently under revision and some restructuring is anticipated. As a result, the information presented in this section may become outdated.

Historically, Russian standards have been prescriptive rather than goal based. On the other hand, incentives to apply new technology or to implement new research findings have not been prioritized through these standards. Russian standards include GOST and GOST R standards (national standards of the Russian Federation) as well as Russian and CIS countries standards and technical regulations for all major industries. These include Building Codes (SNiP, SN, GESN), Industry Codes and Safety Rules (RD, PB), Sanitation Regulations (SanPiN, GN, SP), Fire Codes (NPB, PPB), norms, instructions, methods, cost estimate standards, Russian federal and regional legislation and many others.

Additional standards relevant for Arctic operations, but not covered within this report, can be found in the Arctic Council working group report – Emergency, Prevention, Preparedness and Response (EPPR, 2015).

General and unifying principles for all types of offshore structures are provided in ISO19900 (2013). These principles include exposure levels, limit states design and the partial factor design approach, as well as considerations for structural configuration, robustness, hazards and environmental conditions. There is a relationship among the various International Standards applicable to offshore structures. One International Standard can reference the design provisions of another International Standard in the ISO 19900-series. Users need to be aware of these cross-references when using any member of this set of International Standards.

ISO19906 (2010), published in December 2010, is written as one of the ISO 19900-series of international standards for offshore structures and focuses on supplementary provisions for conditions in the Arctic and cold climate. The standard was written to cover all structural types that could operate in waters subjected to sea ice and/or icebergs; this can include both waters in the Arctic Circle and more temperate latitudes such as the Caspian Sea, Barents Sea, East Coast of Canada. Civil engineering structures such as man-made islands are also included. ISO19906 is divided into Normative and Informative sections. The former sets specific safety levels commensurate with the 19900 series and methods for ice action calculation, while the latter provides guidance with depth on calculation of ice action values. ISO19906 (2010) uses the limit state design approach; for details refer to Thomas *et al*., (2011). For general requirements for the limit state design of floating structures, ISO 19906 relies on ISO19904-1 (2006). The OGP Report No. 422 (OGP, 2010) is to be considered as a supporting document to ISO 19906 as it presents the basis for the load factor calibration and presents case studies for different Arctic regions. The report is listed as bibliographic reference A.7-2 in ISO 19906. The calibration process accounts for weighted combinations of all action effects overall design equations, and load combinations for different resistance models, levels of action effect model uncertainties, levels of statistical uncertainty, and mean action event occurrence rates.

In Russia, ISO 19906:2010 Arctic offshore structures standard has been adopted as GOST R 56000-2014 Petroleum and natural gas industry. Other relevant standards are SNiP 2.06.04-82* Loads and forces on hydrotechnical structures (influence of ice, sea waves and ships) and VSN 41.88 Ice-resistant fixed platforms design.

Users need to be aware that in Russia, the standards are reviewed every 12 years, on average (according to RS Research Bulletin, 2015), thus there could be conflicting requirements and pluralism among some of the standards. One illustrative example of pluralism is the global ice loads formulations in Rules for the Classification, Construction and Equipment of Mobile Offshore Drilling Units and Fixed Offshore Platforms, (2014) and in SNiP 2.06.04-82* Loads and actions on hydraulic engineering constructions (wave and ice generated and from ships) (2014).

Several shortcomings of the ISO 19906 have been identified by the Barents2020 – a joint project between Russian and Norwegian scientists and engineers. Details can be found in Moslet et al. (2010) and Barents 2020 (2012), only a short summary is presented below. The guidance, which is offered for floating structures in the ISO 19906, is limited, e.g., only generalities are offered in the normative part, involving checklists and general recommendations for design, but no guidance on applicable methods on induced ice actions, including ice scenarios is offered. ISO 19906 is weak on guidance for moored structures in ice.

In most methods that concern ice loads, the load itself is assumed to be independent of the stiffness characteristics of the structure and the methods are to a very large extent based on measurements and research on fixed structures. Classically there are three distinctions made on the structures properties: 1) diameter, 2) whether the waterline shape is rectangular or circular and 3) the slope angle (different regime for vertical and sloped structures based on ice failure mechanisms). This could and should also be analogous to floating structures, but there is one principal difference. The structures response can change the properties, i.e. a ship riding up the ice edge during a ram, on the exerted load. This is a classic feedback effect, which may further change the load (see also Quinton 2015 and Herrnring et al. 2017).

Ice management (IM) and/or disconnection are important factors in reducing the magnitude and frequency of ice actions. IM can only reduce design action if it can be documented that the IM system is able to reliably detect and handle ice features causing the design action. However, there is no standard practice on documenting IM efficiency and reliability. ISO 19906 mentions IM by setting performance standards but gives no guidance on how to include IM in design.

Furthermore, there is no guidance (and only limited experience) from handling glacial features surrounded by or frozen into an ice sheet and how to quantify the effects of sea ice management.

Little guidance is provided on how to perform tests with offshore structures in ice and how to accurately model and produce ice ridges, which in many cases would yield the design load in the Barents region.

Ice load calculation methods are given, however little focus is given to the range and validity. Uncertainties are covered in detail, however unclear of the overall uncertainty compares to other offshore standards. For instance, OGP (2014) reports the safety factor calibration is highly dependent upon region and ice-type. For some regions there might be a zero load associated with a 10^{-2} ice event due to their rarity but abnormal ice events could still be significant. For floating platforms, the OGP reports that the current partial environmental action factor does not account for: flexibility of mooring systems; floating structure movement; non-linear interaction between a moored structure and ice; changes in direction of incoming ice for a turret-moored ship-shaped unit; relevant operational procedures (physical ice management and disconnection); action factors for local and global actions may be different from the L1 = 1.35 value which was calibrated for bottom-founded structures. It is also noted that the focus in terms of ice loading had been heavily towards level ice acting on vertical piles, but there was very little around ice effects on floaters. It is also noted that ISO 19906 provides LRFD (load and resistance factor design) environmental action factors, however, the ISO station keeping code for floating structures (ISO 19901-7) is based on a WSD (working stress design) approach.

2.3 Mission-based analysis for ships

Present design methods benefit from the vast experience of small to medium-sized transversely stiffened ships operating in first-year ice. Scantling determination requires a design pressure and occurrence for the target ice class or the operational area in question as well as a design criterion i.e. yield. The rule-based respectively target ice class-based concept is shown by Riska and Kämäräinen (2012). However, the current rule-based design methods are not necessarily transparent by means of design pressure and scantlings determination, because they use intrinsic design criteria.

Ice-induced loads can only be described with stochastic processes due to the unknown distribution in ice strength properties and local contact geometry in the ship-ice interaction process. Besides different operational modes, also the form of the ice influences the ice load directly (i.e. level ice, ice floes and ridged ice containing first-year and multi-year ice). Further, to date there is no mathematical, numerical or analytical model available to describe the physical process of ice breaking, i.e. ship-ice interaction.

Probabilistic, or site-specific, ice load determination allows for a link between statistical data from the operational area of the vessel and the design load. However, current ice class rules are not considering probabilistic methods for determining ice-induced loads, because the requirement to specify the mission of the vessel can be considered a shortcoming by means of liability from a regulator's perspective. The latter link between the design rules and the operation of the vessel is however created in IMO's POLARIS-System, which nevertheless lacks the specification by whom this will be controlled. Yet, probabilistic design methods can be used to enhance the design process by identifying the ice load in a continuous space in addition to the discrete rule-based load. Thereby more refined design decision can be made.

An example of such mission-based probabilistic ice-load determination is presented by Tõns et al. (2015) on the basis of a method by Jordaan et al. (1993), who showed how to use pressure area relationships, obtained from full-scale measurements, to predict extreme loads at a certain exceedance probability level level (see also Ralph and Jordaan (2013) and Ralph et al. 2006).

Erceg et al. (2015) presented the applicability of such probabilistic design load method to ice-going ships operating along the Northern Sea Route (NSR) in comparison to rule-based loads. The rule-based loads were calculated according to FSICR (Trafi, 2010). For the probabilistic local design load, a global ram analysis is first carried out from which an average ram duration and penetration is determined. The local pressures on individual panel areas is modelled using an exponential distribution for peak panel pressures given as:

$$F_x(x) = 1 - exp\left(-\frac{x - x_0}{\alpha}\right)$$

where x_0 and α are constants for a given area and x is a random quantity denoting pressure. To obtain the local peak pressure distribution, the number of events can be modelled as a Poisson-process resulting in

$$F_z(z) = exp\left\{-exp\left(\frac{z - x_0 - x_1}{\alpha}\right)\right\}$$

where $x_1 = \alpha(ln\mu)$ and x_0 is the panel exposure constant. Exposure is modelled as the proportion of events that represent actual impacts between the ice and the structure as

$$\mu = v \cdot r \cdot \frac{t}{t_k}$$

where v is the time period, r is the proportion of events resulting in "direct hits" on the structure, t is the duration of the impact, and t_k is the reference duration associated with a design curve from Jordaan et al. (1993). As a result, the design load z_e can now be calculated for a given exceedance probability $F_z(z_e)$ as

$$z_e = x_0 + \alpha\{-ln[-lnF_z(z_e)] + ln\mu\}$$

For design loads in multi-year ice it is suitable to use the envelope or upper bound curve described by $\alpha = 1.25a^{-0.7}$, where a represents the local contact area. For first-year ice, the following approach may be more appropriate, because the envelope curve overestimates local pressures by a considerable margin: the use of design equations corresponding to the datasets under ice loading conditions, similar to those expected for the design environment; see Taylor et al. (2009).

For illustration purposes, a mission-based example is now presented considering transits along the NSR from the Zhelaniya port (Kara Sea) to the Dezhnev port (Bering Strait), with a distance of approximately 4500 km. The average speed is considered to be seven knots resulting in an approximate duration of one transect of 15 days. In a given year, four months are considered a feasible operational window at a maximum level ice thickness of one meter, resulting in four round trips. Assumptions of stationary ice conditions and ice concentration of 0.5 are made. Additionally, the route is ice-free for two months in a given year. Using an event duration of 0.934 s, calculated as 1/frequency from Kujala et al. (2009), and Poisson's discrete probability for n events to occur, the expected number of events for the chosen period is 1.88 million. The ship is designed to an exceedance level of 10^{-2}, which corresponds to the design point of FSICR, i.e. reaching yield once in a winter. The proportion of true hits is chosen as $r = 0.5$. The exposure constant x_0, dependent on the design area, is calculated according to Taylor et al. (2009) for the North Bering Sea 1983 dataset. With 1.88 million events along the route and Equation (3) we can solve for the corresponding design pressure using Equation (4) and $\alpha = 0.28a^{-0.7}$ for the North Bearing Sea 1983 dataset. The resulting design pressure versus exposure, in comparison to the corresponding FSCIR load value for IA Super, is given in Figure 4. Therein, it can clearly be seen that the probabilistic ice load determination accounts for significantly more impacts resulting in an increase of the design load from 1.5 MPa to 5 MPa. The latter certainly results in higher scantling requirements and thus a heavier and more expensive structure, which in turn will be less vulnerable to ice induced damages.

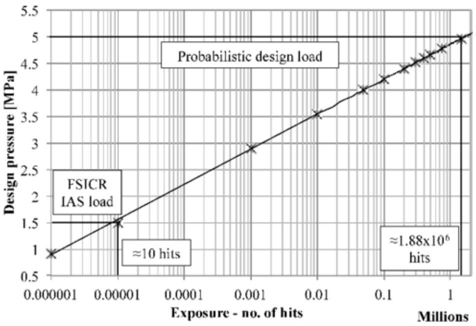

Figure 4: Design pressure for a local panel of ~ 1 m^2 (Erceg et al., 2015)

2.4 *Difference between ship and offshore rules*

Despite the fact that for an offshore structure, "*the designer may utilize the appropriate formulations in guidelines for ice-strengthened vessels of a recognized classification society*" (ISO 19906), the ice class rules are prescriptive and are not reliability-based in the same way as ISO 19906 where reliability targets have been used to calibrate the values of partial action factors. Ice class rules link ice conditions to the ice class, but ice condition descriptions are very vague. The ice class rules are rather more experience-based, linked to insurance and ice breaking service. Floating production unit in Norway does not need an ice class, but in Russia it needs an ice class. In each shelf state the mandatory requirements differ, i.e. in Canada they are required to follow the Canadian adoption of the ISO 19906 standard, but in Norway this is not the case. Similarities and differences between the methodologies of the Arctic offshore standards and the ice class rules are further discussed in Riska and Bridges (2017). A general finding is that prescriptive classification society rules are directly applicable, because they contain straightforward equations with a minimum of prescriptive text left for interpretation. While a general challenge is the fact that even the people writing standards can often disagree on how to use them, e.g. ISO lacks a certain validity of the proposed methods.

The definition of the ice load is the most important part of the hull rules. Summary of the RMRS approach to hull scantling design is presented below. For details refer to RMRS (2015), Riska and Kämäräinen (2011) and Daley (2000), Kurdyumov and Kheisin (1974).

Baltic ice classes - The requirements coincide with the requirements of the Finnish-Swedish Ice Class Rules, 2010 and apply to ships being in service in the Baltic Sea in winter. The design load corresponds to a collision with a level ice edge, a channel edge when the ship is escorted or with the consolidated layer of an ice ridge. The ice load is assumed to be described by uniform ice pressure p, on a rectangular load patch. The effect of the pressure distribution on the response of transversely framed plating is taken into account by introducing an effective plate ice pressure of $0.75p$. Limit state is yield limit, only the elastic response of the structures needs to be derived

Polar classes - The requirements coincide with the requirements of IACS PC, and apply to ships intended for navigation in ice-infested polar waters, except icebreakers. The design load corresponds to a glancing impact on the bow with an ice foe of infinite mass. The ice edge opening angle is assumed constant and equal to 150 degrees. The load is assumed to be described by uniform ice pressure p, on a rectangular load patch. Crushing and bending failure modes are considered. The Popov collision model and the Daley ice crushing model, where flaking is modelled to change nominal contact dimensions versus the actual contact area dimensions, are used. Ice edge spalling and non-uniform pressure distribution are taken into account for by reducing the size of load patch and by introducing a pressure peak factors respectively. The limit state is the formation of a plastic mechanism.

RMRS ice class - Ice load formulations from RMRS Vol.1 Pt.2 Sec. 3.10. Design ice load correspond to a collision with ice floe with a rounded edge and infinite mass. Floe radius is 25 m. The load is assumed to be described by uniform ice pressure on a rectangular load patch. The Popov collision model and the Kurdyumov–Kheisin ice crushing model are used. Ice edge spalling and non-uniform pressure distribution are explicitly taken into account by the Kurdyumov–Kheisin model. The limit state is the formation of a plastic mechanism.

3. STRUCTURAL CAPACITY

3.1 Limit states

A limit state is a condition beyond which a structure or a part of a structure no longer satisfies a specified design requirement and is considered to be failed (DNVGL-OS-C101, ISO 2394, ISO 19900). According to ISO 19900 the performance of a structure, in whole or in part, shall be described with reference to a specified set of limit states.

There is much discussion on the definitions of limit states. Some discrepancies in limit state definitions have been noted. In ISO 19906, limit states are categorised as ultimate limit states (ULS), fatigue limit states(FLS), serviceability limit states (SLS), and accidental limit states (ALS), whereas for the revision of ISO 19900, the ALS category somewhat has been changed, and instead three ULS are introduced as shown in Table 2.

Leaving this discrepancy in limit states definition aside, the information below pertain specifically to ISO 19906 and ISO 19904-1.

Table 2: ULS (Thomas, 2017)

ULS(a):	ULS(b):	ULS(c):
failure of an individual structural component caused by design action effects exceeding design resistance (in some cases reduced by deterioration), including loss of structural stability (buckling, etc.);	loss of static equilibrium of the structure, or of a part of the structure, considered as a rigid body (e.g. overturning, sliding, sinking, or capsizing);	complete loss of integrity of the structure or vital parts of the structure when there is no further system ductility or reserve strength, including transformation of the structure into a mechanism (collapse or excessive deformation), loss of stationkeeping (free drifting);

According to ISO 19906, the ULS design condition shall be based on environmental events which result in extreme-level (EL) environmental actions, with both local and global ice actions considered. In addition, the expected effects of snow accumulation, icing and ice accretion shall be accounted for. For floating structures, it is necessary to consider pressure events due to convergence of surrounding ice (or presence of a coastline).

The combination of environmental actions, permanent actions and variable actions with corresponding partial safety factors are used in the ULS design. The representative values for environmental actions shall be determined based on an annual probability of exceedance not greater than 10^{-2} and include the principal action and relevant companion actions (e.g., ice, wind and waves). The latter can be stochastically independent or stochastically dependent. To determine the representative values probabilistic methods or deterministic methods are used. It is important to realize that selecting the appropriate design conditions for the ice environment may be challenging as neither the largest ice ridge nor the thickest ice necessarily give the largest action effect. In other words, a 100–year environment conditions ≠ a 100–year action ≠ a 100–year action effect.

According to ISO 19906, the design procedures for ULS shall be based primarily on linear elastic methods of structural analysis. Some localized inelastic behaviour is accepted. For foundation design, ULS shall be analysed with the appropriate cyclic action effect history including ice actions. For hull design of floating structures, the designer may utilize the appropriate formulations for ice-strengthened vessels, and IMO national requirements shall be incorporated in the design when applicable.

In accordance with the ISO 19904-1, the following specific limit states are usually evaluated for floating structures within the ULS framework: yielding, global and local buckling instabilities. For ULS checks the representative value of the yield strength is used and the buckling strength is based upon formulations in the recognized classification society or equivalent code formulation.

In NORSOK N-004 (2013) it is added that when plastic or elastoplastic analyses are used for structures exposed to cyclic loading checks shall be carried out to verify that the structure will shake down without excessive plastic deformations or fracture due to repeated yielding. Note that the NORSOK has a temperature limitation to -14C.

It should be also noted that the RMRS's Rules for the Classification, Construction and Equipment of mobile offshore drilling units (MODU) and fixed offshore platforms (FOP) use limit state equations in a form that essentially differs from that in ISO 19900 series, mainly due to different systems of safety factors and load combination factors used and due to some extra factors in Russian version. In accordance with the RMRS rules, the dangerous states such as excessive deformations of material, buckling, fatigue cracks and brittle fracture shall be avoided.

According to ISO 19904-1, non-linear analysis may be used to determine the ultimate capacity of structural components, substructure or the complete structure. A non-linear analysis should include appropriate models for all significant non-linear effects, including elastoplastic behaviour large deflection and criteria for rupture, among others. Refer to ISSC (2015) for detailed information related to buckling and ultimate strength of components and systems of ships and offshore structures. The explicit limit state definition is practically non-existent. Interpretation/understanding of the limit state can be found in Riska and Bridges (2017).

3.2 Response to moving loads

Moving (or sliding) ice loads are hull loads arising from oblique impact, or continuous sliding contact, with an ice feature. They are characterised by both motion in the direction normal to the hull, as well as sliding motion tangential to the hull. Hull response to an oblique impact with ice depends on the relative masses of the hull and the ice, the compliance of each, the impact trajectory, and the speed of the impact. Continuous sliding contact generally occurs when either the ice, or both the ice and the hull, are undergoing considerable damage at the contact interface, and are unable to separate.

Many operational hull impacts (e.g. collision with a single ice floe having a mass considerably less than that of the hull) with ice result in a glancing collision, characterised by elastic hull structural response and little to no sliding action of the ice along the hull. Other operational ice loads (e.g. the hull interacting with level ice, or a ship ramming a multi-year ridge) involve considerable sliding contact between the ice and the hull.

With a few exceptions, practically all hull impacts involve some component of relative sliding motion between the hull and the struck (or striking) object; however, it is common practice to neglect the sliding component when the hull structural response to the load remains elastic.

This is evidenced by the fact that no international rules or guidelines for the design of ships or offshore hull structures presently consider moving loads as a design scenario.

For steel hulls, when the hull responds plastically, the sliding component of these loads has been shown to incite a considerable loss in hull structural capacity (up to approximately 50%), for hull plating and hull framing, when compared with hull response to stationary loads of equal magnitude. Specifically, the greater the amount of plastic damage on the trailing side of the moving load, the greater the loss in hull capacity. This was initially predicted numerically (Quinton 2008; Alsos 2008), then analytically (Hong and Amdahl 2012), and was recently verified experimentally (Quinton 2015). Additionally, Quinton (2008; 2015) showed that the web of a hull frame will plastically buckle under a moving load at a far lower load magnitude than for a stationary load. Huang et al. (2015) proposed a deterministic ice force function to predict the ice loads during icebreaking activity. They modelled a composite ice crushing mode where the icebreaker will interact with the ice face and develop radial cracks. The ice-ship interaction of a multi-purpose icebreaker was analyzed by using the MOSES software. The results revealed that the moving responses are different in heading current or adverse current with different ice velocities.

It is important to note that the structural design point for the hulls of polar class ships (IACS 2016) and Arctic offshore structures (ISO 19906 2010) is a plastic design point. That is, under the design load, these hulls are expected to sustain a small level of plastic damage (e.g. a small dent). The extent to which the capacity loss associated with moving loads affects arctic offshore structures and IACS polar class ships is presently unclear. The work by Quinton et al. (2012), using real-time and real-space moving loads recorded during the 1980s USCGC Polar Sea ice trials, indicates that the level of hull damage sustained from application of the design load is not sufficient to induce any great loss in hull structural capacity. In other words, Polar Sea icebreaker was suitably designed and no damage resulted from icebreaking trials.

3.3 Temperature definitions

There are many different temperature definitions used for the design of maritime and offshore units. Some of the most relevant are listed in Table 3.

One can differentiate between definitions used for selecting appropriate steel grades (i.e. material selection) or for setting winterization performance requirements. For material selection, there are in general two regimes:

- Lowest Mean Daily Average Temperature (LMDAT)
- Lowest Anticipated Service Temperature (LAST)

The LMDAT regime is in general used for ships and offshore units applicable to classification, while LAST originally comes from ISO 19902 and the definition became clarified in ISO 19906. The LMDAT is the basis for selecting the design temperature, where at least a 20-year data series should be used for calculating LMDAT. There are no minimum requirements (for instance minimum number of years of data) for determining LAST (being the extreme low hourly average temperature with an annual probability of exceedance not greater than 10^{-2}). Due to the difference in the definitions LAST can be about 20-30 degrees lower than LMDAT and for some offshore areas LAST can be as low as -40°C. However, as noted by Riska and Bridges the calculation of LAST needs better definition to ensure consistent use. For instance, the height of the measurement point is not specified.

Table 3: Common temperature definitions

Symbol	Meaning	Reference	Use
$t_{D,}$ t_d	Design temperature; Material design temperature	IACS UR S6.3 and DNVGL Rules for Ships	Ship winterization Selecting steel grade
tw	Winterization temperature	DNVGL-OS-A201	Offshore winterization
t1, t2	Design temperature (t1) and Extreme design temperature (t2)	DNV Rules for Ships (pre-July 2013)	Ship winterization
DAT(t)	Design ambient temperature	DNVGL Rules for Ships	Class notation for structural material selection
PST	Polar service temperature	IMO Polar Code	Polar Code compliance
LMDAT	Lowest mean daily average temperature	IACS UR S6.3, DNVGL Rules for Ships, and DNVGL-OS-A201	Setting tD, td, t1, DAT(t), selecting steel grade
LMDLT	Lowest mean daily low temperature	IMO Polar Code	Setting PST, PST ≤ LMDLT – 10°C
ELT	Extreme low temperature	DNVGL-OS-A201	Setting tw, no prescribed definition
LAST	Lowest anticipated service temperature	ISO 19902, ISO 19906	Offshore installation design
RP100	Extreme low temperature with an annual probability of exceedance not greater than 10−2	ISO 19906 and NORSOK N-003	Setting LAST

3.4 Requirements of ductile to brittle transition

While the strength of steel increases under cold temperatures, it is obvious that the inherent risk of unexpected brittle fracture increases as well. All ferritic structural steels suffer from reduced fracture toughness at low temperatures due to the ductile-to-brittle transition behavior (DBT), which is characteristic for steels with body-centered cubic (bcc) crystal structure, see also Figure 5. The figure shows a distinct shift in the ductile to brittle transition temperature due to the differences between the specimens and test conditions. At lower temperatures, the mechanism of stable crack growth behavior changes from plastic blunting and tearing to cleavage controlled brittle fracture. This transition occurs over a narrow range of temperature, typically 30 K (Billingham et al. 2003) and is often characterized by the T27J temperature. This is the temperature where the interpolation of Charpy V-notch impact toughness tests results yields an energy of 27J. Other measures for the ductile-to-brittle transition temperature (DBTT) are the fracture-appearance transition temperature (FATT), where 50% of the fractured surface is related to brittle fracture, or transitions in CTOD (BS 7448-1), KIc (ASTM E399), T0 (ASTM1921), or J-integral (ASTM E1820) test results.

Consider one example for a location where LMDAT is -10°C and LAST is -40°C. The structural design of a primary loading bearing member requires using a steel plate with thickness 70 mm with yield strength 355 MPa.

Using the specification in IACS, steel with such yield strength is denoted ‘higher strength’ steel and the standard further specifies that grade E steel can be used for the specified thickness. At a test temperature of -40°C, the DNVGL-OS-B101 standard specifies that 41 J and 27 J needs to be demonstrated in conventional Charpy V-notch tests (the DNVGL standards DNVGL-OS-C101 and DNVGL-OS-B101 are harmonized with the IACS rules).

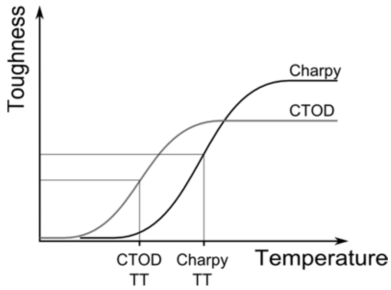

Figure 5: A schematic illustration of a Charpy and CTOD ductile to brittle transition curve.

Using the requirements in ISO 19902 of having Charpy V-notch test temperature 30°C lower than LAST would then mean test temperatures down to -70°C for group II, class CV2 steels. The required Charpy toughness is then specified to be a minimum of 35 J. The ISO 19902 standard recommends. then the EN 10225 standard as a material selection standard for steel plates

While the ISO 19906 standard specifies hourly average temperatures and an annual probability of exceedance not greater than 10^{-2}, the NORSOK N-003 standard specifies a 24-hour average and the same probability of exceedance. At this probability level there is little difference between using a 1-hour average and a 24-hour average. The NORSOK M-120 standard requires the EN 10225 standard to be used for rolled plates.

However, the EN 10225 standard however, only specifies steels with low temperature impact properties at temperatures down to -40°C so can strictly speaking not be applied with such low service temperatures as specified in this example.

Interestingly, the Canadian CSA S.473 standard specifies 35.5 J at a test temperature 30°C lower than the 'toughness design temperature' which is to be specified based on an annual probability of exceedance of 0.5. No attempts have been taken to relate this to LAST or LMDAT for this report.

This discrepancy between the standards regimes have not been under scrutiny much in past since a default design temperature for ships and offshore mobile units have been -10°C.

Ships and offshore structures operating in Arctic regions are exposed to low temperatures as defined above and are thus required to function reliably therein. Current regulations however do not cover the expected temperature range and thus the reliability of structures used in such conditions may be reduced. DNV GL provides some guidance down to -30°C (DNV, 2013), while NORSOK is limited to -14°C (Norsok, 2017). Consequently, there is a lack of guidance in structural behaviour at low temperatures, especially for welds.

3.5 The effects of low temperature on fatigue and fracture properties

For structural assessment, it is therefore required that the DBTT remains below the anticipated service temperatures at all times. However, low service temperatures also influence other limit states. Regarding fatigue limit state design, it is generally assumed that lower temperature will have no detrimental effect on the fatigue properties of steels, see Alvaro et al. (2014) or DNV (2013). This assumption is backed by extensive fatigue crack growth rate testing of base materials for a wide variety of steel grades. In plain steel structures without welds, fatigue life is divided into two parts, fatigue crack initiation and fatigue crack growth. Depending on the geometry, stress state and presence of material defects, one might dominate the other. The mechanism of fatigue damage is known to be the result of complex dislocation arrangement governed by local irreversible plastic flow (Alvaro et al., 2014). Since the static strength increases with lower temperatures, the resistance against dislocation movement is increased and thus both the fatigue crack initiation and the crack propagation are hindered (Alvaro et al., 2014). However, for metals which feature a DBT, the fatigue crack growth rate increases again for temperatures below the fatigue transition temperature (FTT), which can be seen in Figure 6. This phenomenon is sometimes referred to as fatigue ductile-to-brittle transition (FDBT).

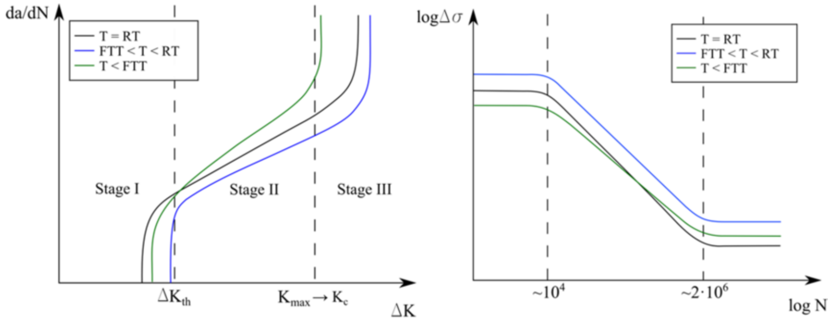

Figure 6: Schematic representation of the effect of low temperature on (a) the fatigue crack growth curves based on Alvaro et al. (2014) and (b) the expected SN-curves

Since low temperatures seem to increase the lifetime of a structure, this effect is usually neglected during fatigue assessment of steel structures at low temperatures. Using medium and high strength steel test, Walters et al. (2014 and 2015), demonstrated that this assumption is not generally true . It was found that the FTT seems to be lower than the FATT, but higher than the T27J temperature, which is usually used as indicator for the DBTT. The FTT is usually not considered in design, and any protection is obtained implicitly by using T27J as a quality control measure for fracture. It showed that the common belief that sufficient impact toughness of the base material at the design temperature will be enough to justify the use of a material at this temperature, might not be enough.

Based on the assumption that brittle fracture occurs before the changing fatigue behavior significantly affects the lifetime of a structure, current regulations for material qualifications are enforcing sufficient toughness values at the design temperature. The main objective of many research projects is therefore to provide a reliable basis for estimating the transition to brittle fracture of base materials and welded structures. On the other hand, compared to the well investigated fatigue crack initiation and growth behavior of plain steel specimens, the effect of temperature on fatigue properties of welded structures is scarcely mentioned in published literature. Experimental tests of Miki and Anami (2001) and Wahab and Sakano (2003) suggest that the DBTT is higher in the heat-affected-zone (HAZ) of welded structures than in the surrounding base material. However, the influence on the fatigue properties of welded structures for offshore applications is not evident, due to the lack of comprehensive studies regarding the change of static and dynamic properties of base material and welded structures at sub-zero temperatures. Bridges et al. (2012) carried out cyclic tension fatigue testing of welded specimens made from AH36 and DH32 steel grades under room and cold temperature conditions. The experimental results revealed that the mean fatigue strength of the tested steel specimens at low temperature is slightly higher than that at room temperature. Braun (2017) presented a first insight into static and dynamic material properties for different welded structural details and material strengths at changing temperatures from room temperature to -50°C in order to establish a physical model that explains the change of fatigue growth behavior at low temperatures based on the changing failure mechanism.

In welded steel structures, it has long been recognized that brittle fractures almost never propagate along the HAZ (Goldak et al., 1977). Charpy V-notch toughness testing of the HAZ is therefore difficult to perform, since the fracture path will not usually follow or stay in the zone being tested. Further, the DBTT varies with the state of stress e.g. the specimen size, type of loading (bending versus tension), geometry, and rate of loading. Despite this, Charpy V-notch testing is the basic method prescribed in codes and standards to ensure sufficient impact and fracture toughness. Although the relation between impact and fracture toughness test results is mainly empirical in nature, the concept has been proven to yield satisfactory results for moderate thickness sections, see Banister (1998). Moreover, Charpy impact testing is usually preferred as a low-cost quality control measure. The latter was also identified by Hauge et al. (2015) addressing also the subject of corrosion control, aluminium structures and steel structural fabrication for low temperature applications in conjunction with the notion of crack arrestability. The paper states that current design codes require 'relatively low requirements to Charpy impact energy (e.g. 27 J)', which as such 'do not prove that brittle fracture can be avoided'. An approach is advocated where fracture mechanics tests are conducted for material qualification, in conjunction with Charpy impact tests during the design and qualification phase. The other subject addressed is corrosion. It is pointed out that the cold environment creates electro-chemical conditions which are rather different from non-arctic environments, which cannot be ignored. The other important influential parameters such as the thickness and load strain rate may also significantly influence both strength and toughness. For example, increased thickness may lead to so called plain-strain condition and therefore minimum possible toughness levels. Therefore, based on nominal toughness level and delivery condition for one structural steel grade and selected minimum design temperature, the maximum allowed thickness for utilization are defined.

3.6 Repair limits

A clear definition of the state of deformation requiring repair is not to be found in the current rules. The Russian Maritime Register of Shipping allows repair of smooth indentations in the hull plating during the next scheduled dry docking, if the following is met:

- the indentations are not larger than 20% of frame spacing and the depth to length ratio is not larger than 1:20;
- local dents are allowed if the depth is not greater than five times the thickness of the plating and the ratio of depth to frame spacing not greater than 1:20 (Benkovsky, 1970).

Further, surveyors may require repair, if the plate deflection is above 1/12 of the frame spacing (Hayward, 2007).

4. ICE LOAD MEASUREMENT AND MODELLING

4.1 Full-scale

Simulation of ice and ice loads, in general, is an extremely complex endeavour. It may appear that direct comparison of full-scale ice load measurements and data to modelling results is a straightforward approach for ice load model validation. This approach is, however, accompanied by several challenges: (1) the measured data on ice loads is somewhat scarce and observations often insufficient (Timco and Weeks, 2010), (2) sample sizes in the experiments are typically low but the ice loads are known to be stochastic and the scatter in data large (Daley at al., 1998; Jordaan, 2001), (3) interpretation of the measurement results is difficult and may have sometimes even been erroneous (Liferov, 2005), and, just simply due to (4) the ice loading processes in full-scale being very complex (Palmer, 1991; Daley at al., 1998).

The range of parameters measured in full-scale is often small and in nature the parameters vary through any given ice field which leaves the question; how to parameterize a model so that it represents the ice conditions during a field measurement? It is impractical and sometimes infeasible to measure all potentially interesting sea ice parameters during full-scale ice measurement set of trials (Palmer, 1991). This is due to the field conditions, the nature of measurements, and often the cost of the measurements (Timco and Weeks, 2010). Even if such measurements could be made, it is likely that the ice properties change during an interaction process due to the inhomogeneity of sea ice. The mechanical properties of sea ice are poorly known and there is only a handful of reasonably well-understood properties.

Ice as a material demonstrates a myriad of mechanical behaviours; including creep, viscoelastic-viscoplastic deformation, and fracture into discrete media where interaction between all discrete and continuous ice pieces are important. With numerous factors influencing the behaviour of ice, modeling ice is exceedingly challenging; and to date, no general ice model, which can capture all the scenario dependent ice behaviours, has been developed. We can, however, limit the number of parameters needed by conducting a design of experiments. Simulations are a good platform for this type of study as they allow full control on parameters in ice-structure interaction. Ranta et al. (2016) used this approach and performed a 2D FEM-DEM study on ice-structure action. They investigated the sensitivity of maximum global ice loads in the process to variety of parameters related them. Namely, the ice-related parameters affecting the loads were: ice thickness, friction coefficient and yield strength of ice. Interestingly, the temperature, having a significant effect on HPZ failure strength, was not included.

Ranta et al. (2016) observed that the effect of ice thickness on the maximum loads far exceeded the effect of actual material parameters of ice. For example, while still showing in the results, increasing ice compressive strength value from 1 MPa to 2 MPa caused about 10-15 % increase in peak ice load values. This observation is in line with widely accepted view that ice thickness has an important role as it is closely related to ice loads, ice failure behaviour, and ship resistance in ice (Timco and Weeks, 2010; Palmer and Croasdale, 2013). One must notice that depending on the scale and application the interesting parameters may change: the compressive strength of ice is obviously of interest if we are interested on local ice pressures.

Another challenge for validation of numerical models is the inadequate sample sizes in field experiments. It would be crucial that the experiments would be repeated a number of times due to typical wide scatter in measurement results. This need is demonstrated by a recent simulation-based study on ice-structure interaction in Ranta et al. (2016): there may be need to run sets of tens of repeated measurements for reasonable error limits on measured loads in ice-structure interaction. These numbers are impossible to reach in well controlled full-scale experiments.

The problems related to interpretation of the full-scale data are discussed below using ice rubble as an example, but is due to limited knowledge on the most important sea ice failure mechanisms during a loading process, and the lack of opportunities for accurate observations in-situ being very limited. While the full-scale experimentation and measurements on ice loads has led to important data on the load values, the field tests remain difficult to analyze, understand and generalize due to the complexity of the ice loading processes: there have been no methods in receiving all the data needed (Palmer, 1999; Kendrick and Daley, 2011).

Ice load records are difficult to interpret in terms of mechanics of the process as they include numerous consecutive short-term peak load events. In statistical studies, short-term peak load events are defined using various techniques, in which commonly a threshold load level is prescribed and used to separate a number of peak load events from the data. One commonly used technique is Rayleigh separation: highest peak load value is first selected from the load record while the next peak load is not chosen until the load has decreased under the chosen threshold value. This definition clearly does not account for the mechanisms in the loading processes, and defining a single peak ice load event from a measured load signal is a challenge. Suominen and Kujala (2014) studied the short-term ice loads on the ship hull using Rayleigh separation, and their study shows that the method leads to load statistics that depend on the choice of the threshold value.

The short-term peak loads may appear and disappear due the ice-ship contact moving away from the load patch, or the peaks may simply be due to, for example, ambient water or ice fragments around the ship instead of the actual ice failing. Suominen et al. (2013) compared the results from the simulations on ice loads on a ship operating in level ice with their full-scale results on ice loads. The simulations mimicked their experiments. The measured full-scale data included a substantial number of peaks that were not predicted by the simulations. It is unclear, which of the peaks were due to actual ice loads.

The model should cover a lengthy interaction process in total and capture the most important mechanisms in this process in order to be truly predictive. There is no reason to assume that an interaction process reaches a steady state that produces a roughly constant maximum load (Palmer, 1991). This especially applies to ice loads on fixed structures, where the earlier sea ice failure and loading process itself affects the subsequent failure process (Määttänen, 1986; Sanderson, 1988; Daley at al., 1998). In short, the ice loading process evolves in time as discussed recently in Ranta et al. (2018). On the other hand, due to this, numerical models that repeat some prescribed failure behaviours and patterns may have only limited use in improving ice load predictions and understanding of ice mechanics.

4.2 Laboratory-scale

Laboratory-scale experiments are an attractive platform for validation of ice load models due to their relatively low expenses and more accurate control when compared to full-scale. Very detailed observations are possible laboratory-scale and, for example, Liferov and Bonnemaire (2005) suggest that the laboratory experiments may be the only practical possibility to get an insight about the failure process of ice rubble. In laboratory one can perform sets of repeated experiments, while having good control on parameterization. Laboratory tests also allow a relative ease for limiting the problem under study. An example of this type of study are the ice crushing experiments by Määttänen (2011) which were modeled using FEM and cohesive fracture by Kuutti et al. (2013).

This opportunity to isolate, at least up to certain length, phenomena of interest in laboratory is of crucial importance, if one of the aims of the experiments is in the development, validation or verification of an ice load model or a predictive simulation tool. In validation of a model, one wishes that the model would first repeat or predict the results, which are measured in a simple ice loading scenario, before advancing to more complex less well-defined ice loading scenarios. The gap in directly going reliably from a numerical model to a general ice loading scenario, in either laboratory-scale or full-scale, is often simply too large.

For validation purposes, it is thus of outmost importance, that properly scaled experiments that are suitable for validation are performed, and as will be suggested below, it would be beneficial that a suite of ice simulation benchmarking data be collected, organized, and made publicly available. The benchmark experiments should include very detailed reporting, and allow fairly simple interpretation through a manageable set of parameters and potential load mechanisms. These experiments should be done apart from the experiments on general ice loading scenarios that have their primary aim in design loads. A design load experiment is usually performed using a given type of model scale ice, they may be too complex for model validation even if useful for the design, and, unfortunately, their reporting may lack due to the goal of solely catching a design load (or some other design feature of interest).

It is a very challenging task to define a definite set of benchmark experiments, which an ice load model should fulfil for it to be validated for design, and for being able to claim that a given model suffices all different ice loading scenarios; There are several different types of ice load sources, loading mechanisms, and ice parameters, which may be important depending on an ice loading scenario and the task of planning benchmark experiments for all of them is difficult. In addition, the importance of different parameters may change during a loading process (Palmer, 1991; Ranta, 2016). It can be said that partly the challenge is due to the complex ice loading processes and ice material behaviour, but also due to the need for better understanding of fundamental mechanical behaviour of various ice features themselves. The model validation is partly a challenge as we do not understand the ice loads and the mechanics of them well enough.

Apart from this, there are also short-comings, and related discussion, in performing just laboratory-scale experiments. A very obvious difference between the full-scale and laboratory-scale experiments is the physical dimensions. Another crucially important difference is in the type of ice used in the laboratory-scale studies. While some of the experiments are performed using normal sea ice, others are done using fresh water ice, ice grown in laboratory, or doped model scale ice with scaled material properties. Different ice types show different behaviour, which is why the type of ice must be accounted for when interpreting laboratory-scale experiments. A minimum standard ice sample production consideration, if attainable, would enable improved interpretation of laboratory test data.

Lubbad and Løset (2011) developed a level ice resistance on ship model for use in real time simulators on. a simplified ice failure model is used. The failure followed a closed form solution for a bending failure of a sheet on Winkler foundation. They found that the simulation results for mean ice resistance levels were in agreement with full-scale measurements in both, model and full-scale experiments. A simulation tool with very similar ice failure model was used by Dudal et al. (2015) for real time simulations on ice structure interaction. Su et al. (2010, 2011a, 2011b, 2014) performed simulations on ice resistance of a ship in continuous level ice breaking. The ice failure in their model was defined to follow a prescribed pattern, which was based on available work on crack patterns in ice. Also in their model, the cracks formed by bending and depended on the characteristic length of ice sheet, ship speed, the frame angle, and a normally distributed random variable. Su et al. (2014) compared the simulation results to model scale experiment results with some success, but note that limited amount of data somewhat restricts the validation of their model. Zhang et al. (2014) studied the interaction between side grillage of a ship and icebergs using finite element simulations and model tests. They were able to validate their simulation tool, which then was used in studies on ship bulbous bow-ice collisions with various velocities.

Having reliable full-scale validation is needed in the development of numerical modelling tools for design, even if they would be in agreement with laboratory experiments in these cases. There have been recent efforts that aim for better understanding of model scale ice behaviours (von Bock und Polach et al., 2013; von Bock und Polach and Ehlers, 2013; and von Bock und Polach and Ehlers 2013, 2015) as it is very important to understand the advantages and limitations of model tests.

4.3 Ice load modelling and validation

The understanding of the mechanics of ice loads is constantly increasing and numerical simulations have a role in this increase, since they may give understanding on the detailed mechanisms behind the ice loads. As described above, the validation of ice load models and simulations for taking them to the level of design is a challenging task. However, ice load simulations and modelling efforts have increased and computational ice mechanics has been performed using various techniques.

Recent numerical modelling work has been done using discrete element method (DEM) (Cundall and Strack, 1979), combined finite-discrete element method (FEM-DEM) (Munjiza, 2004), finite-element method (FEM) with various modelling frameworks, various types of cohesive elements (Camacho and Ortiz, 1996 and smoothed particle hydrodynamics (Gingold and

Monaghan, 1977; Lucy, 1977). In addition to these, modelling of hydrodynamics in ice-structure interaction has been developed using computational fluid dynamics (CFD) and potential flow theory.

Lubbad and Løset (2011) developed a model for use in real time simulators on level ice resistance on ships. The model uses a simplified model for the ice failure. The failure followed a closed form solution for a bending failure of a sheet on Winkler foundation. They found that the simulation results were in agreement with full-scale measurements on mean ice resistance levels in both, model and full-scale experiments. A simulation tool with a very similar ice failure model was used by Dudal et al. (2015) for real time simulations on ice structure interaction. Su et al. (2010, 2011a, 2011b, 2014) performed simulations on ice resistance of a ship in continuous level ice breaking. The ice failure patterns in their model were defined to follow a prescribed model, which was based on earlier work on crack patterns in ice. Also in their model, the cracks in the model formed by bending and depended on the characteristic length of ice sheet, ship speed, the frame angle, and a normally distributed random variable. Su et al. (2014) compared the simulation results to model scale experiment results with some success, but note that limited amount of data somewhat restricts the validation of their model. Zhang et al. (2014) studied the interaction between side grillage of a ship and icebergs using finite element simulations and model tests. They were able to validate their simulation tool, which then was used in studies on ship bulbous bow-ice collisions with various velocities.

Metrikin and Loset (2013), Metrikin (2014) and Metrikin et. al (2015) present a non-smooth DEM based model for modelling ice-structure interaction. According to the authors, the model is suitable for simulating station keeping in a field of ice floes. Recently van den Berg (2016) presented a random lattice based model for sea ice. The work aims to model a variety of ice mechanics problems based on lattice modelling, where discrete rigid bodies are glued together with initially elastic cohesive elements. When an ice sheet is modelled using this type of method, the basic mechanics of the model become similar to those in Paavilainen et al. (2010) who modelled the ice sheet using a lattice of beams that connected rigid discrete elements together. This model was further studied in Lilja et al. (2017a, b) in some fundamental mechanics problems. Further, van den Berg (2016) demonstrates the capability of the model to model consolidated ice ridges in a similar manner than Polojärvi and Tuhkuri (2013). The model is yet to be validated against experimental data.

Kuutti et. al (2013) modelled ice loads on structure using FEM and cohesive elements. The modelling was done on a level of local ice loads, and the authors claim that their model is the first model that able to describe continuous crushing of ice. The load levels from the model compared well against the laboratory experiments in Määttänen (2011), which were done for studying the distribution of local ice loads on a model hull structure. In the experiments by Määttänen (2011) the ice properties were not scaled, albeit the ice was laboratory made. Kuutti and Kolari (2010, 2011) also presented a damage-mechanics-based FEM model with local remeshing procedure, which allowed the cracks to propagate through the finite elements. There was no comparison of the latter model with ice load data. Ice crushing and local ice loads were also recently modelled using FEM by Jordaan et al. (2016) and Gagnon (2011) and by a combination of FEM and SPH by Kim (2014).

Modelling work related to on ice mechanics and, in more detail, ice rubble has been recently performed by Polojärvi and Tuhkuri (2009, 2013) and Polojärvi et al. (2012). The work concentrated on understanding the material behaviour of ice rubble and the model was validated against experimental data, both from model and full-scale. In this case, the model-scale experiments were performed using plastic rubble blocks with a goal in model development to achieve increased insight on the mechanics through exercising punch through tests. Kulyathkin and Polojärvi (2016, 2017) used numerical modelling to study the applicability of the continuum assumption on ice rubble using numerical modelling. Further work on more fundamental ice mechanics was done in von Bock und Polach et al. (2013), von Bock und Polach and Ehlers

(2013) and in von Bock und Polach and Ehlers (2013, 2015). The work aimed to tackle some of the above mentioned challenges in scaling of laboratory-scale results by using laboratory-scale experiments and numerical modelling in parallel to study model scale ice properties.

Role of the hydrodynamics on ice loads has been recently studied by several authors. Gagnon and Wong (2012) studied a simplified bergy bit-ship interaction accounting for hydrodynamics by using a CFD solver. Simulations yielded realistic bergy bit behaviour and ship grillage damage patterns for their model. Tsarau et al. (2014) introduced computationally efficient numerical tool, which combines DEM and a potential flow theory based solver. The model was first validated against simplified laboratory experiments and then applied to more complex ice loading scenario involving a ship and ice floes. Tsarau and Løset (2015) added a vortex element method solver to the same simulation tool to predict ice motion further and used visual observations on laboratory experiments in validation. Tsarau et al. (2016) also used a simplified hydrodynamics model to account for fluid drag forces on ice floes in a modelling study on the effect of propeller flow in ice management (Polojärvi and Tuhkuri (2009) and Polojärvi et al. (2012) presented a similar model for hydrodynamic pressure drag).

4.4 Towards a benchmark data suite

We suggest that a suite of ice simulation benchmarking data be collected, organized, and made publicly available – even if suggesting a set of definite experiments for this is out of scope of this report. One effective way to categorize the data base would be to divide it into three parts, based on simulation scale and ice engineering purpose: large, medium, and small; with large being on the order of kilometres scale, medium being at metres scale, and small being at centimetres scale. (Here we, even if important, leave out geophysical scale and concentrate on ice engineering scale.) Each scale has unique data measurement and availability challenges.

For large scale, some typical sources for data are satellite imagery, meteorological ice and weather records, ice flight observations, ice radar, and ship ice-trials databases. Much of this data, as well as data collecting philosophy is based in 20th century technology. Nowadays, with satellites, cell phones, GPS, and the internet of things, it is possible (and recommended) to have access to live-streaming real-time meteorological ice related data virtually everywhere. This access will enable development of onsite ice-operation related decision support tools; de-risking these operations and streamlining productivity.

Medium scale scenarios are typically on the order of metres, or tens of meters, and involve the interaction of a one or more ice pieces with a structure and other ice pieces. Models for this scale are dependent on ice physical properties, on relationships prescribing ice behaviour (such as ice friction models, or ice contact pressure as a function of contact area), and on understanding of the underlying mechanical phenomena. Benchmarking data for this scale should thus include measured, scenario dependent physical ice properties, and detailed observations on scenario-dependent mechanical processes.

Small scale scenarios occur at the scale of centimetres, and are typically centred on replicating small-scale laboratory experiments, or extrapolating/investigating ice behaviours that are difficult to study in the laboratory. These models strongly depend on the physical properties of ice and on the modelling assumptions. (Benchmarking data required for these types of simulations are similar to the physical properties data required for medium scale simulations, however, often more in-depth and higher quality data is required). Due to the extreme scenario-dependence of small scale simulations, it would be impractical to consider all possible small scale ice loading cases. For benchmark database, a table characterising the scenario and conditions, under which the data was collected, should be carefully contrived.

Regardless of scale, developing a suitable material model for ice is a key issue in order to run reliable simulations of different scenarios. At least for small and mid scale scenarios, the ideal material model should be able to reproduce laboratory experiments in a simulation, regardless of the type of expected ice behaviour. For this purpose, experimental data could be put into a standard framework, such as the one proposed in Figure 7. Here, the peak stress ice can sustain is given as a function of the triaxiality of the stress state η. Moreover, exemplary stress-time curves are given for different types of behaviour.

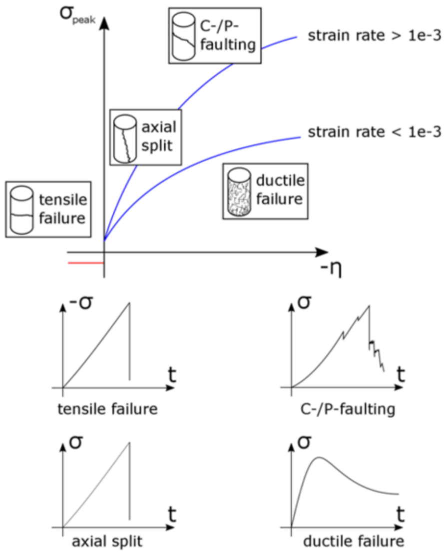

Figure 7: Concept proposal for a small scale benchmark data suite. Diagrams without scale. (Kellner et al. 2018).

Such a framework could be useful in many ways. Firstly, it could help to identify knowledge gaps of available experimental data. Secondly, it could serve as benchmark data for material models which aim at the simulation of small and mid scale scenarios. The ideal material model should be able to reflect the behaviour shown in Figure 7 for different states of stress with curves similar to the ones depicted. It could also help to show the limitation of current material models with a standardized "language". The triaxiality is suggested to be calculated based on principal stresses as follows:

$$\eta = \frac{\frac{1}{3}(\sigma_1 + \sigma_2 + \sigma_3)}{\frac{1}{\sqrt{2}}\sqrt{(\sigma_1 - \sigma_2)^2 + (\sigma_1 - \sigma_3)^2 + (\sigma_2 - \sigma_3)^2}}$$

4.5 Propeller ice interaction

One third of vessel repair cost following damages in ice are related to the machinery, of which 40% is related to the main engine and 25% to the propulsion system (Henderson, 2010). Current rules and ice-propeller prediction models do however not consider propulsion machinery as a coupled system even though the ice-propeller torque is not equal to the shaft response torque. Therefore, an inverse model of the propulsion machinery is required for transforming the propeller shaft torque response to the ice-propeller torque

Polic et al. (2016a, b and 2017) present a propulsion machinery model capable of transforming the propeller shaft response to the propeller load and present the following three objectives: a propulsion machinery model capable of calculating the propeller shaft response based on the known transient propeller load; the correlation between propeller shaft response and propeller load within different propulsion machinery systems; and a reliable inverse propulsion machinery mode capable of calculating the propeller load based on the propeller shaft response. The propulsion machinery model that combines the complete rigid body motion of the crank mechanism, flexible crankshaft, flexible coupling, finite-mode propeller shaft with three flexible modes, and rigid propeller with rule based and random ice-related propeller torque load is presented and used for calculating the propeller shaft response. The calculated response is successfully transformed back to the propeller load by considering potential energy in flexible modes of the propeller shaft and rigid body (kinetic) energy from propeller and propeller shaft. In addition, robustness of the inverse model, used in transformation process, to noise in the propeller shaft response and starting time (static or transient state) is demonstrated. Yang et al. (2015) carried out the transient torsional vibration analysis of ship propulsion system for ship navigation in ice by using the Newmark method. It was found from numerical results that the transient torque is bigger than steady torque due to the ice impact, and its amplitude depends on the relationship between the natural frequency of the propulsion shaft and ice stimulated frequency. The blade frequency exciting component was found by time-frequency analysis and it is necessary to avoided the blade number order resonance of ice impact.

4.6 Ice induced vibration (IIV)

Besides static ice loads, significant load levels can occur due to periodic, dynamic loading. This is also called ice-induced-vibration (IIV). First cases of IIV were encountered about 50 years ago at the first Cook Inlet offshore structures in Alaska (Määttänen, 2015). Since then, many cases of IIV have been recorded. The consequences range from human discomfort and gas leakage to fatigue failure in secondary structures (Määttänen 2015, Yue et al. 2009, Wang et al. 2013). One event that almost led to the loss of a structure was recorded at the Molikpaq platform in 1986. Here, a floe was continuously crushed against the side of the platform. The resultant vibrations almost made the sand core lose its ability to withstand shear stress (Jefferies and Wrigth, 1988). The field monitoring data of ice-resistant platforms in Bohai (Yue and Bi, 2000) revealed that the risks induced by ice vibrations are more serious than the extreme static ice load. The significant ice-induced vibration not only causes significant cyclical stress of tube node but also great acceleration response, which can endanger the pipeline systems on the platform and discomfort the crew members (Zhang et al., 2015a).

In general, IIV events are not fully understood and some of the connected topics in ice mechanics are still at the heart of ongoing discussion. However, since the first IIV incidents, observations and measurements have led to some understanding of the involved processes. In the current ISO standard three types of crushing are described: intermittent, frequency lock-in and continuous brittle crushing (ISO 19906:2010). Of those types, a frequency lock-in is considered to be the most dangerous. Simply put, under certain conditions the ice crushing failure can synchronize around the structure and vibrations start to build up. In other words, the ice fracture sequence locks in to the oscillation of the structure (Ziemer and Deutsch 2015, Palmer and Bjerkås 2013).

Significant attention by the research community has been given to frequency lock-in vibrations. One of the first models to simulate IIV was introduced by Matlock in 1969. He proposed a simple spring mass damper system in connection with an ice crushing model. Most of the research in this area is still focused on a basic understanding of IIV and frequency lock-in, hence such simple models are still being developed today (Hendrikse and Metrikine 2015, McQueen and Srinil 2016, Withalm and Hoffmann 2010). Zhang et al. (2015b) performed the ice-induced dynamic response analysis of a jack-up platform in Bohai sea based on the field monitoring data of ice-resistant platforms and model experiment of ice loads on the jack-up platform. The results show that the acceleration response is lower than the displacement response of deck under steady ice force and it is necessary to pay attention to the effect of ice-induced vibration on structural fatigue.

A more sophisticated and verified numerical model does not exist yet (Määttänen, 2015). The reasons are the lack of publicly available full scale data and the complexity of the process. In addition a verified and reliable material model for sea ice is not available yet.

Taking everything into account it is reasonable to assume that a frequency lock-in can only be modelled with a coupled simulation. This simulation should take into account a flexible structure, a suitable material model for ice and a CFD simulation for the sea water.

Further, the design of OWTs has to account for localized and dynamic ice loads. The solution is to estimate possible ice loads for the desired installation location. The susceptibility of the structure to ice-induced-vibration can also be assessed in advance. One option is to engage an ice expert. Typically, he will estimate the loads based on experience and additional methods. IIV is still not well understood and there are a number of different developments and active discussion related to the topic. Due to the lack of full understanding, the estimates on the severity of IIV vary, and it may even appear that some of the approaches are not transparent enough for a designer (ISO 19906:2010). There have been several empirical and semi-empirical approaches in the design against IIV, and also new approaches that are based on phenomenological models are developed (Hendrikse and Metrikine, 2016). There is also IIV studies that use DEM, FEM with damage models, and FEM using a foam analogues and cohesive elements (Ziemer and Deutsch 2015, Palmer and Bjerkås 2013, Hendrikse and Metrikine 2015, McQueen and Srinil 2016, Withalm and Hoffmann 2010). Many of the current approaches focus on ice crushing and compressive failure, and some of the most recent ones, on buckling (Hendrikse and Metrikine, 2016).

Many formulas use a projected area multiplied with the ice pressure or the compressive strength of ice, respectively. An extensive early work was done by Korzhavin, based on measurements in Siberian rivers (Withalm and Hoffmann 2010). Subsequently, many works applied similar approaches, mostly based on field or laboratory measurements, for instance Croasdale et al., Michel and Toussaint or Frederking et al. (Croasdale et al., 1977, Michel and Toussaint, 1977, Frederking et al, 1999). The use of formulations based on project area and a nominal average ice pressure is used by several standards for instance the ISO 19906 standard.

Furthermore, some work has been done to compare the methodology and applicability of the different formulas. Masterson et al. (2003) investigated the methodology behind standards. Masterson and Tibbo (2011) compared ice loads for different fictitious cases, taken from (Timco and Croasdale, 2006, Tseng, 1998). Frederking evaluated different standards using typical offshore structures (Frederking, 2012). Popko et al. (2012) compared different guidelines and standards with focus on integrated sets of design loads. Overall it was shown that the results of different formulas can vary significantly. In order to presented the suitability of these empirical approaches. Kellner et al. (2017) compares them to each other and where possible to measurements. Previously, design ice loads with measured ice loads for the Nordströmsgrund lighthouse. This was done with three standards and for just one ice thickness (Määttänen, 2015).

In addition to numerical modelling of IIV events, research efforts have also been directed toward understating what happens in the ice and at ice/structure interface and how it affects response of the structure (Sodhi et al. 1998, Nord et al. 2015, O'Rourke et al. 2016).

4.7 Ice induced fatigue

Ships also experience fatigue and there is more experience and knowledge about ice-induced fatigue on ice going vessels, see for example Bridges et al., (2006) and Ehlers et al. (2012). Fatigue assessment of the lifetime of ship and offshore structures is generally performed by means of linear damage accumulation (Palmgren-Miner rule) since service loads and thereby stresses are stochastically distributed over time, see also Ehlers et al. (2010). When the long-term stress range distribution for the whole service life is expressed by a stress histogram it is possible to calculate the fatigue damage by splitting the stress histogram into a number of representative blocks of equivalent stress range. This allows calculation of the damage contribution of each block individually. The fatigue life is consequently defined by the sum of damage accumulated in each block independently. However, blocks with high mean stress effects can lead to changes in fatigue crack growth (e.g. Führing, 1977) and therefore the hypothesis of linear damage accumulation loses its validity. In other words, sequences with high ice loads, which will cause such stress effects, invalidate the assumptions of independent damage accumulation. Current standards for fatigue design of ship and offshore structures introduce design fatigue factors to reduce the acceptable fatigue damage. Alternatively, a load history with its variation in amplitude accounting for the ice-structure interaction of the offshore structure besides the open water wave loads can be used. Consequently, the fatigue damage can be accumulated over this variable amplitude loading history and the life of the offshore structure can be assessed. The latter is however challenging, because the fatigue critical loading histories must be known for the specific design scenario. Furthermore, the influence of low temperatures must be assessed, due to exponentially increased crack growth at stress ranges that initiate crack extension by cleavage fracture modes, see also Braun (2017), Ritchie and Knott (1973) and Walters et al. (2016). Consequently, this also requires a definition of the design temperature, see chapter 3.3.

5. SUMMARY AND RECOMMENDATIONS

For ships and offshore structure, it is important to define the ice loading in order to design a compliant structure. Offshore structures are required to be designed for ULS and ALS with a corresponding probability of exceedance of 10^{-2} and 10^{-4} when establishing load levels. Therefore, probabilistic rules are often, but not always, applied to reach compliance with the location specific conditions, such as ice conditions and exposure. Ships are however designed differently using industry-wide rules and regulations, where the design load is based on the target ice class in a deterministic framework. Thereby, the design and scantlings of ships are obtained based on prescriptive and experience-based methods. Beneficial to this is approach for ships is the fact, that during their design life, they may experience different operators and missions. Therefore, such industry-wide ice class approach ensures that the experience from various conditions leads to safe designs. However, a first principle based approach, which defines the design load based on the vessel's mission including the target ice conditions and exposure allows for a more optimised design. The shortcoming is naturally that the life-time mission must be known and deviations (for instance that the ship is operated differently than what the probabilistic design assumed) may lead to structural failure. On the other hand, a probabilistic approach can be used to identify a vessel to be chartered for a specific mission to be accomplished. In other words, a link between the *assumed* operations and design for ice class can be established.

The rules currently cover good operational conditions with good visibility, but they fall short for accidental scenarios. Furthermore, the PC rules do not cover accidental impact with icebergs, nor specify a safe operating speed or how to check different hull arrangements and vessels for different scenarios. Therefore, it is useful to establish a connection between a safe operational envelope and physical construction of the vessel. Such a safe envelope must account for both, qualified experts operating the ship as well as somewhat uncertain operators, to identify the associated uncertainties. This could feed directly into the polar water operating manual as part of compliance to the Polar Code.

Generally, it would be very useful to instrument ships and offshore structures to monitor and record ice loads in addition to ice maps to learn from the behavior and make better predictions in the future. Together with shared damage reports on ice induced damages this would contribute to a solid basis for improved rules and regulations. In order to achieve such goal, the ice community should be more open to share knowledge and data, other than through publications with selected contents, which usually do not allow the reader to reproduce the results in full.

In order to make actual use of the presented simulation methods and models for design compared to the limited amount of large-scale experiments available we need agreed benchmarks test to validate numerical models. The experiments underlying these benchmarks need to be designed for numerical modelling and thus numerical modelling should drive the experiment to ensure that the required parameters are measured. Corresponding publications shall be accommodated with the numerical codes and numerical analysis should supplement the numerical model as well. Thereby a public community-based database containing ice data, experiments, as well as agreed standards for laboratory ice production and specimen geometries should be established. Thereby non-transparent ice load models can be avoided with unphysical parameters requiring validation for each application, which naturally makes them unusable for design load predictions.

In summary, the following strength-related research challenges can be identified:

- Definitions of limit states;
- Design procedures-based on ULS;
- Plastic effects of moving ice loads;
- Consistent design temperature definition;
- Fatigue and fracture of base material and welded structures at low temperatures; and
- Appropriate toughness evaluation method.

And further, the following ice load-related research challenges can be identified:

- Link between ice-related parameters and ice loads;
- Definition of design relevant events considering peak loads;
- Relationship between local HPZs and global pressure;
- Scaling of model versus full-scale ice including ice resistance;
- Agreed set of benchmark experiments for numerical models;
- Validated ice load models and simulations for design load predictions;
- Propulsion machinery model transforming propeller shaft response to propeller load;
- Simulation models for frequency lock-in vibration;
- Formulas for crushing type of ice failure; and
- Fatigue critical loading histories induced by ice load.

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APPENDIX

A.1 GUIDELINES FOR THE NONLINEAR ANALYSIS OF MOVING ICE LOADS

This section presents guidelines (Quinton 2016) for the nonlinear finite element (FE) assessment of the structural capacity of the hull of a ship or steel hulled offshore structure subject to moving ice loads. The guidelines presented pertain primarily to the assessment of the hull structural response to a given moving load. A discussion of some existing finite element methods for modelling ice follows this discussion.

FE code type

Moving loads may induce highly nonlinear geometric and material behaviours, sliding contact, and short-duration structural instabilities. It is theoretically possible to model these behaviours using an implicit (static or dynamic) nonlinear finite element code, however, it is often practically difficult and highly inefficient. This is primarily due to the extremely short time-step that is required to adequately capture the structural deformations at the translating point of application of the load. Note: the fact that implicit codes are unconditionally stable does not imply that long timesteps will accurately model events of short duration. Even excepting all other practical considerations, the necessarily small time-step will generally render implicit codes inefficient for models of suitable scale to assess moving loads on hull structures.

Analyses of the nonlinear response of hull structures to moving loads are generally best suited to an explicit time-integration code with nonlinear geometric, material, and constraint capabilities. According to the stability criterion of the explicit time-integration, the time-step is less than or equal to the critical time step which is approximately defined be the ratio of the smallest element length to the wave propagation speed in the finite element model. This will always be sufficient to capture unstable, transient, nonlinear hull responses due to operational/accidental moving loads on commercial hull structures, and the calculation efficiency per time-step generally results in efficient model run times.

The remainder of this discussion focuses on the application of explicit time-integration finite element techniques to the modelling of moving loads on commercial ship and offshore structure hulls. These guidelines are broadly applicable to any brand of explicit finite element solver.

Mesh requirements and element type: Structural instabilities often occur at much lower load magnitudes for moving loads, than for stationary loads (Quinton 2008; 2015), and capturing these localized deformations often requires a high mesh density. It is common and practical to model hull structures using shell elements, and a higher mesh density increases ratio of element thickness to length and width, implying that the shell elements may require “thick shell” or Reissner-Mindlin plate theory. Further, reduced integration shell elements with warping stiffness and (at least) five through-thickness integration points are recommended. Beam elements are not recommended in areas achieving highly nonlinear material and geometric behavior, as their inability to change their cross-sectional shape limits their usefulness in this respect.

Boundary Conditions: Should be sufficiently distant from the area of application of the moving load, so that the local boundary conditions of loaded structural components are not artificially stiff. Further, plasticity at the applied boundary conditions should be avoided.

Material Model: A bilinear kinematic elastic-plastic material model is sufficient for thick plates. Thinner plates exhibiting plastic membrane stretching, and frames in general, may require a multi-linear elastic-plastic model. Special consideration for repeated/cyclic loads should be reflected by appropriate implementation of isotropic/kinematic hardening. Strain-rate effects may be included.

Contact: A standard penalty formulation is recommended for steel-rigid contact. A modified penalty formulation may be required if the compliance of the impacting objects is significantly different.

Load: Application of ice loads is a tedious and complex subject. Some guidance is given below.

Nonlinear Finite Element Numerical Ice Models
Ice-structure interaction is a highly non-linear transient dynamic problem. Ice exhibits a myriad of failure mechanisms, including: creep, elasticity, plasticity, crushing, fracture (spalling), extrusion/comminution of crushed/spalled material, melting/re-freezing, and cohesion. To date, it has not been possible, to capture all these mechanisms in a single omnibus numerical ice model. It is possible to accurately model the creep, elasticity and plasticity behaviours of ice, using either implicit or explicit finite element codes, however these behaviours are only dominant at very low to low rates of strain. Melting/refreezing and cohesion are difficult to model numerically, but again these behaviours generally do not dominate the interaction of ice with ship hull structures. The remaining failure mechanisms - i.e. crushing, spalling, and extrusion/comminution - generally do dominate for typical ship and offshore structure ice-structure interactions, and are difficult to model numerically. These mechanisms are highly non-linear transient dynamic processes which are not suited for simulation in an implicit finite element simulation environment. Furthermore, ice-structure interactions often occur over very short periods of time (e.g. bow-shoulder impacts). Such scenarios are better suited to explicit finite element codes.

Flexural Failure
Cohesive Element Method: Separate solid elements are connected using zero-volume cohesive elements (various authors), and the ice is modelled as elasto-plastic material. This bulk material behaves like a solid until the failure criteria in the cohesive elements are met. When this happens, the cohesive elements fail, thereby freeing the bond between adjacent box elements and effectively modelling flexural failure.

Erosion Method: Another way to model flexural failure is to model ice cover with solid elements that are far smaller than would normally be practical, and then set a failure strain for them. Therefore, when the failure strain in a very small cube element is exceeded, it erodes (i.e. disappears), instigating crack propagation. The elements need to be small so that the mass loss due to the disappearing elements is negligible. A major downside is the time it takes to solve the model as the timestep in an explicit simulation is directly proportional to the size of the smallest elements.

Pressure (non-contact) Modelling
The "4D Pressure Method" (Quinton, Daley, and Gagnon 2013) uses a sophisticated algorithm to model the ice as a time series of spatially changing pressures, applied directly to individual structural elements. It has been used to apply discretised natural (i.e. from 1980s field trials of the USCGC Polar Sea) temporally/spatially changing pressure distributions to hull structures.

Hail Impacts
Carney et al. (2006) developed a novel, calibrated, material model for modelling hail impacting a space shuttle. This material model was successfully used in an arbitrary Lagrangian-Eulerian formulation to capture small-scale, high velocity ice-structure interaction; including fracture/spalling behaviours.

A.2 SIMULATORS

Aalto Ice Mechanics DEM

The Aalto Ice Mechanics DEM code is an in-house development, which is currently used for research purposes by the Aalto University Ice Mechanics group. The simulation tool is based on techniques, which are well reported in scientific literature by the group. The simulation-based analysis by the group has provided new insight on ice mechanics and phenomena behind ice loads. Namely, the studies have focused on ice-structure interaction process, on understanding ice rubble behaviour and resistance, and on ice rubble material modelling. Part of the code development in Aalto is rigorous validation, which, in laboratory scale, is partly enabled by the Aalto University Ice Tank. Aalto invites researchers in the ice mechanics community to use and further develop the code, but does not provide technical support or open access to the code.

CARD Stationkeeping Simulation Model

To simulate the complex dynamics of the broken ice field and to assess the sensitivity of different scenarios on loads experienced by the station-keeping system, an interactive dynamic discrete element model (DEM) is developed. For simplicity, the model approximates the shape of managed sea ice floes by circular discs of random diameters (to be updated to polygons in next iteration). The mechanics of the broken ice field is driven by the contact forces between individual floes. A viscoelastic contact model is used with boundary conditions and environmental forcings that vary both in time and space. Once a certain contact force between floes or between a floe and the structure is exceeded, the interaction mechanics switches to ice crushing model. The influence on loads of (1) floe size distribution and concentration; (2) stiffness of the station-keeping system; and (3) changes (including rate) in ice drift direction can be examined. The ability to correctly model these factors is critical for effective ice management operations. The model is used to study and highlight the relative importance of those factors for evaluating operational ice management strategies and for defining operating envelopes.

MUN GPU Event Mechanics (GEM)

MUN's GEM software is a novel simulation tool that simulates ice-structure and ice-ice interaction in hyper-real-time, for multiple ships and/or offshore structures operating in pack ice. These interactions are modelled by strategically solving numerous analytical and semi-empirical equations appropriate to each interaction. For each body in the simulation, ice impact forces are based on a modified Popov method. Each impact is treated as an 'event'. Other physical 'events' such as floe bending fracture and rafting are also included. Each ice body has equations of motion with additional inputs of wind and current drag. Vessels have additional forces from rudders, thrusters, moorings. The software is presently limited to convex bodies. All motions are solved in two-dimensions (2D), though certain aspects are treated in three-dimensions (e.g. Popov collision loads assumes 3D, as does ice floe flexure, and mooring mechanics). While GEM resembles other discrete multi-body simulations, GEM is focused more on operational decision support than on scientific analysis.

NTNU Simulator for Arctic Marine Structures

A high-fidelity numerical simulator for precise load calculations used for design and engineering of ships and structures to be operated in realistic ice conditions is developed at NTNU. The simulator, Simulator for Arctic Marine Structures (SAMS), comprises a module to generate realistic ice and environmental conditions, a multi-body dynamics module with realistic generalized contact compliance based on contact crushing assumptions. In addition, SAMS enables ice failure in bending, splitting and crushing, as well as more advanced hydrodynamics such as added mass and modelling of wave dispersion in ice and ice breakup in waves. SAMS does also consider ships on DP, mooring or sailing. The simulator applies for designing ice-going ships and offshore floaters both for intact sea ice (level ice and ridges) and broken ice conditions.

TUHH simulator for ice-breaking and ice-going ships

A numerical model for simulation of viscous flow ship-ice interaction in level ice conditions is being developed at TUHH. Unlike most existing interaction models, TUHH's model features realistic modelling of the icebreaking pattern, i.e., allowing the bow shape design to influence the results, as well as a rigid-body dynamics approach. Rigid-body dynamics approach takes into account all non-hydrodynamic influences (gravitational, buoyancy, damping and contact forces) on the bodies in the domain. The coupling of the rigid-body system with a Lattice Boltzmann based free surface flow solver supplements the hydrodynamic forces to update the positions of the floating objects in the simulation. Two main direct outcomes of the simulation model are local ice loads that act on the ship hull, and the level ice resistance force, calculated as a sum of the instantaneous ice forces in longitudinal direction. A wide range of applications include level ice resistance predictions, bow shape design based on contact and load distribution, as well as ship performance and transit simulations in ice.