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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.

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KEYWORDS

Ship and offshore structures in ice, rule-based and first principal-based ice loads, mission-based design

CONTENTS

1. INTRODUCTION

Oil and gas, mining, transport, fishing and tourism activities are continuously increasing in arctic regions and in need of reliable structural designs. The arctic region in this report is understood as a sea area with seasonal or year round, partial or full, ice coverage and cold climate, see Figure 1.

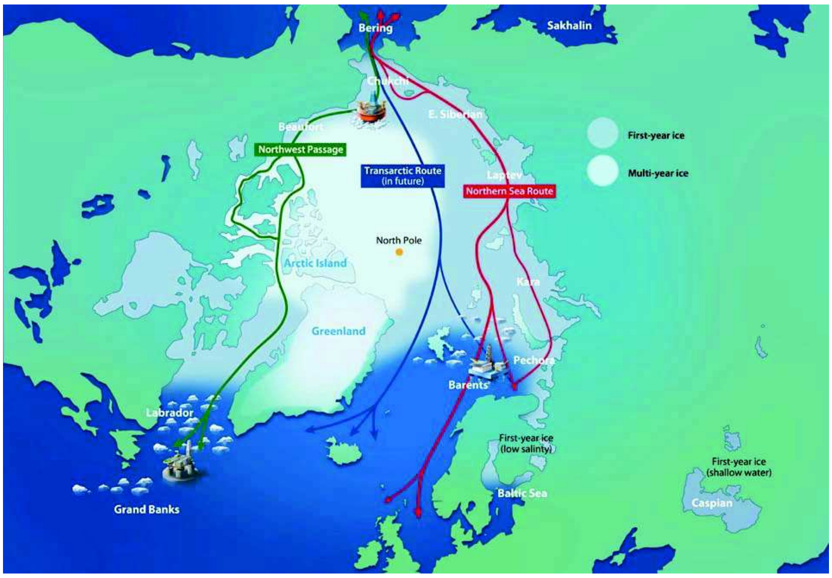


Figure 1. Illustration of the Arctic region (Illustration: Bjarne Stenberg, Copyright: NTNU).

The presented report is focussing on the safety of vessels in ice and offshore structures, i.e. ice forces and stresses, but in general the following issues should also considered for arctic operations: Environment, Social aspects (offshore), Human factors, Operational aspects including ice management, Engineering, Installation and Decommissioning.

To obtain reliable structural designs, present design methods benefit from the vast experience of ships operating in first year ice. The elements of interest in these design methods, and consequently in this report, are the design ice-induced pressures and their occurrence as well as the corresponding minimum scantlings determination and their applicability to new operational areas. However, the current design methods are not necessarily transparent by means of design pressure and scantlings determination using intrinsic design criteria. This concept is presented in Figure 2, which indicates the dependency of the design criterion and pressure on the resulting scantlings, respectively plate thickness. For the design of offshore structures for arctic regions the design pressures and their occurrence are supposed to be site specific, however, they are primarily for iceberg encounters, apart from Prirazlomnoye and the Sakhalin structures, since practically no offshore structure is deployed today at a location dominated by multi-year ice.

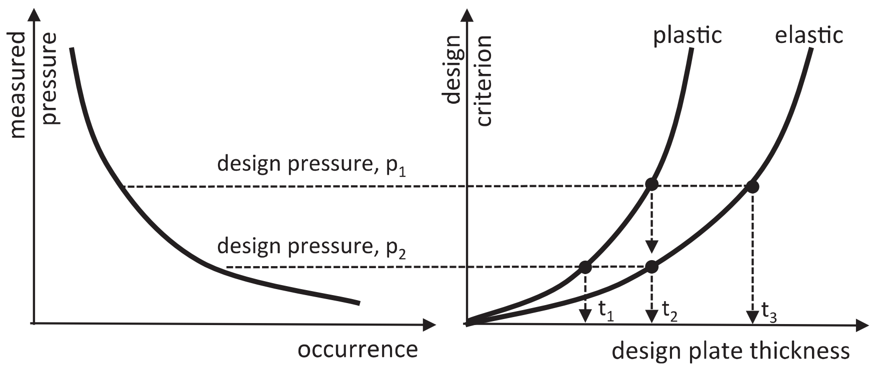


Figure 2. Present design method variations to obtain scantlings based on design pressures and design criteria.

This report seeks to at first discuss present design methods followed by first principle-based pressure and occurrence determination methods to obtain corresponding scantlings. Consequently, these first principle-based methods may contribute to the design of structures beyond the current minimum requirements as well as for new operational areas in the arctic region and to the further development of the present design methods. To demonstrate these first principle-based methods this report includes two case studies, a transit operation along the Northern Sea Route (NSR) and a floating offshore structure located in iceberg-prone waters. In conclusion, we will motivate for a more mission-based design methodology in addition to the present design methods using the presented first principle-based methods.

1.1 Limitations

The influence of the following aspects on the overall design of ship and offshore structures are not addressed in this report: still water and wave loads, specific metocean and environmental conditions, cold-climate in general, extended periods without daylight, remoteness and the lack of infrastructure including communication. Polar lows, which can cause unidirectional icing on exterior surfaces and thus stability problems are not addressed, because they are winter phenomena while shipping takes place mostly in the summer season. Further, hull girder strength issues caused by icing on the deck relevant for loading or unloading operations at port are not considered, in spite of the lack of a load margin relevant for such cases besides the wave load margin. The overall design of ships and offshore structures must however consider all these phenomena from an operational perspective. The latter is addressed in the conclusive chapter on future perspectives and challenges.

2. PRESENT DESIGN METHODS

This section presents at first the current regulatory design methods to be used to identify design ice loads and corresponding scantlings. Further, first principles-based methods to obtain actual pressures and exposures to be used for design scantling determination are presented as possible way forward.

2.1 Ships

Larger ships are entering ice-covered waters even though present design methods are based on the experience and ice load measurements from small ships. Furthermore, large ships are stiffened primarily in longitudinal direction, for which there are no observations or measurements as to how longitudinally framed structures experience ice loading on large ships. The ships operating in Arctic Sea and particularly along the Northern Sea Route (NSR) consist of conventional ice strengthened ships with ice breaking or bulbous bow. Most transits along the NSR are destinational traffic where hydro carbons and minerals are shipped out of the Arctic. Hydrocarbons and minerals are transported year around mainly by Sovcomflot from Varandei and Prirazlomnoye in Pechora Sea and by Norilsk Nickel from Dudinka along the Yenisei River. This transport is done by modern double acting ships. Communities along the Russian Arctic coast and Siberian rivers are supplied during the summer months by traditional ice going ships. Ice class IA (FSICR) or its IACS equivalent PC 7 or RS Arc 4 is the most common ice class among the ships sailing through the NSR in 2013 (CHNL, 2013). The second most common class is ARC 5 (IACS PC5 or IA Super). Most modern ships have higher ice class up to Arc 6 or IACS equivalent PC 4 and they are equipped with azimuthing propulsion and operate as a double acting ships (DAS) (Juurmaa et al., 2001). Norilsk Nickel and Sovcomflot (Niini et al., 2007) operate these ships. This concept is also selected for the new ice classed LNG Carriers (LNGC) for the Yamal LNG terminal. The Yamal LNGC is membrane type LNG carrier with a capacity of 170k m^3 in 4 cargo tanks, being the largest in arctic region to date, see Figure 3. The underlying design aspects consider the following: operate in the Kara Sea with independent operation (Arc 7 requirement), RS Winterization (–50°C) and open water performance of 19.5-knot design speed. Thus, the DAS-concept with 3 PODs was chosen to allow for moderate open water performance as well as a continuous speed in 2.1 m of level ice. Von Bock und Polach et al. (2014) discusses the conflict of designing a vessel for both, open water and ice, and and introduces the Combined Ship Merit Factor (CSMF) as a part of a design methodology operating in ice and open water in detail. In the astern mode, the Azipods are working in a pulling mode, which together with the specifically designed aft hull shape, do not require an ice knife to protect the struts. Further, the LNGCs have a reinforce bottom above the rule requirements due to the shallow water depth in the Ob bay, which also imposes a challenge on the draft limitations due to the additional structural weight increase. The ship side structure, also including a double hull for the engine room section, was reinforced according to ARC7 with steel grades complying to an external air temperature of –50°C.

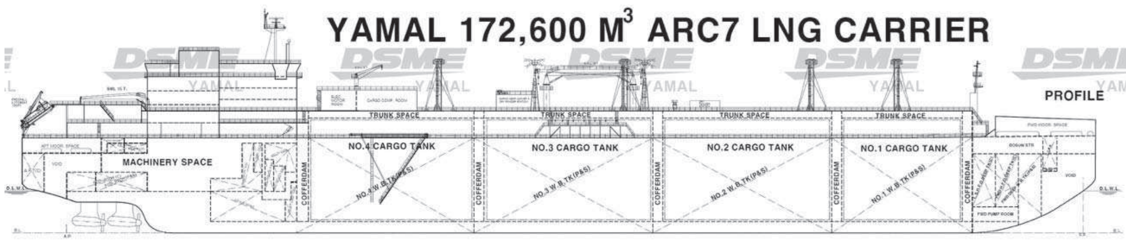


Figure 3. Yamal LNGC (DSME, 2014).

The icebreaker development has also taken steps ahead. AkerArctic (2013) has developed a concept of an oblique icebreaker that is breaking wide channel sideways. In Russia nuclear powered icebreakers are under construction to replace aging fleet of existing icebreakers. Construction of a nuclear icebreaker LK-60 has been started and two nuclear icebreakers are ordered in Russia (Barentsobserver, 2013).

However, most of the structural design follows a conventional approach to define ice strengthening as an add-on to open water scantling. Therefore, Pedersen et al. (2014) presented an integrated approach to identify the compliance to a target ice class by means of optimization, see Figure 4, and concluded that that an optimum structural arrangement can differ for different ice classes and thus the inclusion of ice strengthening as an add-on to an existing open water design may not result in the lightest or most economic structure.

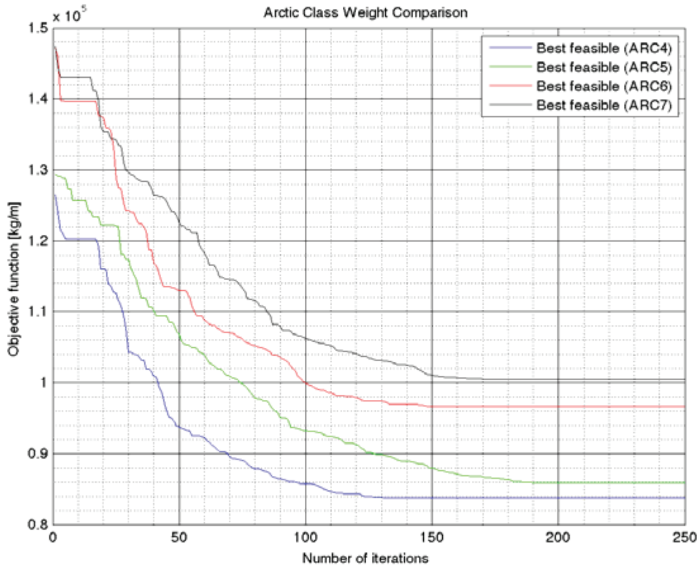


Figure 4. The optimisation-based progression of weight for Arc4 to Arc7 for an LNG tanker (Pedersen et al., 2014).

2.1.1 *Rules*

An international legislative framework regulates the design and operation of arctic ships. 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) by the United Nations (UN), whose aim is to promote rights at work, encourage decent employment opportunities, enhance social protection and strengthen dialogue on work-related issues (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 states and as port states. 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 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" (IMO, 2014b). As a result, any IMO member (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 IMO standards (IMO, 2014c). This complex framework regulates the design and operation of ships in general.

The Finnish-Swedish Ice Class Rules (FSICR) can be considered as the industry standard for ships operating in first year ice. The FSICR have been developed as part of the Finnish-Swedish winter navigation system, because during an average winter every Finnish port and every Swedish port north of Stockholm is ice bound. Thus, economical feasibility of the ship-based import and export depends on safe and efficient winter navigation through ice-covered waters for these countries in the Baltic Sea. However, it is also this economical feasibility which conflicts with the ship design criteria as the current rules develop along a thin line of acceptable ice induced damages, see Hänninen (2004), and acceptable CAPEX, VOYEX and OPEX-additions for the vessels' ice capabilities in view of changing environmental conditions and freight rates. Additionally, the cost of the escorting icebreaker fleet of each country is covered by the vessels' harbour fees, which decrease with increasing ice class. Hence, these fees may also motivate the choice of ice class. A detailed description on the evolution of the FSICR is given in Riska and Kämäräinen (2012). It must be noted, that even though these rules appear to be made for level ice breaking, they in fact design the ship for brash ice conditions, e.g. a broken channel in level ice, with the design point being the impact of the ship with the channel edge. Therefore, a simplified rectangular pressure patch has to be applied to the structure, where its height relates to the level ice thickness at the channel edge. Thus, a higher ice class (IA Super, h_i= 1m) calculation requires a higher loading height compared to a lower ice class (IC, h_i= 0.4m) for the same nominal pressure. The latter does also not impose any speed restrictions, i.e. velocity dependency is not considered. However, the magnitude of the nominal ice pressure is a constant value of 5.6 MPa for all ice classes, thus resulting in different design forces for each ice class due to the different load heights to be used. Furthermore, the dependency of the ships propulsion power and displacement on the ice pressure is considered through a single factor, which accounts for the possibility of the vessel to collide with ice at a high speed and is based on ice damage statistics. Ice load measurements of two icebreakers operating in the Baltic Sea unveiled a maximum level of 2 MN/m, which appears to confirm the maximum rule height of 0.35 m at the nominal ice pressure and is thus used as an upper limit value for the scantling design. Since the FSICR have been released in 1971, the next revision occurred in 1985 as a result of ice load measurements, see for example Kujala and Vuorio (1986), showing that the load height compatible with the measured ice load and structural response is much less than the ice thickness. As a result, the load height was adjusted to be a function of the ice class, while the overall ice pressure remained equal for all ice classes. This development is shown in Figure 5 together with the line-like contact.

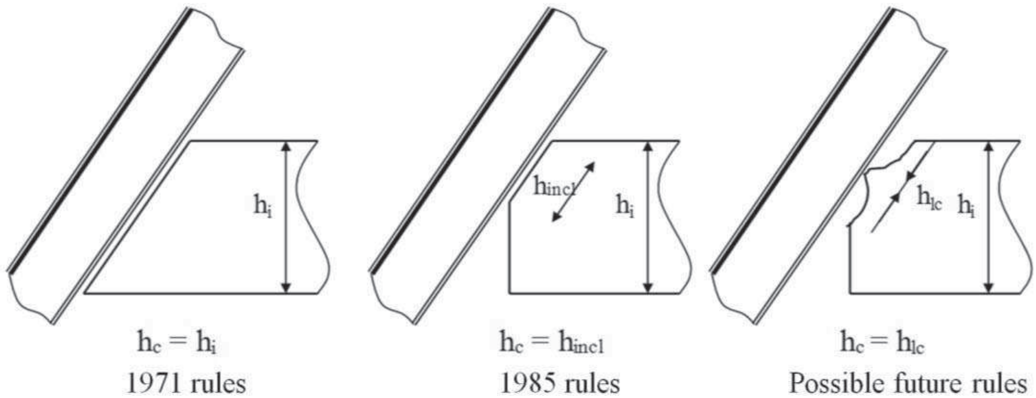


Figure 5. The FSICR load height developments (Riska and Kämäräinen, 2012).

The International Maritime Organization (IMO) Polar Code is a ship focused code with specific provisions for ship structure, subdivision, stability, equipment carriage (i.e. life-saving, navigation, and communications), crew training, and environmental protection for ships in the Arctic (N of 60oN) and Antarctic (S of 60oS). Consistent with other IMO codes (i.e. ISPS Code), the Polar Code contains both mandatory and non-mandatory provisions. The Polar Code provisions are additions to the IMO Conventions (Safety of Life at Sea (SOLAS), Prevention of Pollution from Ships (MARPOL), and Standards for Training, Certification, and Watch-keeping (STCW) that will take effect through amendments to these instruments. The Polar Code requirements will apply only to ships to which the SOLAS and MARPOL conventions apply. In general, these are large commercial internationally trading cargo ships, tankers, and passenger ships. Key provisions of the Code include: Mandatory requirements for Certification, risk assessments, and voyage planning; ice strengthening, cold temperature protection, tank protection, and ice navigation training where appropriate; and additional restrictions on the discharges of wastes, including zero discharge of oily mixtures. The Maritime Safety Committee of the IMO adopted the Polar Code in November 2014. The Marine Environment Protection Committee is expected to adopt the Polar Code in May 2015. The Polar Code is then expected to enter into force in January 2017.

In August 2006, the International Association of Classification Societies (IACS) released the “Unified Requirements (UR) for Polar Ships”, which standardized global ice classification specifications. A general description of seven polar classes is given therein in terms of nominal ice conditions where the highest class is approximately equal to the highest Russian Register of Shipping ice class and the lowest to FSICR IA Super. The intent of the technical requirements is to assist owners in matching the requirements for the ship with its intended voyage or service. For each polar class, factors are provided to scale design forces according to the expected severity of ice loading conditions. While polar class ship will experience a complex mix of ship-ice interactions during its operational life, the glancing shoulder bow impact scenario has been selected as the basis for the scantling requirements. The scenario includes initial ship/ice edge contact over a small area, with growing contact area until the entire structural grillage is loaded. The design ice load is characterized as an average pressure uniformly distributed over a rectangular patch load of height and width. Since concentrated pressures exist within the load patch, peak pressure factors are assigned to account for pressure concentration on localized structural members.

The new ice class by the Russian Maritime Register of Shipping were published in 2010 (RMRS, 2010). The new ice classes are named as ARC4 to ARC 9. ARC 4 and ARC 5 result in similar scantlings as the Finnish Swedish ice class IA and IA Super and ARC 9 is the highest ice class enabling navigation in all ice conditions. The new rules define the link between ice class requirements and the ice conditions in winter/spring or summer/autumn for the different Russian Arctic seas; see also Figure 27. In addition, the type of navigation has also an effect on the ice lass needed and is thus divided into the following items: independent navigation, icebreaker escorted navigation, extreme navigation (average periodicity once in ten years), hard, medium and easy navigation (average periodicity once in three years). The scantling requirements are mainly based on the ship's displacement and shape of the hull.

The Lloyd's Register (LR) rules concern the structural integrity of the vessel in the form of ice class rules, but generally, the equipment and operation for operation at low temperatures are the prerogative of the owners' specification and behest. They include the Canadian Arctic Shipping Pollution Prevention Regulations, Finnish and Swedish Ice Class Rules and the Russian Maritime Register of Shipping. LR's rule philosophy is to align with these regulations supplemented by LR's service experiences and technology development in the form of additional notations and guidance. For ships operate in first year ice condition, Lloyd's Register rules are aligned with the FSICR. For ships, which transit waters in which multi-year ice is present, LR rules incorporated the IACS UR for Polar Ships. A notable feature of the LR rules is that a wider range of shell, including bottom shell, is required to be ice-strengthened. This might stem from the consideration that ice is pushed passing the bottom of a ship as the ship advances in more open water with swells. In addition, LR released the new procedure, ShipRight Fatigue Direct Assessment (FDA) ICE, in July 2011, which assesses the potential for structural fatigue in vessels designed to trade in ice-covered waters and thereby helps to reduce the risk of fatigue damage in the hull structures of their ice-strengthened vessels.

DNV GL has three categories of their Rules for Classification of Ships for operations in ice. These range from the lowest ice classes intended for very light ice conditions to the highest ice classes covering year-round operation in all ice-covered waters. The basic ice classes (ICE-C and ICE-E) are intended for service in waters with light ice conditions. This category typically applies for vessels, which are not designed for continuous operation in ice, but need ice class for commercial or operational reasons. The structural reinforcements for these classes are generally limited to the bow area. The structural arrangements are often similar to open water ships, but plating is thicker and intermediate ice frames are placed between the main frames in the waterline at the bow area. The second category sets requirements for service in the northern Baltic Sea in the winter or areas with similar ice conditions to the FSICR. The majority of commercial ice-strengthened vessels fall in this category. Additional guidelines for the propeller blade design using direct calculations and ballast system design are provided. The third category is for IACS Polar Class vessels. The requirements are in general equivalent to the IACS Unified Requirements for Polar Ships (URI1 to URI3). Ships designed for ice breaking, e.g. PC-1–PC-6, may be given the additional Icebreaker notation. This notation sets additional requirements for the propulsion machinery system and bow form. Further, requirements for the steel are provided and for winterization of ships to ensure compliance to cold climate. Three different levels of winterization are defined in the rules covering operations in light winter to extreme Arctic conditions. Additional notations for redundancy, noise and vibration and reduction of the risk to the environment are provided.

The ClassNK Ice Class Rules (CNKICR) are based on the FSICR for single-year ice and the IACS UR for polar ships. Different to FSICR, CNKICR also considers the vessel's bottom area for ramming loads. Further, the adopted load scenarios are divided into a local load scenario and a global load scenario. In the local load scenario, glancing impact between sea ice and side shell is considered. In the global load scenario, ramming is considered in order to check the longitudinal strength of ships. The design ice loads and the corresponding requirements for shell plating and for longitudinal strength are excerpted from the IACS UR for polar ships.

The Unites States Cost Card (USCG) policies design USCG icebreakers to follow the US Navy design methods with additional considerations of ice loadings (based on Polar Star/Polar Sea and other icebreaker ice load measurements) rather than any class society rules apart from the IACS UR for polar ships for minimum scantlings design and Popov (Popov et al., 1967) based ice impact simulations, see Yu et al. (2007). The procedure relies on the application of environmental and operating loads with analysis of the structural response, as opposed to scantling determination by empirical formula, see Daidola and Sheinberg (1988). As an example of USCG framing design POLAR STAR and MACKINAW have a "haunched" transverse/vertical framing with varying section area properties to minimums at mid span through the ice belt. The contractor-designed HEALY ice frames incorporate essentially straight nonvarying sections with bracketed end connections. For the POLAR STAR/POLAR SEA, HEALY and MACKINAW designs with the specified ice loads, the calculation requirement was for an elastic analysis with allowable stress levels up to yield. Linear elastic FEA was performed to validate the stress levels under ice loads. Further, the hull girder bending load cases associated with ice operations include the case where the bow has risen up on an ice edge or ridge with an associated concentrated vertical load at the bow and the waterline at the stem at the ice knife or stopper.

The Ministry of Transportation of Russian Federation regulates sailing along the Northern Sea Route (NSR) (NSR, 2013) in a legislative framework that came in force in January of 2013. Management of the navigation of ships in the water areas of the NSR is conducted by the Northern Sea Route Administration Office (NSR, 2014) established as a federal government institution, which operates under the Ministry of Transportation of Russian Federation–Agency for River and Sea Transport. Application of permit for sailing the NSR (no fee is paid for the permit) is to be submitted to the NSR Administration and is evaluated on the basis of data provided by the ship owner, which include the following: information about ship and voyage, classification and measurement certificates, documents certifying availability of the insurance, other special certification if needed. In addition, to the structural compliance of the vessel in line with the NSR rules, additional requirement concerns the ice pilot presence on-board during a vessel sailing the NSR. In case that a permit for sailing is granted, the ship owner is informed of considerations regarding the ice conditions along the route and is advised under which circumstances sailing is allowed and whether or not icebreaking assistance is needed. Ice conditions are described as: heavy (20% more severe ice conditions than multi-year average for certain part of the route), medium (multi-year average ice conditions for certain part of the route) or low (20% less severe ice conditions than multi-year average for certain part of the route). Ice conditions are evaluated by the Arctic and Antarctic Research Institute (AARI, 2014) and are available at the NSR Administration website. Rules are clearly defining the operational window for allowed sailing, which is dependent on the vessel's ice class and ice conditions along the route. Vessel's ice class in terms of hull strengthening, machinery system and winterization is assessed according to rules set by Russian Maritime Register of Shipping (RMRS, 2014). Icebreaking assistance is usually provided by Rosatomflot (ROSA, 2014) and the fee in USD per ton is directly negotiated with Rosatomflot representatives.

2.1.2 First principles

The basic concept to determine scantlings based on first principles is presented in Figure 2, if a design pressure and occurrence is defined for the operational area in question to obtain design scantlings using a corresponding design criterion, i.e. yield.

For the FSICR this concept may be shown according to Riska and Kämäräinen (2012) with the example load measurements and Gumbel-I-based estimations predicting the most probable load for a given time period as shown in Figure 6. The next step to determine the scantlings is the selection of the design point as a function of a limit state and the frequency with which this limit state is reached for the operational area in question. If this limit is denoted as *w*, eventually representing yielding, and the structural detail as *d*, than the limit state can be presented as

$$q = f(w, d)$$

Following the most probable load and its return period, $q = g(T)$, and the design scantlings according to the ice loading statistic the design equation for the structural detail in question can be obtained as

$$d = h(w, T).$$

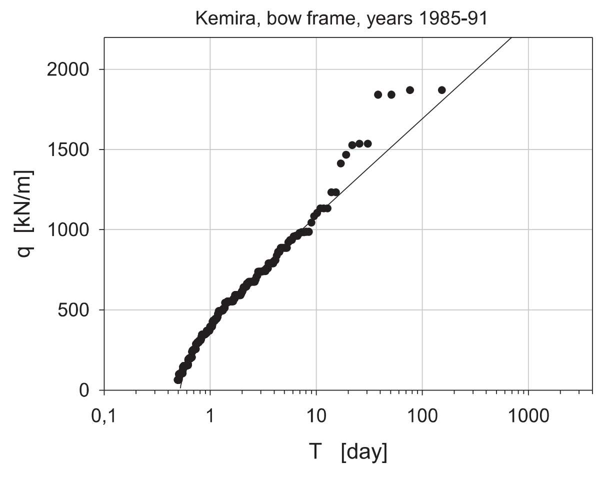


Figure 6. Example of measured and estimated load versus return period for a bow frame (IA Super rule value is 790 kN/m) (Riska and Kämäräinen, 2012).

The design point of FSICR is reaching yield at least once per winter. Therefore, some ice damage is likely during lifetime. Kujala and Ehlers (2014) investigate the possibility to align eventual structural damages following ice loading requiring repair in a risk-based assessment that considers foreseeable repair intervals of the vessel. As a result, they identify the required increase in design load and the corresponding savings for one example vessel; see Figure 7.

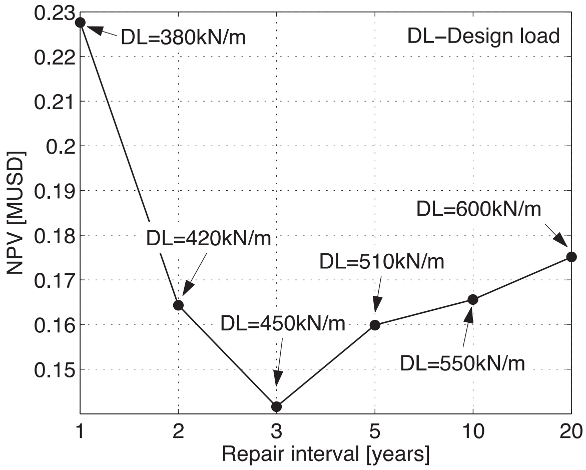


Figure 7. Net Present Value for different structural alternatives, repair intervals and corresponding design load levels (Kujala and Ehlers, 2014).

Ehlers et al. (2014a) presented a possible utilization of line-like contact as presented in Figure 5 for structural compliance calculations by means of a simplified, non-uniform, pressure patch (SNPP). They compare their simulations to medium-scale measurements with level ice at low velocities, where the line like contact phenomena occurred as well. Generally, the consideration of a line-like contact is important, because local pressures of up to 60 MPa (Frederking and Sudom, 2008) have been observed. By doing so, the influence of the temperature and impact velocity on the local contact mechanics must be considered.

Sub-zero temperature compliance of the base material and welded structures is still scarce in the current regulatory ship-specific frameworks and is typically concerned with the fracture toughness alone, given as a Charpy requirement. Generally, classification societies suggest the material grade for ship structures based on temperature, plate thickness and importance of structural members according to IACS unified requirements. However, various steel grades emerged that can comply with cold climate, i.e. increase in yield strength, in Lüders-plateau length and in ultimate strength and similar fracture strain as found for ambient temperature, see Ehlers and Østby (2012). Furthermore, they showed that even the crashworthiness of structures under sub-zero temperatures can be improved significantly using such arctic materials, while Ehlers et al. (2013) identified the possibility to even increase the global hull girder ultimate strength under arctic and non-arctic conditions with optimized structures using arctic materials.

In case of the IACS rules the choice a glancing shoulder bow impact scenario does not suffice, because it represents a collision avoidance manoeuvre only. Head on collisions are necessary, particularly for the highest ice classes, and should be considered, i.e. if a bulk carrier or icebreaker needs to transect a large flow, it must ram head on until it breaks through. The designer or a carrier may choose to not design his vessel for head on ramming, and accept delay, but the requirements should allow for such choice and account for the indented operational scenario. Thus the question arises if a plastic response formulation for plate and stiffeners for a glancing blow represents the most conservative interaction scenario already, given that a certain level of permanent set in the plating and framing is expected, see also Figure 2. In addition, global hull-girder loading due to ramming operation is specified. To investigate this further, the probabilistic methods identified by, e.g. Ralph and Jordaan (2013) can be used to interpret the deterministic treatment of ship design in the IACS Polar Code. One finding is that CAC4 vessels may carry out direct rams of a limited number; possibly the glancing blow scenario covers these rams. This finding resulted from a revision of the Canadian Arctic Shipping Pollution Prevention Regulations (ASPPR) in 1989 as in Carter et al. (1992). In the latter work, a probabilistic basis for the ASPPR revisions was provided. The revisions involved four arctic classes: CAC1, CAC2, CAC3, and CAC4. Probabilistic support was provided by consideration of the number of rams into ice per year, which varied from a few to thousands, depending on the class. This is essentially a measure of exposure. Furthermore, the analysis of Kigoriak results supported the local pressure formulation in the standard and use of the equation $\alpha = 1.25a^{-0.7}$; see also Figure 8. As for IACS, and in spite of the vessel experiencing a complex mix of ship-ice interactions during its operational life, the glancing impact scenario has been selected in ASPPR as the basis for the scantling requirements, due to the availability of a relatively mature model describing this type of interaction. In this approach, repeated rams are not explicitly addressed. Thus, it is assumed that what is meant is that the "single ship/ice interaction event" is the worst of a set corresponding to the arctic class. Furthermore, it was observed during the ASPPR review process that multiyear ice does not come in a set of thicknesses, it varies in thickness and ridges can be randomly placed in a floe and have random thicknesses too. It was suggested in Carter et al. (1996) that exposure might be better measured by number and severity of significant interactions. An example of how to assess exposure is presented in the chapter 3 of this report. Figure 9 shows that global area for ship impacts are consistent and possibly predated with those for other structures.

A rational approach to design of arctic ships based on probabilistic methods is detailed in Ralph and Jordaan (2013) including global impact forces and local panel design. Using such probabilistic approach, extreme design events can be identified by combining annual, seasonal and regional variability in environmental conditions with model uncertainty, and integrating these directly in the design methodology. Extreme design loads are estimated based on the annual number of significant interaction events (i.e. multi-year ice interaction), and the design strategy–target exceedance criteria established based on general public safety. The approach also provides a comprehensive basis for the selection of an appropriate ice class given certain operational requirements (e.g. an icebreaker for facility protection, or suitability of a tanker, bulk carrier or cruise liner, having minimal ice class, to operate through a particular season). Otherwise, design for extremes is largely based on observational experience and judgment from one or more experts and such experience only reflects a relatively short span of natural occurrence. Neither is it appropriate to arbitrarily establish the most extreme condition imaginable.

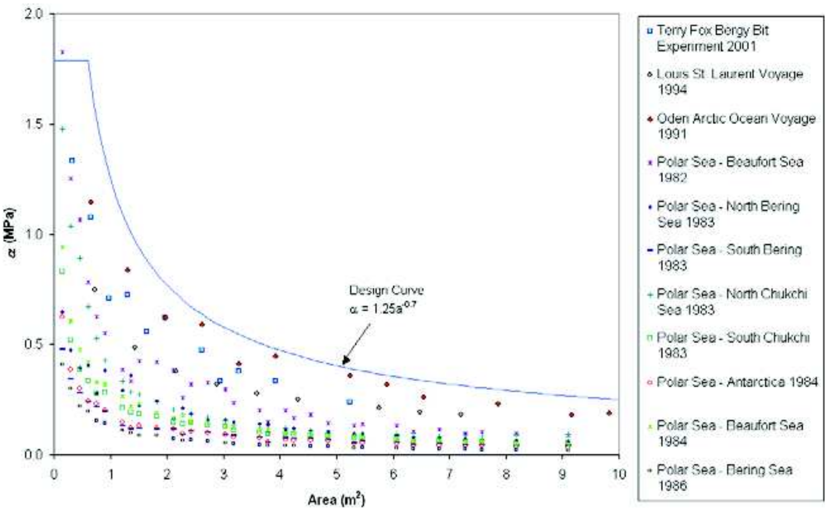


Figure 8. Design pressure area curve (Jordaan et al., 2005).

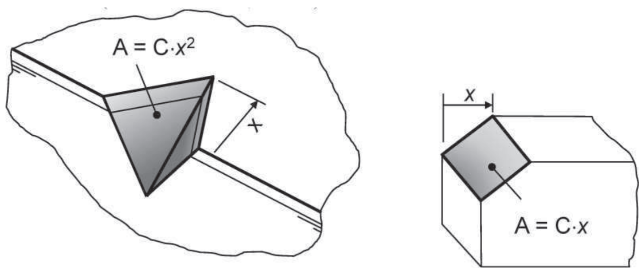


Figure 9. Global areas for ship-ice interactions (derived from Riska (1995)).

For design, concern is for the safety of personnel, the structure and the environment, specifying design loads that are appropriate. A design strategy references a specified load level from a distribution of annual maximums that corresponds to some annual target exceedance probability p_e. The influence of the number of interactions in a year (or period) in developing an extreme value design load distribution from a *parent* distribution is illustrated in Figure 10. With increasing interactions per year the design load distribution will shift to the right of the parent distribution; with multiple years between interactions, the design distribution shifts to the left with a probability spike at zero load (Jordaan, 2005). For design, one strategy may reflect a 1 in 100 year *extreme level ice event* (1% annual exceedance probability). The corresponding structure may be designed elastically with some plasticity depending on whether local damage (e.g. a dent) is tolerated without loss of vessel integrity–failure mode is important. Another strategy may reflect a 1 in 10,000 year *abnormal level ice event* corresponding to a full plastic ultimate limit state (ULS) design. A load exceeding this level may cause substantial damage crippling the vessel and require immediate repairs but not catastrophic loss of the vessel. The strategy may also consider risk mitigation through detection and avoidance. In no case should loss of life or environmental damage occur.

Using this design approach, one can quantitatively consider different classes of vessels based on number of annual encounters. The classifications used in the ASPPR include CAC1 through CAC4. Here, maximum force would be estimated for the highest class (CAC1) and then factored for reduced classes (i.e. 1.0, 0.8, 0.6, 0.4). The linear trend in loads with a step change in arctic class corresponding to an exponential change in exposure (e.g. 10,000, 1000, 100, 10 impacts per year for vessel classes ranging from CAC1 through CAC4 respectively (see Carter et al. (1996)) is observed. Based on interviews with Arctic Captains, the assignment of annual number of rams (i.e. 10,000s, 1000s, 100s, 10s) for the categorical CAC1 through CAC4 vessel types in Table 1 was considered reasonable. Impact simulations based on characterization of environmental conditions, including concentration and size of MY floes in addition to number of transits per year also verified that this assignment of exposure is reasonable (Carter et al., 1996). As a reference point, the MV Arctic was classified as a CAC4 equivalent and encountering on average 10 to 15 MY impacts per year. The corresponding impact force is on the order of 35 MN.

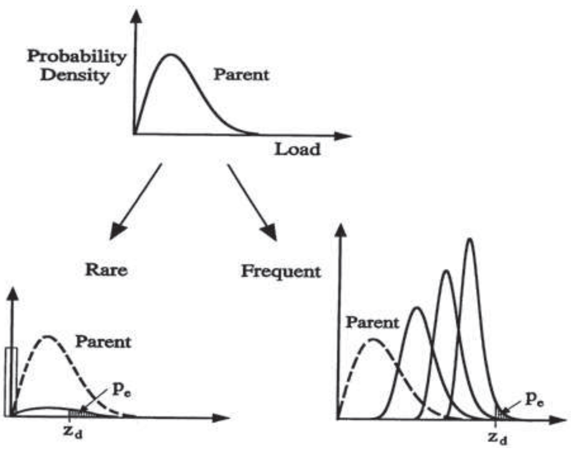


Figure 10. Illustration of design point and corresponding annual exceedance probability p_e including influence of rare (i.e. years between interactions) and frequent (i.e. many interaction per year) events in developing extreme value distributions from the *parent* per event load distribution (Jordaan (2005), Ralph and Jordaan (2013)).

Using the *parent* distribution of measured *MV Arctic* vertical bow forces, an extremal analysis was conducted using an exponential fit to the tail of the measured forces (Ralph and Jordaan, 2013). Forces for different classes based on expected number of class rams (or significant interaction events) is illustrated in Table 1. Reasonable consistency is demonstrated between class factors in the Canadian ASPPR (1995) rules and estimated design forces (based on expected number of rams) normalized to highest class CAC1. This demonstrates that correlating class factors and force with the number of annual interactions is quite reasonable. Otherwise, decisions concerning class are prone to subjectivity, relying on expert judgment.

Table 1. Illustration of ASPPR class factors, estimated force and normalized force based on annual number of rams (Ralph and Jordaan, 2013).

Class	CAC class	Number of significant interactions per year	Force at 10^{-2} annual exceedance probability	Force normalized to CAC1
CAC1	1.0	10.000	54.3	1
CAC2	0.8	1.000	46.0	0.85
CAC3	0.6	100	38.8	0.71
CAC4	0.4	10	31.5	0.51
		1	24	0.44

Further analyses considered vertical concentric bow impact forces, estimated using the IACS UR for polar ships and comparing with estimates using the rational probabilistic approach discussed using measured full scale *MV Arctic* data for the *parent* force distribution (see Table 2 and 3). The analysis illustrates how measured forces and expected exposure can be directly used for design and classification, as well as calibration. Forces are presented for design strategy and annual exceedance probabilities corresponding to both 10^{-2} (1/100 years) and 10^{-4} (1/10,000 years). As noted earlier, a 10^{-2} design strategy may correspond to elastic-limited plastic design where an occasional minor dent may be tolerable without loss of structural integrity. A 10^{-4} design strategy may correspond to a fully plastic ultimate limit state (ULS) design.

The preliminary results highlight some interesting points regarding exposure and classification. The PC3 force aligns with on average 1 ram per year at a 10^{-2} annual load level. The PC2 force aligns with 10,000 rams per year and a 10^{-2} annual load level. A rather broad range of exposure exists between PC2 and PC3. It is possible that an owner may wish to build a vessel that is more capable than a one (1) ram per year level but less than 10,000 ram per year level. The PC1 force is considerably higher than the rational based load for 10,000 annual rams and a 10^{-4} exceedance level, which seems quite conservative. Guidance on the design strategy used for a 10^{-4} load level (i.e. ULS) compared with a 10^{-2} level should be considered.

Table 2. MV Arctic particulars (Ralph and Jordaan, 2013).

Length bp	Breadth	Draft	Displacement	Stem ange	Bow opening angle
199 m	23 m	11 m	39.000 t	30°	33°

Table 3. Comparison of IACS Polar Class design forces for *MV Arctic* with rational based forces based on annual number of rams for 10^{-2} and 10^{-4} design strategies (Ralph and Jordaan, 2013).

IACS		Rational design approach			
Polar Class	vertical bow force [MN]	Number of rams/yr	max bow force* at 10^{-2} [MN]	max bow force* at 10^{-4} [MN]	normalized 10^{-2} max bow force
PC1	82				
PC2	56	10.000	54	70	1.00
		1.000	46	62	0.85
		100	39	55	0.71
		10**	31**	46	0.57
PC3	25	1	24	40	0.44
PC4	16				

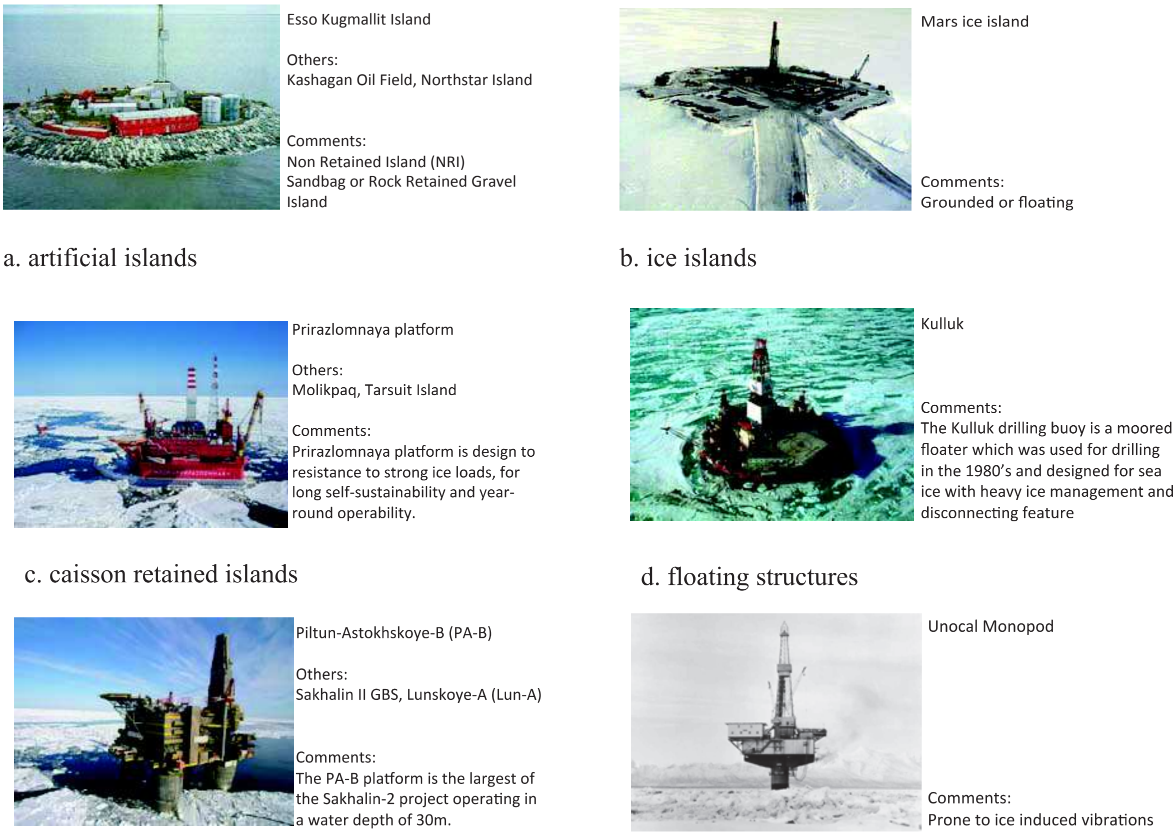
*Max. vertical bow force estimated with extremal analysis and parent distribution from *MV Arctic* trials
** *MV Arctic* is a CAC4 equivalent encountering on the order of 10 rams per year

2.2 *Offshore structures*

Up to now, the Arctic fields developed are in water depths up to 125m and have used the Gravity Based Structures and detachable FPSOs, see Table 4, besides other systems such as jacket platforms and islands used in shallower water as shown in Figure 11. Current developments of various arctic stakeholders include drill ships for arctic regions, especially for the Kara, Beafourt and Chucki Sea. The design basis currently stems from ice going vessels with dedicated ice breaking lines in the bow area, which are upgraded with platform and drilling components for harsh environments. Some existing offshore structures involved in production in presence of icebergs include the following gravity based structures (GBS): Steel Drilling Caisson (SDC), Molikpaq (now Sakhalin), Concrete Island Drilling System (CIDS), Hibernia GBS, Prirazlomnoye Platform and the Lun-A & PA-B Platform. Floating production structures include the Terra Nova and White Rose facilities involved in oil production on the Grand Banks. Probabilistic design methods have been used for some of these structures (for example in the Sakhalin area) and in particular those on the Grand Banks.

Table 4. Summary of floating platforms in Arctic waters.

Location	Stationkeeping method	Type of operation	Length of operation
Beaufort Sea (Canmar drill ships)	Disconnectable mooring lines through the waterline	Drilling	Long term 1976 to late 1980's
Beaufort Sea (Kulluk)	Disconnectable submerged mooring system	Drilling	Long term 1983 to 1993
Grand Banks (Terra Nova)	Disconnectable submerged turret mooring system	Hydrocarbon production	Long term 2002 to…
Grand Banks (White Rose)	Disconnectable submerged turret mooring system	Hydrocarbon production	Long term 2005 to…
Pechora Sea	Loading tower	Offloading	Long term 2000 to…
Sakhalin	Dynamic Positioning	Diving	Short term 1999
Arctic Basin	Dynamic Positioning	Core drilling	Short term 2004



a. artificial islands
b. ice islands
c. caisson retained islands
d. floating structures
e. Gravity Based Structures (GBS)
f. Pile Based Structures

Figure 11. Offshore structures for arctic regions.

Mooring system of floating structure operated in Arctic waters shown in Table 4 may encounter extreme ice loads including iceberg encounters to which the mooring lines have to comply. In case the capacity of the mooring system is below the incoming load, disconnect must take place as a mitigation measure. The latter may further require that the turret be submerged to a safe depth below the iceberg. The disconnectable mooring system of the Terra Nova, the first FPSO site in the Grand Banks, uses a Thruster Assisted Position Mooring System (TAPMS) consisting of 9 mooring chains attached to the base of the turret which hold the FPSO in position together with five 5MW thrusters, (2 forward, 3 aft), which allow the FPSO to control heading and position in severe environmental conditions.

Aggarwal and D'Souza (2011) indicated that the strongest chain available with minimum breaking load of 31MN, with 24 mooring lines would provide maximum capacity of approximately 77MN and a maximum offset of 33m. In comparison, the detachable 3x3 chain mooring system found at the Terra Nova FPSO has a capacity of about 20MN. Furthermore, the mooring system may consist of other materials such as ultra-high strength molecular fibre rope with even higher capacities. The maximum ice load estimated for existing fixed platforms in shallow waters ranges from 500MN to 1,000MN depending on their locations and the size of the multi-year ice or icebergs to be encountered. Thus, mooring systems may not be adequate for all locations, but may be quite suitable in certain locations depending on the ice conditions present.

John Fitzpatrick of CJK Engineering Ltd. of Calgary has developed a concept for these conditions in the arctic. This is shown in Figure 12. Tension Leg Platforms (TLP's) are for the most part compliant with respect to horizontal wave loading. However the concept illustrated is non-compliant for both wave and ice loading conditions. For extreme ice loads it becomes compliant to avoid catastrophic over load. In the compliant condition, lateral movement of the structure absorbs energy. Up to 10,000 MJ of energy can be safely absorbed without damage or tilting. This amount of energy is equivalent to a 1500m diameter by 50-meter thick ice island floe impacting with a speed of 1 knot.

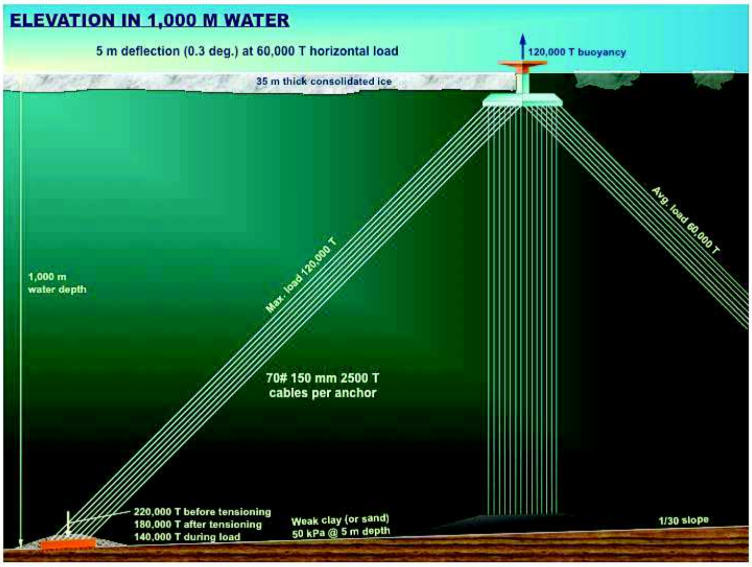


Figure 12. Arctic TLP Concept by CJK Engineering Ltd.

Dynamic Positioning (DP) based stationkeeping in ice is an integrated operation between a DP vessel (the protected vessel) and an ice management system consisting of one or several icebreakers, an ice monitoring system, and ice risk management Van der Nat (2012), see also Figure 13. However, traditional DP control systems have not been designed to handle large and rapidly varying sea-ice loads, and DP stationkeeping has been done in manual joystick mode. Furthermore, a stationary vessel lacks the momentum available from forward movement of a transiting vessel to overcome the ice load maxima. Additionally, ice-monitoring systems are not custom-designed for online surveillance of sea-ice. Ice monitoring region is vast, satellite images are infrequent, sensors are unreliable and have too low resolution to give sufficient details, and sensor carriers are manned (Aggarwal and D'Souza, 2011). In addition, ice breaking has been developed based on transit and shipping, but ice breaking for ice management needs icebreaker vessels with different properties, typically higher capability, and a paradigm shift in how the icebreaking operation is carried out (Liferov et al., 2011).

The current challenges for successful offshore DP operation in ice range from sea-ice load detection, vessel design, hazard identification and mitigation strategies. Sea-ice loads on the DP vessel are large, rapidly varying, and there is a lack of models to accurately estimate and predict the loads based on feasible measurements. DP vessels must typically be designed for optimal operation both in ice (Liferov et al., 2011) (with sufficient DP-Ice capability) and in open water (transit and open water DP capability. Keeping heading–bow against drifting ice is required. When the ice-drift direction changes, a massive increase in ice loads and potentially dangerous situations may occur. This is especially critical for a DP drillship that is connected with riser and the allowable positional offset is small. Reliable hazard detection, identification, tracking, and forecasting of icebergs and severe ice features are not sufficiently developed. Online monitoring of necessary ice properties and ice dynamics for safe situational awareness and estimation/prediction of load evolution on DP vessel including the integration of an ice surveillance network consisting of many sensors and sensor platforms, such as on-board sensors, underwater stations and vehicles, aerial sensor platforms, and satellites (Aggarwal and D'Souza, 2011). In addition, the optimal operation of the icebreaker fleet to minimize loads on protected vessel is required. Therefore the efficiency of ice breaking must be modelled with sufficient fidelity to be able to plan and predict icebreaking patterns. Present sea-ice parameters (sensors, sensor platforms, data processing, decision support tools, etc.) for online calibration of models are required. This shall lead to an efficient deployment and the icebreakers for an optimal ice-breaking pattern to guarantee that the maximum loads on the protected vessel are below acceptable limit within specified T-time. Therefore, online measurements and analysis of the resulting efficiency of the ice management (e.g. providing real-time data on floe size distribution in the ice management area) are needed. As a result, this shall ensure sufficient safety of integrated operation between DP system and ice management system. Limiting conditions (design loads for DP vessel, ice management capabilities, etc.) must be identified.

The current trends to meet these goals are the introduction of new sensors and ice surveillance decision support systems (Loenhout, 2012), new icebreakers are built and physical ice management experience is growing, sophisticated numerical simulators capable of reasonable simulation of loads and motions on floating structures in sea-ice, are emerging (Bauduin, 2011), and DP control systems are becoming better to handle sea-ice loads (Baan, 2011). The latter includes the following 4 steps: 1) Retuning existing DP controllers to more aggressively estimate and reactively compensate ice loads; 2) Development of improved ice characteristics models and corresponding redesign of DP software to reactively handle ice loads based on existing sensors; 3) Utilization of new sensors to directly estimate ice forces and reactively compensate by feed forward (as for wind forces); and 4) Development of a sophisticated online ice monitoring system that is capable of locally predicting the future evolution of sea-ice loads on DP vessel, for proactive compensation of sea-ice loads. This gives the DP system time to build up sufficient Thruster forces to compensate incoming load variations before they hit the vessel. Furthermore, guidelines for integrated stationkeeping operations in ice regarding surveillance zones, alert levels, T-time, repair time, emergency procedures, etc., under development.

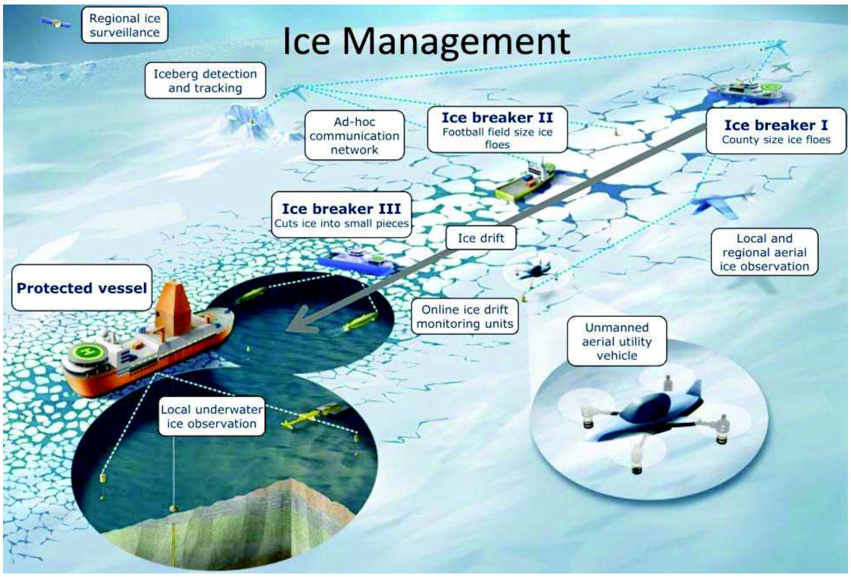


Figure 13. Offshore Dynamic Positioning operations in ice (Illustration: Bjarne Stenberg, Copyright: NTNU).

2.2.1 *Rules*

The main set of rules is the new ISO 19906 “Petroleum and natural gas industries–Arctic offshore structures”, International Organization for Standardization, 2010. In brief, there are three “Exposure Levels” (L1, L2, and L3) that depend on factors such as whether the platform is manned, whether it is planned to evacuate, and consequence categories that relate to the potential risk to life and the environment and to possible economic loss. The standard was calibrated to target safety levels, see Table 5, using a special calibration exercise.

Table 5. Target safety levels in ISO 19906 for the three Exposure Levels.

Exposure Level	Reliability target expressed as annual failure probability
L1	1.0×10^{-5}
L2	1.0×10^{-4}
L3	1.0×10^{-3}

Both extreme-level (EL) and abnormal-level (AL) events are to be considered, with associated ice events (ELIE and ALIE respectively). These events or actions are specified at annual exceedance probabilities of 10^{-2} and 10^{-4} respectively.

It is to be noted that “Exposure” in the ISO context above refers to the exposure with regard to safety, a “classification system used to define the requirements for a structure based on consideration of life-safety and of environmental and economic consequences of failure”. This related to the exposure with regard to human life, for example. This ISO usage is different from the other connotation often used of the exposure of a structure to environmental hazards, for example the number and duration of interactions with ice features. This latter interpretation is used below.

There are some deterministic provisions in ISO (19906), mainly aimed at providing estimates for the 100-year loads. The calibration work was very similar to that which had been carried out for CSA S471, Canadian Standards Association CAN/CSA-S.471-04, "General Requirements, Design Criteria, the Environment, and Loads" which is the first of five CSA Standards that formed the "Codes for the Design, Construction, and Installation of Fixed Offshore Structures." The Standard set safety objectives for the code as a whole. The Standard distinguished between Safety Class 1 and 2, with "Safety Class 1" being defined as a structure in which "failure would result in great risk to life or a high potential for environmental damage, for the loading condition under consideration". This standard introduced 10^{-2} and 10^{-4} loading events in the context of frequent and rare occurrences. This standard is being superseded by the ISO but was the precursor of risk-based offshore standards with consideration of ice loading.

The ISO 19906 and CSA S471-04 standards are the first standards to base the ice loads or actions on full scale data obtained by the monitoring of offshore structures in areas such as the Beaufort Sea, Cook Inlet, the Baltic Sea, the Gulf of Bohai and to a limited extent the Sea of Okhotsk. Thus the loads obtained from the methods of these two standards tend to differ from those obtained by standards based on small scale data (Masterson and Tibbo, 2011).

Furthermore ISO 19906 defines criteria regarding material properties under Arctic conditions as a general statement without concrete requirements. The offshore industry in the North Sea has used –14ºC as the lowest operational temperature and little experience below this temperature is available.

A brief summary of different codes including International (ISO), American (API), Canadian (CSA), Russian (SNIP and VSN), Norwegian (NPD and NORSOK), as well as Class Society (DNV and Lloyds) is given in Annex 1 of this report. The CSA and ISO Standards have many similarities with care taken in writing the ISO standard to consider methods used in the SNiP code.

An example code comparison using illustrative calculations according to Masterson and Tibbo (2011) is now provided. The comparison is made for deterministic ice loads or actions calculated using methods contained in ISO 19906 as well as those contained in API (American Petroleum Institute) RP2N (1995), CSA (Canadian Standards Association) S471-04 (2004), and Russia's SNiP 2.06.04-82* (1996). Scenarios considered are given in Table 6. Resultant loads are illustrated in Table 7. Specific details for the calculations can be found in Masterson and Tibbo (2011). It can be seen that the deterministic loads are quite comparable. API loads for Scenario 3 do not consider aspect ratio and reduction in pressure on wider structures as well as reduction in pressure for increasing ice thickness. SNiP load for Scenario 3 is considerably larger due to high-specified global pressure for MY ice.

2.2.2 First principles

Methods to determine design loads include probabilistic approaches, which offer a rational method to obtain realistic designs. The analyses are rarely tractable in closed form—although parts may be—so that Monte Carlo methods are generally used. Probabilistic methods are advocated in the ISO 19906 Standard, which was calibrated to a set of safety targets. Software to obtain EL and AL is exemplified by C-CORE's Iceberg Load Software (ILS) and Sea Ice Load Software (SILS) (C-CORE, 2012). Figure 14 shows a general flow chart for a probabilistic analysis.

Table 6. Example offshore code comparison according to Masterson and Tibbo (2011).

Scenario	Description
1	*A level sheet of ice of 1.2 m thickness interacting with a fixed offshore structure in mid-winter. Assume that the ice is moving at a rate of 0.2 m/s, and the structure is vertical-sided with a width of 100 m and in deep water.*
2	*A first-year ridge of total thickness 10 m interacting with the same structure as Scenario 1. Assume a keel-to-sail ratio of 4.4, a consolidated layer thickness of 1.5 m, and a width of 23m. Assume that the ridge is imbedded in an ice sheet with the same characteristics of Scenario 1.*
3	*Multi-year Floe–A large drifting multi-year ice floe, approximately 1 km in diameter impacts the structure at an impact speed of 0.5 m/s. The floe has thickness of 6 m, and an average temperature of –5ºC. The floe has some roughness but no significant ridges.*
4	*A level first-year ice sheet of thickness 1.5 m surrounds the structure for a distance of 50 km. The ice is level with no appreciable ridges or roughness. A wind gradually increases from 0 m/s to 25 m/s over a period of 12 hours. Ice velocity increases over the same period and reaches a maximum value of 0.05 m/s. Assume that there is no ad freeze at the beginning of the event. A conical-shaped structure with a 45º slope lies offshore in Arctic waters. The width of the structure is 50 m at the waterline. Assume that it is a perfect cone and that it has a low friction coating.*

Table 7. Summary of ice loads in MN according to Masterson and Tibbo (2011).

Scenario	ISO (ELIE 10^{-2})	API	CSA	SNiP
1	156	180	170	199
2	201	244	223	299 to 398
3	597	900	540	1166

Design for ice loads requires consideration of the following.

1. Global loads, representing the total force applied to the structure, and
2. Local loads, representing the force (or pressure) on particular areas of structural importance such as the plate between frames or other assemblies of structural elements that are important in design.

It is important to have clear definitions for these two areas associated with the two design load situations.

The global interaction area (also termed the nominal interaction area) is the area determined by the projection of the structure onto the original shape of the ice feature, without any reduction of the area for spalls and fractures that take place during the interaction (see Figure 15). The global interaction area can be determined from the shape of the iceberg and the shape of the structure. Within this area, there will be areas that carry little or no pressure, as well as the high-pressure regions. When analysing data to formulate relationships for global load estimation, the analysis must also be done in terms of the global interaction area as just defined.

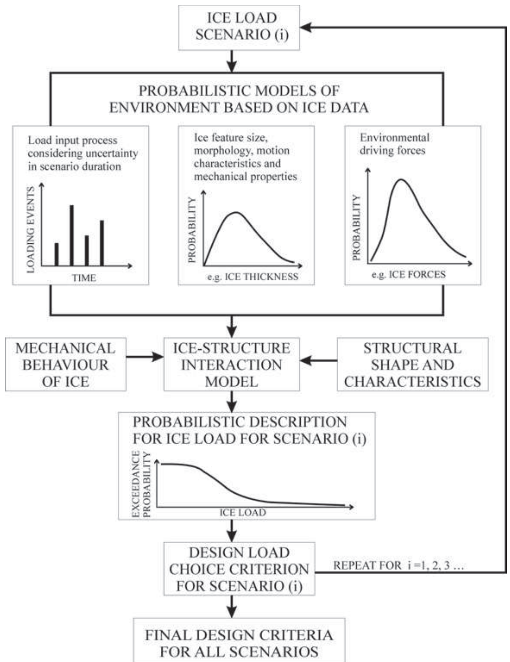


Figure 14. General flow chart for probabilistic analysis (DNV_Canada, 1986).

For design purposes, one needs to consider the local design area, which is the area of part of the structure, for example the plate between frames or a panel that is under consideration in design. This is a fixed area on the structure. The area might traverse through an ice feature during an interaction. Figure 20 shows the concept. One can think of the global area as being fixed to the ice, but within the structure face, and the local area as being fixed to the structure.

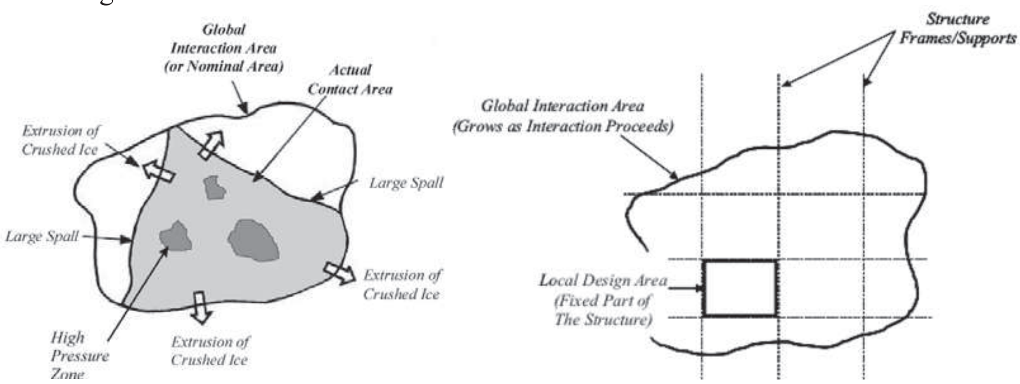


Figure 15. Global and local area definitions for iceberg impacts (Jordaan et al., 2005).

Figure 16 illustrates the Monte Carlo approach to analysis for iceberg impacts. The determination of iceberg design loads requires the following inputs for the simulations:

- size, velocity and shape of the icebergs;
- concurrent sea state and associated hydrodynamic effects on iceberg motion;
- eccentricity of loading to account for oblique impacts;

- global ice pressures developed on the basis of pressure-area relationships (derived from analysis of ship rams into hard, multiyear ice); and
- local ice pressures associated with the design loads (a function of the duration of individual impact events and the frequency with which they occur).

The full analysis is quite complex and only a flavour of the methodology can be given here.

Inputs and models for the software including environmental and iceberg population data are summarized. The inputs required for the model are presented in Table 8, while Table 9 describes the various sub-models contained. Ice environment factors considered for this example include the areal density of icebergs and the distributions of iceberg size, iceberg drift speed and sea state. The areal densities of icebergs have been calculated using data obtained from the International Ice Patrol (IIP) for the years 1984 to present. The iceberg drift speed model is based data collected during the mid 1980's along with more recent data collected by PAL Environmental Services.

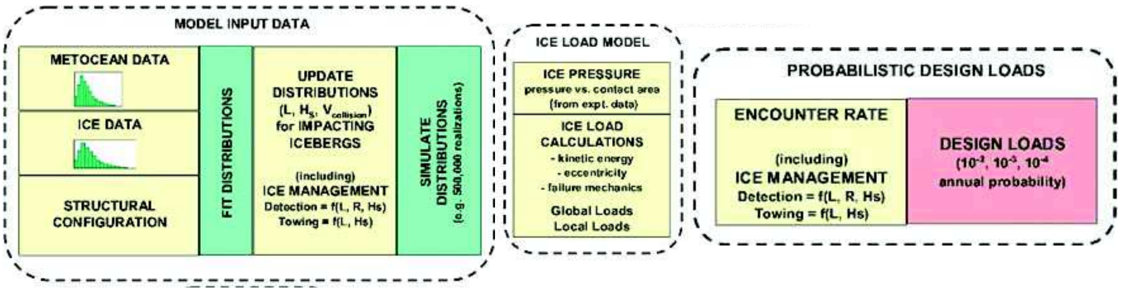


Figure 16. Methodology for iceberg impacts (Stuckey et al., 2008).

Consideration of iceberg detection, physical management and disconnection (when applicable) can be a basis for revision and possible reduction of ice loads; see Figure 17. Detection capabilities are based on an interpretation of enhanced marine radar capabilities in the vicinity of the structure. In practice, other methods such as aerial reconnaissance, HF radar, and satellite-based radar and ship observations will be used. Figure 18 shows a typical input. Physical management capability is based on past towing experience on the Grand Banks and offshore Labrador.

The iceberg impact loads include consideration of wave-induced iceberg motions, mass, shape, eccentricity and strength. A random pressure-area relationship is an option for the global pressures and results can be compared with results using a constant ice pressure. Local pressures are based on a detailed analysis of ice pressure distributions from ship impacts.

A basic parameter guiding several aspects of the analysis is the iceberg length, and several other parameters are linked to this. A large amount of analysis has been made for each of the required parameters; details are not given here. Figure 19 gives an illustration of one of the inputs into analysis of iceberg shape.

Figure 20 illustrates global load estimates at 10^{-4} exceedance probabilities for design accounting for iceberg encounter rate; note that the exceedance probability on the vertical axis pertains to the parent distribution, i.e. without consideration of encounter rate. Figure 21 shows a typical result for local pressure.

Table 8. Outline of inputs and probability distributions.

Quantity	Basis
Iceberg drift velocity, V_D	Gamma distribution (μ,σ)
Sea state, H_S	Empirical CDF based on data
Iceberg waterline length, L	Iceberg measurements, 2 combined (weighted) exponential distributions
Draft, D	Empirical relationship with associated uncertainty
Mass, M	Empirical relationship with associated uncertainty
Added mass, Ma	Empirical relationship based on iceberg length, width, draft, and water depth
Iceberg shape	Based on C_A = modified lognormal distribution with (μ,σ) and $D_A = f(C_A)$
Contact point	Based on iceberg profiles and structural configuration
Areal density, r	Mean value based on iceberg sightings

An outline of progress for the design of structures in the presence of ice will be given now. Figure 1 illustrates the areas in the northern hemisphere where such calculations might be made. We shall first discuss fixed offshore structures. There are various structure types that can be considered, e.g. Figure 22. A flow chart for Monte Carlo analysis in the case of interaction of a structure with vertical walls with multiyear ice is given in Figure 23. The area definitions for vertical structures, Figure 24, are an extension of those previously given for iceberg interactions as shown in Figure 15.

In C-CORE's SILS, consideration is also given to sloping structures in Table 10. There is considerable uncertainty surrounding loads on sloping structures as a result of lack of full-scale measurements. Analyses of FPSOs or FPUs in sea ice have received little attention, but have been carried out for concepts in the Barents Sea. In practice this will need attention to ice management, which will certainly be required in heavy ice conditions. Detection and disconnection are again aspects that need careful study.

Table 9. Models in the software.

Model	Basis
Encounter rate	$f = p\left(\overline{L} + W_S\right)\overline{V}$ where W_S is the structure width
Area-penetration	$A = C_A \delta^{D_A}$
Global pressure	P is constant or random given as $P = C_P A^{D_P}$ where C_P is a lognormal distribution and D_P is a normal distribution
Local pressure	Impact duration; Cumulative distribution given as $F_z(z) = \exp\left[-\mu \exp(-z/a)\right]$ where z is the pressure, m is the exposure, $a = 1.25a^{-0.7}$ where a is area
Eccentricity and resulting iceberg rotation at impact	Profiled icebergs, Inertial parameters, G factor calculated for each orientaitation, Independent of the other parameters (dependent on contact depth)
Impact velocity	V_D, L, H_S and iceberg RAO's
Ice management	Detection performance (based on L, H_S, range R), Towing performance (based on L, H_S, time t)
Impact force	Kinetic energy model based on models above

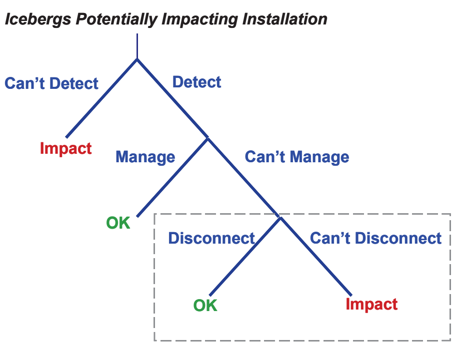


Figure 17. Event tree for analysis of effect of iceberg management and FPSO disconnection on the probability of an iceberg impacting a structure (Jordaan et al., 2014).

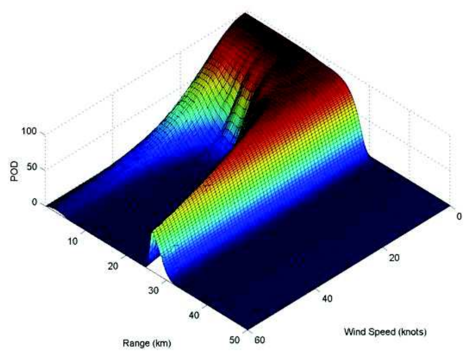


Figure 18. Hibernia, X band detection of a 50m Iceberg, Single Scan (Jordaan et al., 2014).

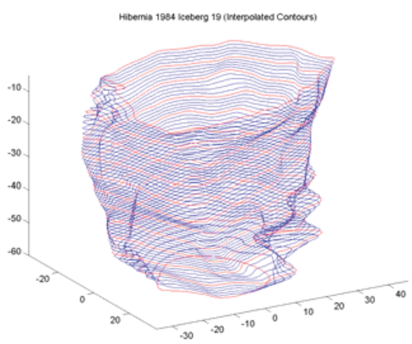


Figure 19. Typical 3-D shape constructed from contour data (to 1 m resolution) based on Dobrocky data set (Jordaan et al., 2014).

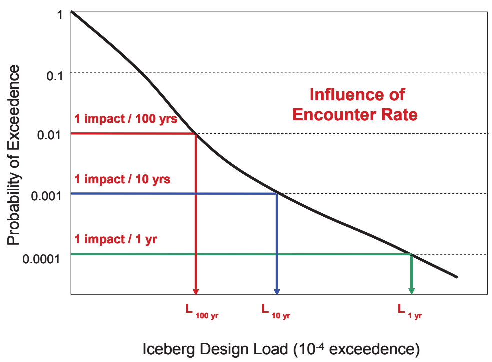


Figure 20. Illustration of influence of encounter rate on iceberg design loads at 10-4 exceedance probability. The probability of exceedance on vertical axis refers to that of the parent distribution, without considering the encounter rate (Jordaan et al., 2014).

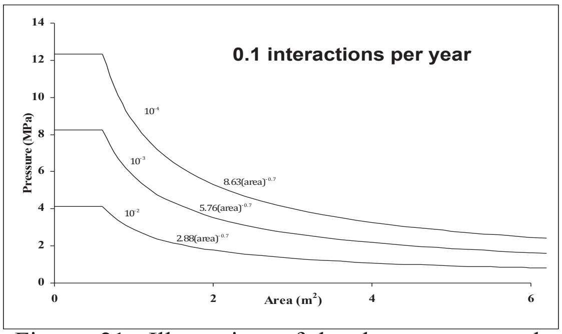


Figure 21. Illustration of local pressure result (Jordaan et al., 2014).

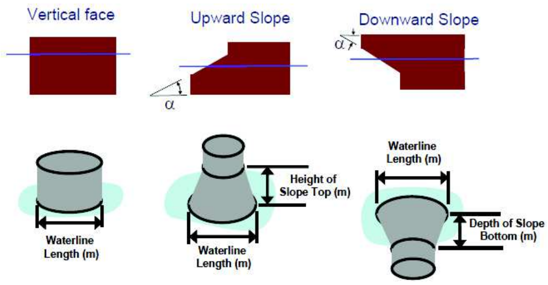


Figure 22. Some possible structure types.

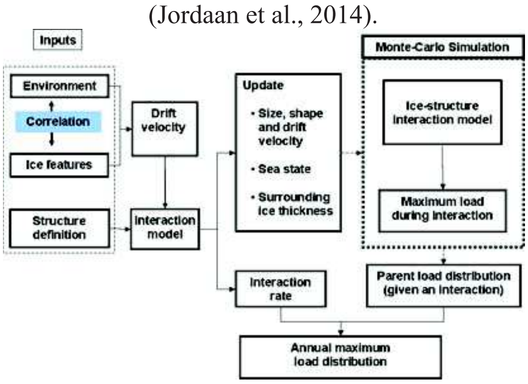


Figure 23. Flow chart for probabilistic analysis of multiyear ice interactions with structures with vertical faces (Fuglem, 1998).

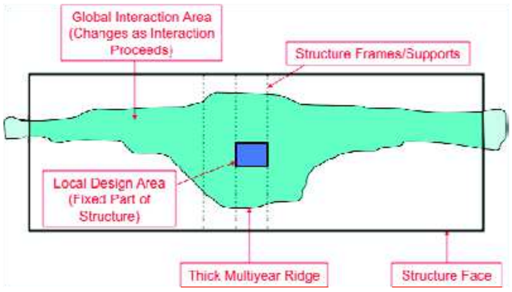


Figure 24. Area definitions for interaction with vertical faces (C-CORE, 2012).

Table 10. Assumptions regarding general structure shape for ice load models available in SILS.

Ice conditions	Structure face	General structure shape
Level ice and consolidated layer of first-year ridges	Vertical	Crushing models consider ice thickness and contact width, the structure shape in plan is not explicitly taken into account except for development of contact width.
	Sloped	Croasdale model is a 2D model with a 3D correction to account for limited structure width. Strictly speaking the model is applicable for level ice moving perpendicular to a flat face. Nevel model is applicable to conical structures
Unconsolidated layer of first-year ridges	Vertical and sloped	Combined Croasdale/Dolgopolov model considers only the thickness of layer and the width of the structure.
Multi-year ridges	Vertical	Crushing models consider ice thickness and contact width, the structure shape in plan is not explicitly taken into account except for development of contact width.
	Sloped	Nevel and Wang models consider and idealized conical structure where the ice rides up the front centerline of the structure.

2.3 *Validation methods*

Validation methods are of crucial importance for all analytical and numerical calculations conducted. This is especially true for the assessment of ice-induced loads due to the complex nature of the ship-ice interaction and due to the large variation in ice conditions and ice properties found in natural sea ice. Therefore, this section presents recent examples on validation methods including full-scale and model-scale measurements and observations. In addition, Annex 2 of this report seeks to summaries large- and full-scale experiments to obtain ice loads carried out to date.

Full-scale measurements are the most reliable method to validate theoretical models. Since the early 1970's large- and full-scale measurements have been carried out in various ice-covered waters of the world, see also Annex 2. Often strain gauges are installed on hull structures and then by finite element modelling or by physical calibration (see e.g. Suominen (2013)) the correspondence between the measured strains and ice-induced loads can be evaluated. Generally, the stochastic nature of ice-induced loads causes one of the main challenges when analysing such measured ice loads. Further, the need to establish a link between ice conditions, ship parameters, operation situations and these ice-induced loads exists. Long-term data obtained over a number of years can provide a link between the stochastic nature and the prevailing ice conditions (see e.g. Kujala (1994), Taylor et al. (2010), Jordaan et al. (2005)). However, long-term measurements, i.e. over several winters, have been performed only in Baltic and Antarctic waters. Ice loads from various measurement campaigns have been collected as 10-minute maximum load values in the EU SAFEICE Ice Load Database (Kujala et al., 2007). Local ice loads from impacts with ice features have been studied using motion reference units that record the ships' motions with 6 degrees of freedom. Measurements have been performed on CCGS Terry Fox (see e.g. Ritch (1994), in Russia (Krupina et al., 2009), Norway (Nyseth, 2006) and in the Baltic (Valkonen, 2013). Further, global loads on ships from ice impacts are important for the design of the hull girder strength and for the design of the liquid cargo or LNG storages for ice impact loads. Local loads are measured with a strain gauge panel on board Canadian, US and Swedish icebreakers; see e.g. Ritch (1994). Long lasting fibre optic strain gauges has proven to be reliable instrumentation on KV Svalbard and SA Agulhas II (Mejlænder-Larsen and Nyseth (2007), Suominen (2013)). Concerning larger vessels, only one large shuttle tanker operating between Murmansk and the Varandei terminal in Russia has been instrumented with local ice load measurement systems (Choi et al., 2009). Iyerusalimskiy et al. (2011) published interim results from these measurements.

Another challenge is the need to define the prevailing ice conditions. The ice conditions are typically observed by visual observations and only lately new approaches are developed to measure the prevailing ice conditions using e.g. Electromagnetic (EM) measurements and stereo cameras (Suominen et al., 2014). Unfortunately, no sound approach has emerged yet to link the stochastic ice induced loads with prevailing ice conditions in spite of extensive efforts done by analysing full scale data (see e.g. Suominen (2014)).

Ice damage statistics are another important measure to validate the design load level, i.e. if damages are too frequent the design load level may be increased or decreased if no damages occur. Unfortunately, such damage statistics are mostly not publically available. In the Baltic Sea, two damage measurement campaigns were carried out to validate the design load level found in the FSICR, see Kujala (1991) and Hänninen (2004).

The analysis Automatic Identification System (AIS) data also allows for the evaluation of the ship's progression behaviour in various ice conditions. Kujala et al. (2014) studied the probability of ships to get stuck in moving ice, which can cause compressive loads on the hull and subsequently damage. Figure 10 shows the speed profile of a bulk carrier (21355 DWT, ice class 1AS, engine power 9720 kW) navigating in March 2011 in the Bay of Bothnia. The ship sailed 94 nm in 14 h due to the severe ice conditions, causing her to ram ice features multiple timed and forcing her to idle in ice for three hours. The total recorded data contains significant variability in environmental conditions influencing the ship's speed, as depicted in Figure 25. Therefore, Kujala et al. (2014) utilized Bayesian-based statistical models to identify the probability of a ship to get stuck in ice to be 0.03.

Model-scale testing is used to evaluate the ship performance in various ice conditions. Latest research results indicate, however, that the model scale tests may also be used to investigate ice-induced loads (Kujala and Arughadhoss, 2012). Therefore, I-Scan 210 tactile sensors were used to measure the pressures induced by ice. The total dimension of the sensor sheet is 238 mm by 238 mm and the area of one sensing element is 5.4 mm by 5.4 mm, corresponding however to very few measurement point through the ice thickness. The sensing elements were arranged in 44 by 44 grids with a sample rate of 50 Hz. In addition to these measurements, the total load on the same area was measured by installing force transducers on the model hull (Suominen, 2013). Thus, the spatial and temporal distribution of the local pressure can be captured. However, great care is needed to scale this type of data to full-scale. However, straightforward Newtonian scaling suggests a good comparison to full-scale data, see Figure 26, in spite of the underlying assumptions and uncertainties in this comparison. The daily maxima of the measured ice loads between the years 1979 to 1985 form the basis of the statistical analysis of the long-term data (Kujala and Vuorio, 1986). The maximum ice thickness in the Bay of Bothnia during 1985 varied from 1.07 to 1.10 m with a higher probability of ice ridges or rafts. Whereas the maximum ice thickness during the ice tank measurements for MT Uikku was only between 0.63 and 0.79 m of level ice. This explains why the measured load values of IB Sisu are higher than the MT Uikku load values. In addition, it has to be noted that the measuring time in an ice tank is only a few hours. The load level on-board MS Arcturus is somewhat higher than on-board MT Uikku. This is understandable as the measuring period of MS Arcturus in full-scale was longer than the measuring period used for MT Uikku in the model-scale. In addition, the full-scale ice conditions can naturally vary significantly unlike the model ice conditions.

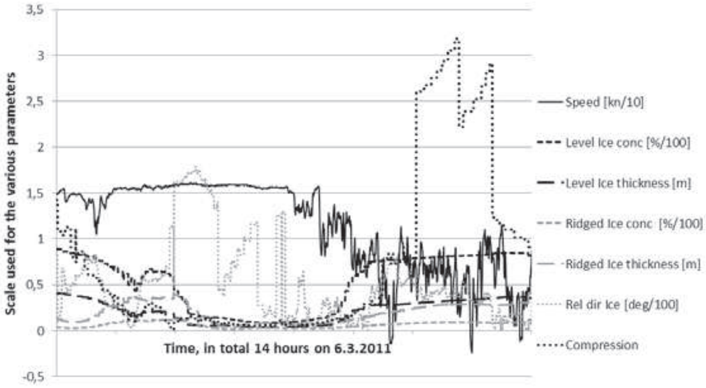


Figure 25. Time series of a bulk carrier navigating in varying ice conditions in the Bay of Bothnia on March 2011 (Kujala et al., 2014).

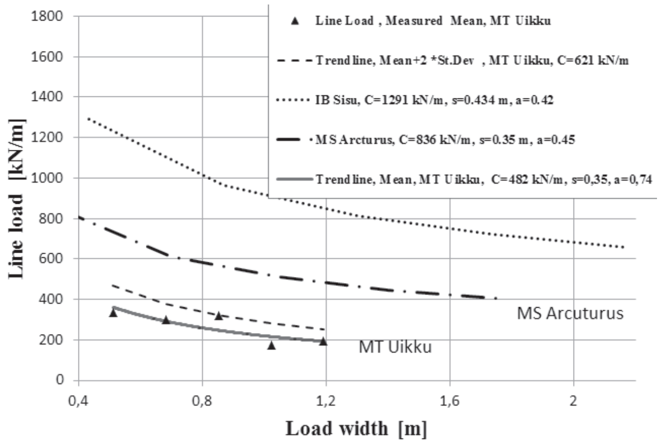


Figure 26. Comparison of model-scale test with MT Uikku with the full-scale data obtained on-board IB Sisu and MS Arcturus. Maximum ice thickness in model-scale corresponded to 0.8 m at a speed of 8 kn (Kujala and Arughadhoss, 2012).

The mechanical properties and the differences between model ice and full-scale ice was investigated by Von Bock und Polach and Ehlers (2014) based on a new approach to simulate numerically the failure of model-ice as a result of numerous model-ice property tests (Von Bock und Polach et al. (2013), Von Bock und Polach and Ehlers (2013)). They conclude that the number of unknown phenomenon in the internal mechanical processes of model-scale ice adds to the uncertainty for the scaling process from model-scale to full-scale and suggest various aspects to be investigated prior to general conclusions.

3. CASE 1: SHIP TRANSPORTATION IN ARCTIC WATERS–THE NSR

In this chapter, we seek to present the applicability of first principle-based methods to assess ice loads relevant for the design of a ship operating along the NSR in compliance and comparison to the above mentioned design methods as an alternative to be used for ships operating along the NSR.

Draught limitations along the NSR, e.g. in Sannikov Strait at New Siberian Islands used to be around 13 m, but latest measurements indicate that up to 17 m are feasible. The administration of the NSR defines three different ice condition categories (easy, medium, heavy) and ships are allowed sail independently or with icebreaker depending on their ice class. A description of ice conditions along the NSR is given by Ragner (2000). Figure 27 shows areas along the NSR where ice can typically be observed during the summer sailing season. Naturally, variations between different years exist and the shown ice massifs might appear in different compositions each year. Currently, first year ice is the predominant ice type along the NSR, while the southwest Kara Sea is known to have heavy ice conditions with ridged ice. A description of historical ice conditions in the Arctic and along the NSR is given e.g. by Romanov (1995). In the summer season (August–October) most of the NSR has been ice-free in resent years, at least for a short period of time. Ice typically remains the longest in the Vilkitsky Strait and in the Laptev Sea. The summer sailing season is characterised by various amounts of melting ice along the route. The extent of the Arctic summer sea ice has been decreasing in the last decades (Stroeve et al., 2012) and also the local volume of Arctic sea ice has decreased (Laxon et al., 2013). Predictions of the future ice extent show even further decrease (Overland and Wang, 2007). Besides ice, fog is typical phenomena in the summer season in the Arctic and forces ships to reduce their speed due to the low visibility where also possible ice floes are harder to spot. Further, fog affects also eventual search and rescue operations significantly. In the later part of the sailing season the nights are getting longer in the Arctic and darkness along with snowfall reduce visibility at the same time the sea is freezing up.

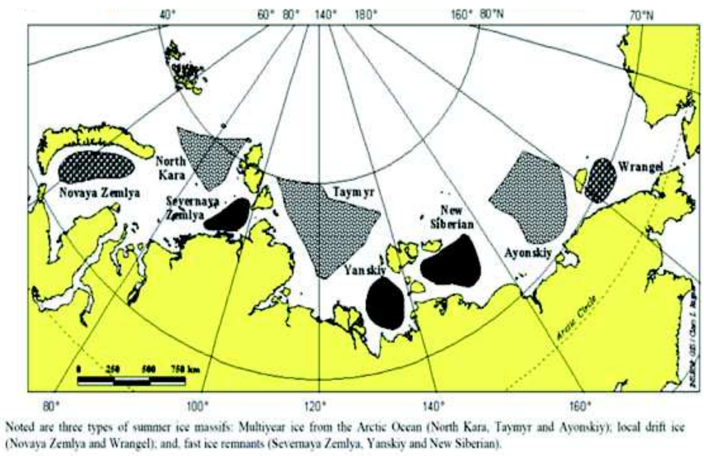


Figure 27. General locations of summer ice massifs along the NSR. Source: Ragner (2000), Published with permission from the original author Claes Lykke Ragner, FNI.

The example calculation procedure consists of 5 steps as indicated in Figure 28 and is derived from Ralph and Jordaan (2013). They linked the number of expected interaction per year with a parent distribution to estimate the extreme load for certain probability level. This methodology is further based on Jordaan (2005). The procedure requires the definition of waypoints along the NSR route, see Figure 29, and the corresponding ice conditions shown in Figure 30. The expected interaction must be assessed to further utilize a parent distribution corresponding to the ice conditions to obtain the extreme load prediction.

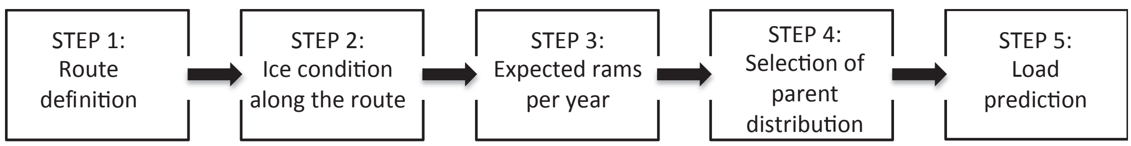


Figure 28. Steps of a probabilistic ice load assessment (derived from Ralph and Jordaan (2013)).

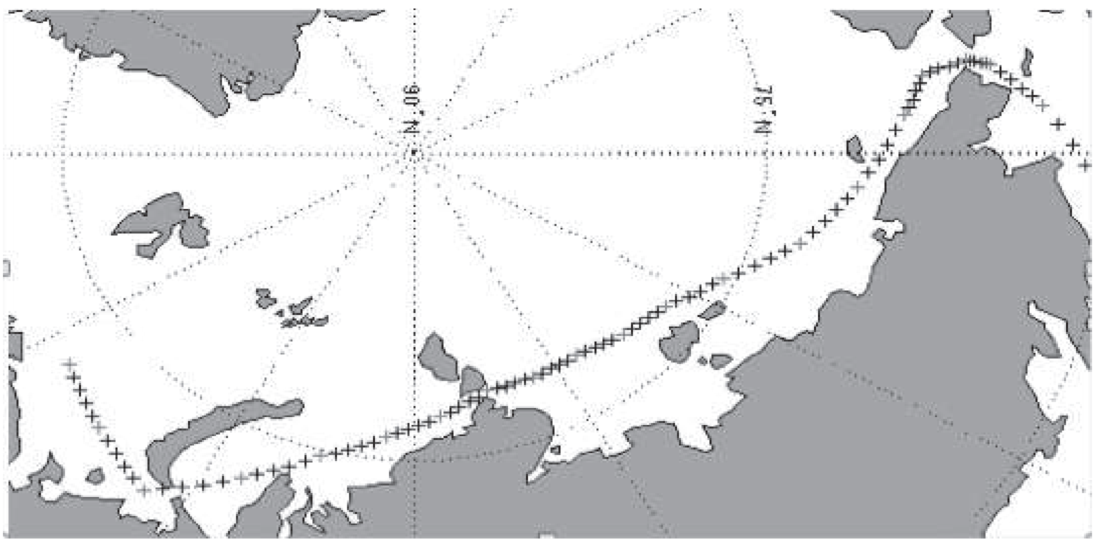


Figure 29. The NSR sailing route for this case study (Tõns et al., 2015a).

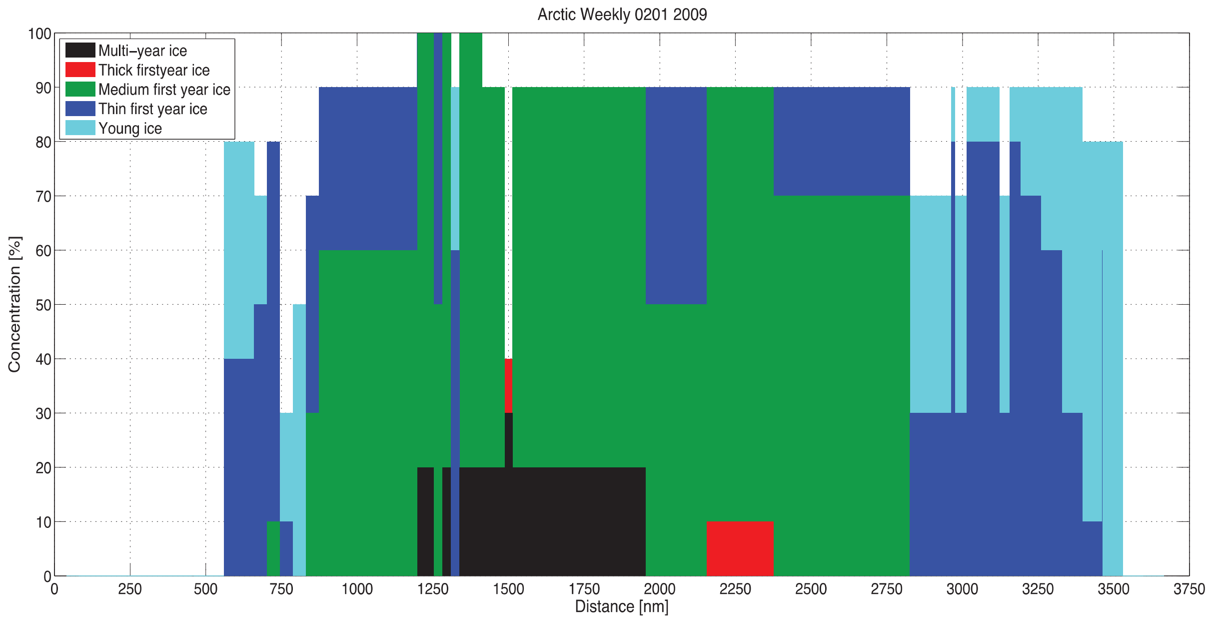


Figure 30. Example ice concentration and ice type along the route for a week in February 2009 (Tõns et al., 2015b).

The example ice conditions presented in Figure 29 are based on satellite images provided by the U.S National Ice service, which relevant weekly and bi-weekly data since 1978. In this example, weekly data ice utilized consisting of concentration for the two most dominating ice types. For this case study, weekly data for one year is utilized for the defined route as shown exemplary in Figure 12. Therefrom the distance travelled in specific conditions can be assessed where different ice types are assigned according to their share in concentration. For this example, it is further assumed that the vessel is sailing for 5 round trips along the route in one year.

The USCGC Polar Sea full-scale measurements performed in the Beaufort Sea in 1982 are used to describe vessel interactions in multi-year ice. The total number of 167 impacts was reordered in multi year ice during the reference voyage with 3.2 events per hour. For the thick first-year ice full-scale measurements performed in North Chukchi are considered. This dataset consist of ice impact measurements combined with first-year and multi-year ice. In total 513 impacts were recorded with a frequency of 3.6 events per hour, mainly in medium and thick first-year ice of 0.9 m to 1.8 m. Furthermore, the pressure-area relationship based on the Polar Sea measurements in the North Bering Sea was used for the reference loading in thin and medium first-year ice. The ice thickness during the recorded 8.2 impacts per hour was approximately 0.15 m to 1.2 m. Consequently, these recorded impacts per hour together with the maximum USCGC Polar Sea speed in corresponding ice conditions results in the total number of expected impacts for this case study, see Table 11. The illustrative calculations are based on the assumption that the ship operates along the route all year round or 8760 hours. Floe size and ice concentration could influence exposure, which is however not taken into account in this case study. This follows the statement by Ralph and Jordaan (2013), that the global and local ship ice interaction process causes the loads to the hull and vessel to which it has to comply. Thereby, the design relevant load is typically caused by the most severe ice action encountered, which may be in order of severity: brash ice, single year ice, multi year ice and ridges.

To predict the 100-year extreme ice load based on the obtained ice conditions along the NSR parent distributions following full-scale measurements are utilized from Figure 8. Based on Ralph and Jordaan (2013) the design load for a 100-year return period can be estimated as:

$$z_{100} = x_0 + \alpha\left[-\ln\left(-\ln F_z\left(z_e\right)\right) + \ln\mu\right] = x_0 + \alpha\left[4.6 + \ln\mu\right]$$

where μ represents the actual panel hits and can be calculates as $\mu = v \cdot r \cdot t / t_k$ where the average impact duration is, t, is assumed to be 2s, the proportion of true hits is set to 0.5, the exposure parameter x_0 is considered 0 and t_k is the reference impact duration based on the parent distribution. The resulting extreme load prediction is presented in Figure 31.

Table 11. Number of expected impacts for the case study.

Ice type	Operational speed [kn]	Duration [hours/year]	Impacts [events/year]
Open water	18	2964	
Medium first year ice	9	1887	16000
Thick first year ice	3	2969	10000
Multi-year ice	2	1213	4000

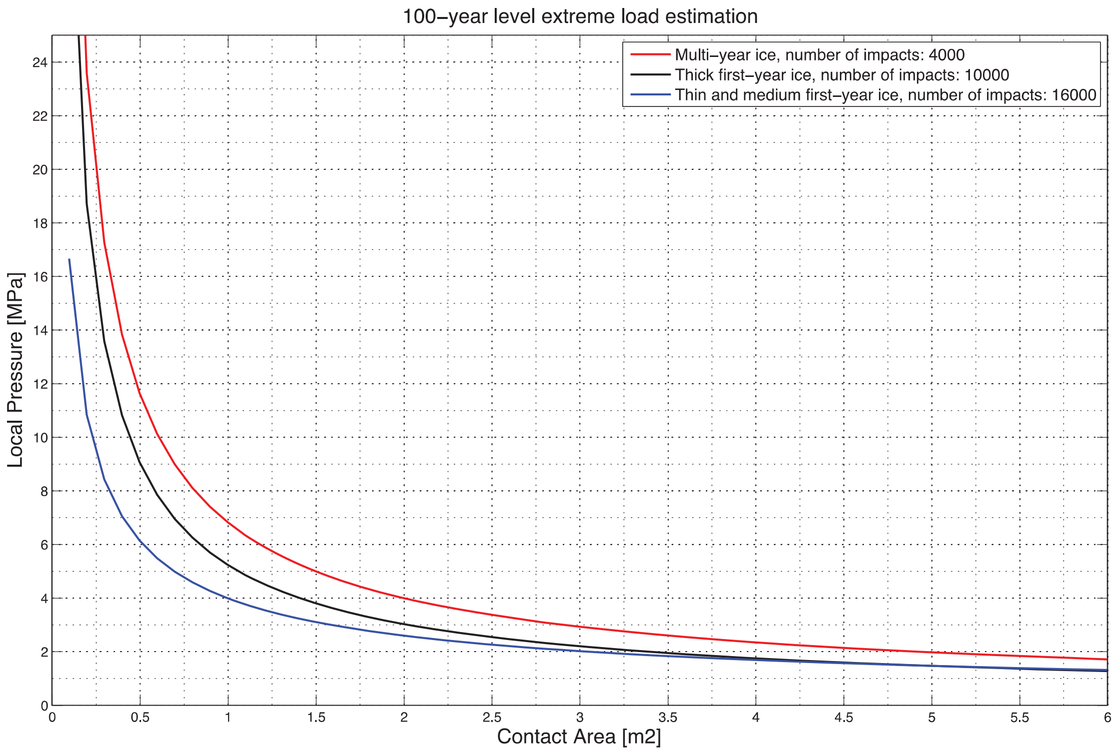


Figure 31. Predicted extreme load for the specified route (Tõns et al., 2015b).

4. CASE 2: FLOATING OFFSHORE STRUCTURES IN ARCTIC WATERS

In this chapter, we seek to present, as an example, the applicability of first principle-based methods to obtain ice loads relevant for the design of a floating offshore structure in iceberg prone waters.

Icebergs occur in many areas of the arctic and subarctic, for example West Greenland, east of Baffin Island and Labrador, on the Grand Banks, southeast Greenland, in the area neighbouring Svalbard, in the Barents Sea, and many other areas in the Russian arctic, see also Figure 1. Determination of iceberg loads for design of offshore facilities for exploration and especially for production is an important engineering task.

Engineering design aims at an appropriate balance between safety and economy. The use of probabilistic methods offers a solution that assists in obtaining such a balance. The specification of iceberg loads is guided by the (ISO, 19906) International Standard. The methodology used in the present study results in load-exceedance curves, which can be used to determine design loads at a desired annual exceedance probability. In ISO 19906 the Extreme Level Ice Event (ELIE) and the Abnormal Level Ice Event (ALIE) for the design of an offshore platform are defined at annual exceedance probabilities of 10^{-2} and 10^{-4} respectively for L1 exposure as defined earlier in this report.

Ice loads have been modelled using Monte Carlo methods, which take into account the underlying probabilistic distributions of the areal density of the ice feature (for example the number of icebergs per 10,000 km^2), the size and mass of the features, their added mass, their velocity, eccentricity of the collision, forces from surrounding pack ice, compliance of the structure, and the strength of the ice. Previous work focussed on the Grand Banks, where two floating production platforms are now operating, the Terra Nova and Sea Rose FPSOs. Probabilistic methods were developed for these developments. Extension of the methodology for use in other areas is of considerable interest. An example is suggested in Figure 32 The moderating influence of the North Atlantic Current results in conditions north of Norway and in the region of Svalbard that are similar in many respects to those offshore Newfoundland.

The floating vessel considered in the analysis is illustrated in Figure 33. The determination of iceberg design loads requires the following inputs for the simulations:

- areal density of icebergs
- size, velocity and shape of the icebergs;
- concurrent sea state and associated hydrodynamic effects on iceberg motion;
- eccentricity of loading to account for oblique impacts;
- global ice pressures developed on the basis of pressure-area relationships (derived from analysis of ship rams into hard, multiyear ice, or other relationships such as constant-pressure); and
- local ice pressures associated with the design loads (also derived from analysis of ship rams into hard, multiyear ice, and a function of the duration of individual impact events and the frequency with which they occur).

In addition to these, detection and management of icebergs, and possible disconnection of the floating unit are modelled.

Models have been developed for iceberg management based on Canadian experience on the Grand Banks. Three key elements of iceberg management include detection, towing and disconnection. Detection performance is based on special "ice" radar that is designed for small target detection in high seas. The system processes multiple scans to minimize clutter and false targets. Performance is based on the probability of detection (POD) of icebergs given iceberg size, sea state and range from the platform. Figure 18 illustrates a typical input.

Without any management, the encounter frequency is about 5×10^{-3} per annum—less than the value at which extreme-level design should be considered, but certainly greater than the value used in the abnormal-level case. Figure 34 shows a typical result of calculation of the mechanics of interaction. The dynamic analysis results in much reduced loads as compared to the values based on quasi-static analysis; for example, the quasi-static 10-3 and 10-4 exceedance loads of 10 and 150 MN reduce to about 5 and 40 MN respectively (without management). Iceberg management reduces the value at the 10-4 annual exceedance level to 26 MN.

A comprehensive methodology has been developed for obtaining design loads due to iceberg impacts, which was illustrated here and can be found in the previous chapter of this report, the original area of interest being the Grand Banks. In the present study, the methodology was applied to a region with much reduced areal densities of icebergs, and a greater proportion of bergy bits. The Extreme-Level loads were found to be zero, but significant loads and local pressures have been found at the Abnormal-Level (10^{-4} annual exceedance probability). Arrival rates, global forces including the effects of dynamics of iceberg and vessel, mooring loads and local loads have been determined using the methodology.

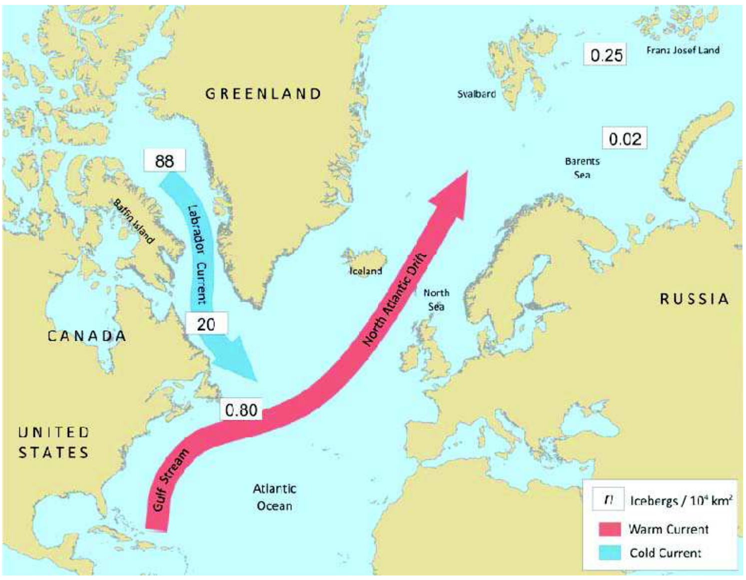


Figure 32. Some geographical areas with approximate areal densities of icebergs (excluding bergy bits) per 10^4 km^2 indicated (Jordaan et al., 2014).

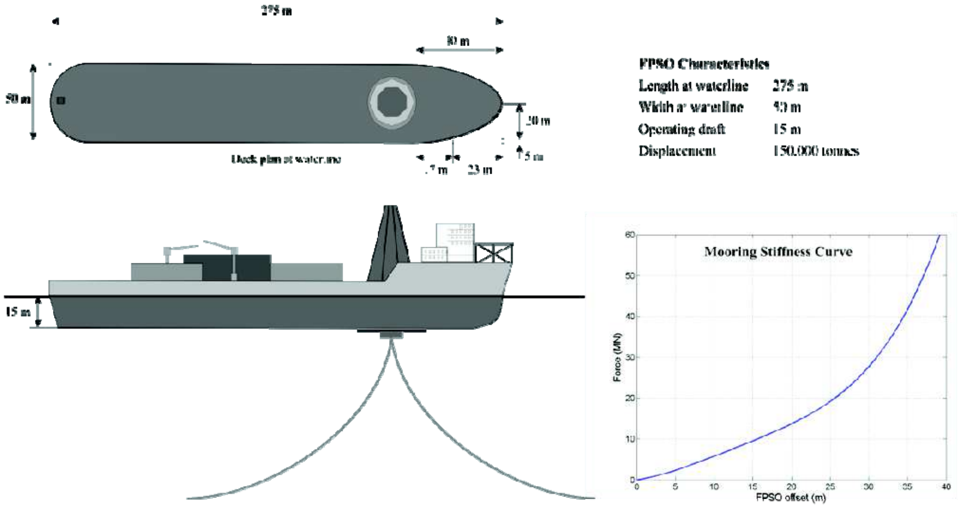


Figure 33. Schematic of generic floating vessel used in study (Jordaan et al., 2014).

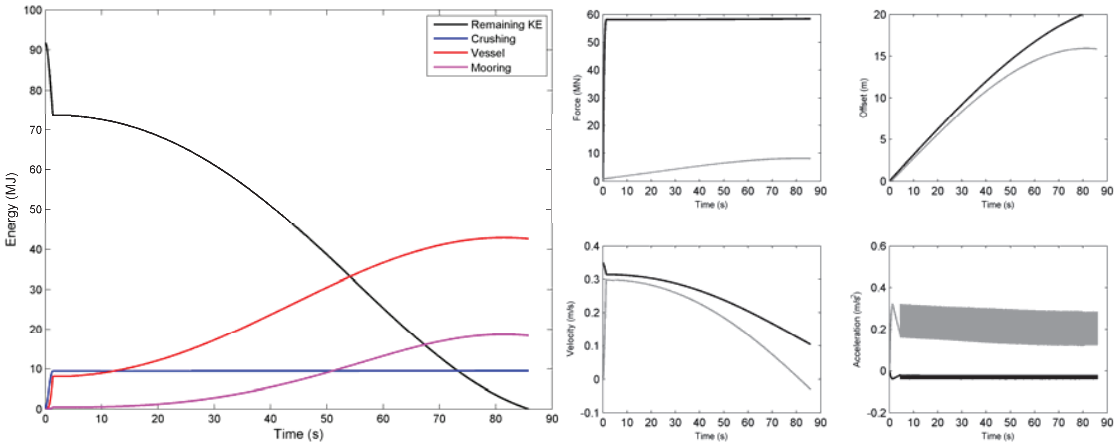


Figure 34. Results for floater inertial response including mooring stiffness. Mass = 1×10^6, V = 0.30 m/s (black line–iceberg, and gray line – mooring and floater) (Jordaan et al., 2014).

5. FUTURE PERSPECTIVES AND CHALLENGES

New projects in the arctic region need to consider operational and technical aspects as well as social and physiological aspects. Thus, prior to such project, these aspects must be assessed to ensure agreement of all relevant stakeholders from day one. Therefore, the non-exclusive items presented in Table 12 shall be considered.

Table 11 clearly indicates that each project in the arctic region must be approached with a tailor-made solution, because it is not possible to copy one project from one location to another location, even if the defining parameters appear to be rather equal. However, lessons learned from existing projects are invaluable to any new tailor-made project. When addressing items 1 to 5 from Table 11, no rules or proven concepts are available and thus they have to be by an integrated consisting of at least psychologists, sociologists, operators, mariners, engineers and managers. The current report only contributes to item 6 and 7, yet these important challenges are crucial to the overall success or projects in the arctic region.

Table 12. Non-exclusive items to be considered for new projects in arctic regions.

Item	Description
1	Involvement of 1st nations, their fears how they can be accounted for
2	Social and physical environment existing and/or to be created to ensure that people can work there efficiently and satisfied
3	Environmental and environment protection aspects to be considered and maintained
4	Identification of the project's main purpose and how it will be achieved
5	Operational aspects to be considered and to be achieved
6	Technical challenges of the project and the availability of adequate technology
7	Assessment of the project risk and evaluation of the risk mitigation measures

During the last decades great efforts have been put into the human safety and the protection of the environment wherefore both risk and reliability analysis are important decision support means. The development of structural reliability analysis in general started over 35 years ago as a new discipline in engineering, after probabilistic theory linked reliability to rules. Standardized methods, guidelines, and related software tools nowadays support structural reliability analysis. The basis for the methods and terminology may be found in (ISO, 19906). However, since about 1980, risk analysis has been mandatory within the offshore industry to identify risks, implement risk reducing measures, and to alert operators to the risks connected with their activities. Integration of risk and reliability analysis into the design process leads to risk-based design and Bainbridge et al. (2004), Moan et al. (2006) place this into the context of ship design. Furthermore, Jordaan et al. (1987) and Ralph and Jordaan (2013) developed an approach for a probabilistic design criterion for arctic shipping.

Reliability for ice-going vessels concerns the assessment of uncertainties related to ice-induced service loading, i.e. structural reliability analysis (see e.g. Kujala (1991), Kaldasaun and Kujala (2011)). The assessment of risk in ice refers to the consequences of accidental ice-induced loading, which leads to a risk-based methodology. Therein, all analysis shall be performed in a consistent way, by explicitly aiming at a common and transparent general criteria and analysis methods. This approach is in line with Goal Based Standards (IMO, 2014a).

Although the risk-based approaches are already established quite well in the maritime industry and can be found for passenger ships, and some examples of cargo ships, e.g. MSC 76/INF.15, MSC 82/23/3, there is a difference between risk assessment in the oil and gas industry and in the maritime industry. In the oil and gas industry each facility is assessed separately while in the maritime industry it primarily is done industry wide to establish rules and regulations. However, the approval of a ship can only be done for agreed operational and ice conditions, thus the imminent possibility that the ship operates outside these agreed conditions, due to the lack of knowledge of arctic wide conditions, may result in unwanted consequences.

A way forward is a mission-based treatment of the design relevant features and their identification to ensure safe arctic operations and transport.

The "mission-based" context is introduced here to pinpoint the need to consider site and route specific conditions in the design philosophy and widens the risk-based design scope from structural to operational aspects. Mission-based design shall include: definition of hazard scenarios, their occurrence probability and consequences, see Figure 35. For arctic operations, the definition of all three elements is challenging. The definition of hazard scenarios has to include the possible variation in ice conditions and operation principles in the arctic region. For shipping we can have independent navigation or navigation with icebreaker assistance e.g. in level ice, ice floes and ridged ice with various amount of first year and multi-year ice features. In addition, the possibility of moving ice has to be included as well as dynamic seasonal variations in ice conditions and long-term ice condition changes due to climate change.

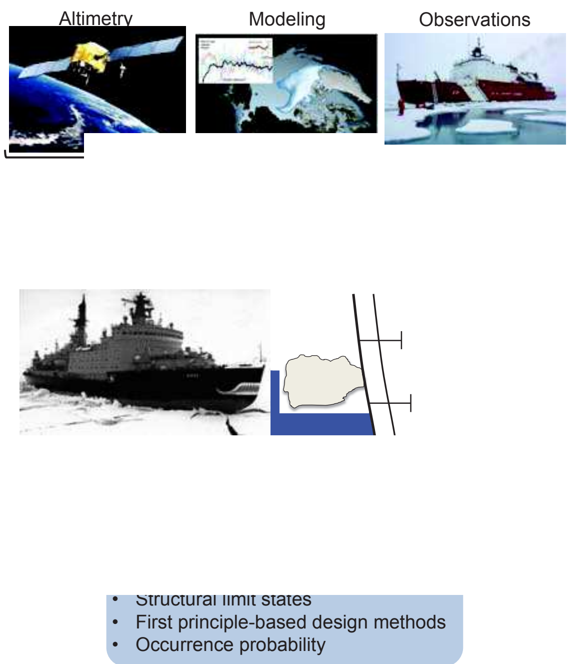


Figure 35. Mission-based design with risk control by design using first principle methods (Ehlers et al., 2014b).

The first task for mission-based is to define the most relevant ice condition in a format suitable to design for the operational scenario in question. Thereafter first principle tools shall be used to evaluate the ice induced loads and their occurrence probabilities. Based on this, the occurrence probabilities of various extreme and accidental limit states can be determined by applying structural analysis methodologies. The possible consequences of each limit state, including the environmental effects, shall than be evaluated so as the conceptual design in question. Figure 36 summarizes this process. Therein, the mission-based treatment can be achieved through a consistent link between these elements and the analysis of their effects on the conceptual design phase.

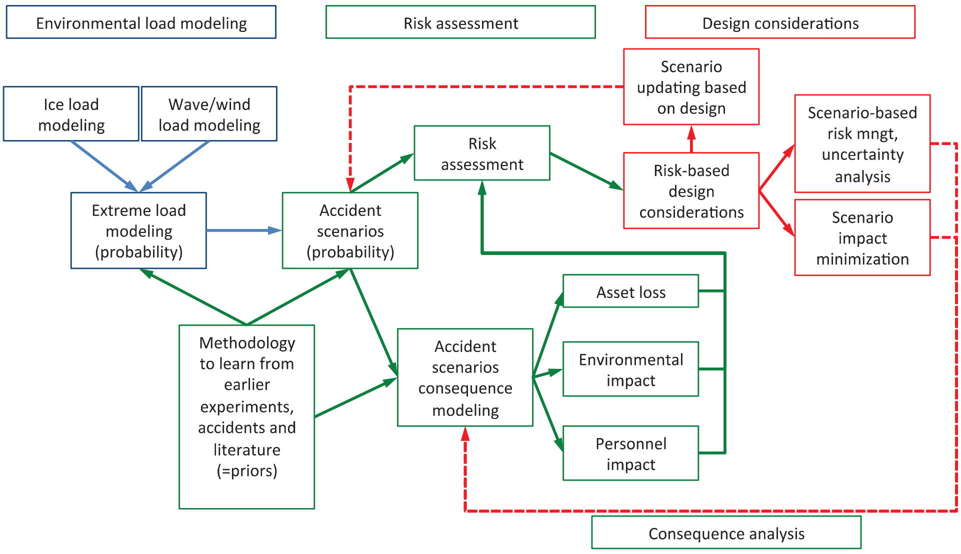


Figure 36. The basic elements and the process needed for a mission-based design approach (Ehlers et al., 2014b).

The mission-based design of ships sailing in ice-covered waters can come possible when the uncertainties related to the service, accidental actions and the ship operations are assessed. Ideally, we seek to identify the exact safety margin using the accurately assessed uncertainty related to the ice-induced load. As a result, there would be no need to speculate if a design load suffices, since the compliance to the safety level for a given environmental condition would be clearly identified. Thus the risk level for different designs must be quantified. In fact, risk shall be used to measure the safety performance. Therefore, with having safety measurable, it is possible to effectively optimize the ship design by introducing risk minimization as a new objective along standard objectives. In other words, one additional constraint enters the design optimization as follows:

$$R_{design} \leq R_{acceptable}$$

where R_{design} is the risk of the considered ship or system and $R_{acceptable}$ the acceptable risk. Furthermore, the trend is to apply the ALARP (As Low As Reasonably Possible) principle, which relates the acceptable probability of fatality, pollution and economic loss as a function of the magnitude of the consequences to the costs of reducing the risk. However, in order to assess the risk from accidental ice-induced loading, the consequences, i.e. the structural response and strength, needs to be obtained. The evaluation of the consequences of alternative accident scenarios has to cover the process from accident occurrence to its consequences, to ecosystem response and recovery including related uncertainties. Assessing the consequences to a vast number of possible accidental scenarios requires efficient computational methodologies to optimize the structural layout to minimize this risk. However, in order to minimize the risk of a ship subjected to accidental ice-induced loading, conflicts are often faced. For example, being incapable to create a lightweight, safe and inexpensive ship might lead to conflicting objectives. Therefore multi-objective optimization is needed to foster proper treatment of global objective to minimize the risk, i.e. maximize safety.

Concerning ship structures, multi-objective optimisation of ship structures can be found e.g. in Shi (1992) and Parsons and Singer (2000) while Ehlers (2010) and Ehlers (2012) presented structural optimisation procedures for accidental loading suitable for computational risk-assessment.

5.1 Numerical simulations

Present design methods use empirical data to assess design pressures as a result of structure-ice-interaction. Therefore, this chapter presents recent developments in numerical simulations towards the development of theoretical and first principle-based design pressure calculations. The primary challenges in structure-ice-interaction simulations concern the ability to simulate the phenomena found therein, i.e. the damage and fracture process and the formation of high pressure zones as shown in Figure 15. Thus, it crucial to consider the basic behaviour of ice adequately, i.e. its visco-elastic behaviour, creep and damage, rather than to violate it by using inappropriate commercially available analogies in material modelling.

The predictions of ice failure, i.e. fracture; under various loading rates at temperatures around its melting point represent a challenge when modelled. Thus, local ice failure includes transitions between different phases. Impact induced ice failure typically involves compaction around the centre of the impact location, possible closed micro-cracks in the confided area and flaking of the free edges as a result of tensile cracks. Depending on the impact speed ice behaves ductile with visco-elastic deformations and damage during low loading rates and brittle during high loading rates and generally it is temperature dependent. Experimental data available concerning the microstructural behaviour of ice (creep, constant-deformation-rate) can be found in Melanson et al. (1999), Meglis et al. (1999) and compressive behaviour of ice is available by Jordaan et al. (1997). Therein, pressure within high-pressure zones of up to 70MPa-100MPa have been found as well as the fact that recrystallization to very small grains and softening under pressure leads to extrusion resulting in crushed ice (layer formation). In addition, this recrystallization without fracture can occur besides spall damage. Moore et al. (2013) presented damage process and fracture process based on stress history for each element in the form of softening. Furthermore, the multiple-scales involved in any structure ice interaction process shown in Figure 37 cause various numerical challenges including local contact issues and general scale effects. Thus the scaling laws must cover a wide range of scale all the way from atomistic Korlie (2007) up to the km range. Therein, tension fracture scaling appears to apply in the 0.1–100 m range (Mulmule and Dempsey, 1998). In the case of compressive failure size effects are significant according to Blanchet (1998). In smaller laboratory scale the importance of inhomogeneities and polycrystallinity have been established to play important roles, but no approaches on how to transfer this to larger scales exists. Furthermore, the size effect at smaller scales seems to be clearly linked to the combination of several possible failure modes (tension or shear fracture, shear localization, evolution of damage, etc.). Consequently, Jordaan (2009) presents scale effects indicating that local contact phenomena can changes the local ice behaviour up to a million times.

Another topic is the different behaviour of fresh and sea water ice. There have been developed constitutive models for fresh water ice; however, these do not apply to saline water ice due to differences in microstructure (Schapery, 1997). Specific physically based models, applying dislocation and grain-boundary relaxation, have also been developed to describe inelastic deformation in sea water ice (Cole et al., 1998). Furthermore, it has been shown that strain-rate and time effects are important in fracture of ice, and constitutive models addressing high strain rate have been developed (Sain and Narasimhan, 2011).

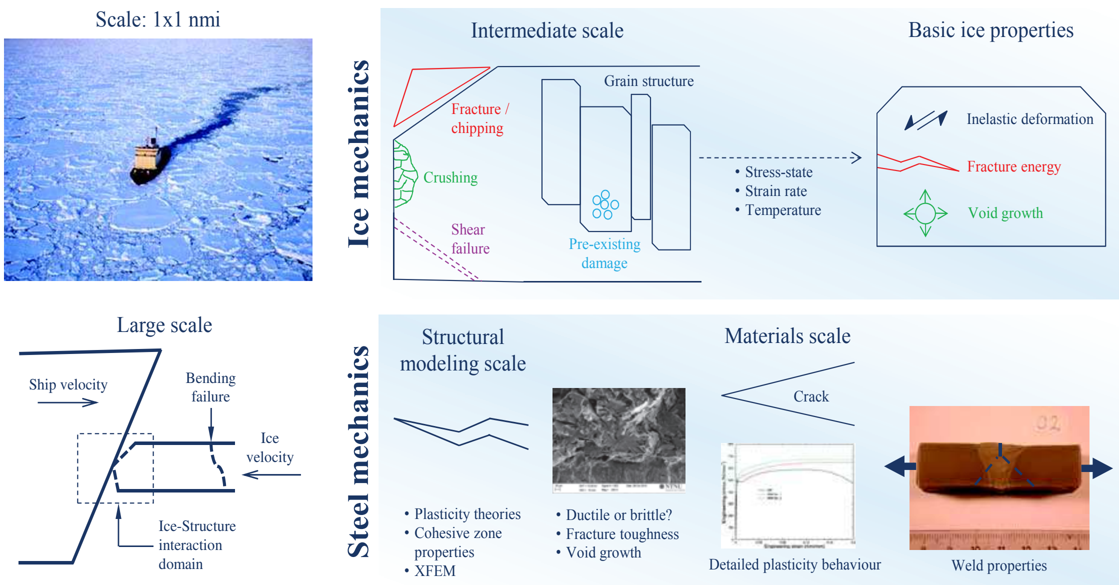


Figure 37. Example range of scales involved in structure ice interaction processes (Ehlers et al., 2014b).

Jordaan (1986) analysed floating masses, such as multi-year floes and their interaction with offshore structures and discusses the need for efficient numerical methods to produce quantitative results in the future. In general, ice may be discretized by finite elements and failure treated by element erosion or deletion. If the mesh is fine, then erosion may approximate initial failure in the continuum representation of the ice well (Yu et al., 2007). Explicit modelling of the anisotropy and damage, e.g. distributed ice grains, air and water, has been carried out by Von Bock und Polach and Ehlers (2013) for model scale ice, which is however different from natural ice as discussed in Von Bock und Polach and Ehlers (2014).

Besides ALE discretization approaches, which proved effective for relevant short cracks being in plain strain condition according to Schapery (1997), while the simulation of rate dependent long cracks still presents a challenge. For qualitative analysis of brittle fragmentation Polojärvi and Tuhkuri (2008) presented a BEM-based specialized simulation tool, which is suitable for 2D beam-based models with cohesive cracks for rubble formation, but not for local ice mechanics. Rubble formation was simulated using 2D combined FEM–DEM by Paavilainen et al. (2011), which concerns the rubble build up and internal contact. Furthermore, Ranta et al. (2014) concluded that material parameters for ice are not sufficient to determine the load level of ice interaction against an inclined wall. Consequently, both numerical models and experiments are needed to understand the underlying processes, see Polojärvi and Tuhkuri (2008). One rapidly developing tool to analyse these processes is the integrated finite discrete (DEM) and finite-element method (FEM), in which both the ice breaking process and loose ice pieces can be modelled, see Paavilainen et al. (2009). Heinonen (2004) and Liferov (2005) present pseudo-discrete models in the form of continuum models for ice rubble formation. Lau et al. (2011) modelled free-floating level ice with three-dimensional plate bending elements using a DEM-Code for ice-related problems. The general shortcoming of these approaches is their utilization of discrete energies for the involved damage modes, which are not known for the discretization scale, hence the simulations can only be calibrated using experiments and thus their general applicability may be achieved. Sawamura et al. (2008) study the dynamic bending behaviour of a floating ice-sheet subjected to the dynamic force by using the explicit FE-method. Lately, Su et al. (2011) applied a numerical method to simulate a ship moving forward in uniform or randomly varying ice conditions. Furthermore, Su et al. (2011) investigated both global and local ice loads on ship hulls by simulating a full-scale icebreaking trial considering the interdependence between the ice load and the ship's motion as well as the 3D-rigid body equations of surge, sway and yaw. As a result, their simulations comply with the overall resistance of the trial in various ice conditions. However, their model does not consider localized ice failure directly, assumes a certain ice fracture pattern and due to its calibration based on large-scale measurements it may not be applicable to new ships in general. In conclusion, the above-mentioned simulations may contribute to a better understanding of the processes involved in ship-ice interaction. A step ahead would be to consider localized pressures and the response of the ship structure, specifically the steel and weldments under sub-zero temperature.

In general, failure of steels, either due to plastic collapse, ductile fracture or brittle fracture, has been studied heavily in the offshore, ship, and automotive industries. However, how these phenomena change and interact at sub-zero temperatures is still subject to large uncertainties. There is a common belief that although the yield stress and tensile strength increases with decreasing temperature the fracture strain decreases leading to poorer impact resistance at lower temperatures. However, recent results, combing experimental tensile data and numerical modelling, strongly indicate that this is not always the case (Ehlers and Østby, 2012). Furthermore, beside the general tensile and fracture properties of steels as a function of temperature, the performance of weldments plays an important role. Laser-based welding is much used in the ship industry, however little systematic work has been done regarding the sub-zero temperatures behaviour. Also the possible transition from ductile to brittle behaviour in steels with reducing temperature has not been studied with regards to ship-ice interaction. This presents the backdrop for the need to further investigate and obtain understanding of the performance of steel and associated weldments, and underlines that the linking of this new physical understanding with the general structural response of ships will be essential to achieve in the future.

5.2 Ice induced fatigue

Fatigue damage is a common problem for structures subjected to cyclic loading, such as ships and offshore structures exposed to wave and wind loads. Ice-going ships experience additional loads due to crushing of ice and ramming of ice floes. According to Zhang et al. (2011) fatigue cracks were found in both ice classed and non-ice classed ships after an averaged time of 13.0 years and 12.7 years, respectively. This indicates that structural design according to fatigue limit state (FLS) is equally important for both ship types. Moreover, most cracks were found in the forward region of ice-going ships, while in non-ice classes ships cracks are more often found in the mid region of a ship, see Figure 38.

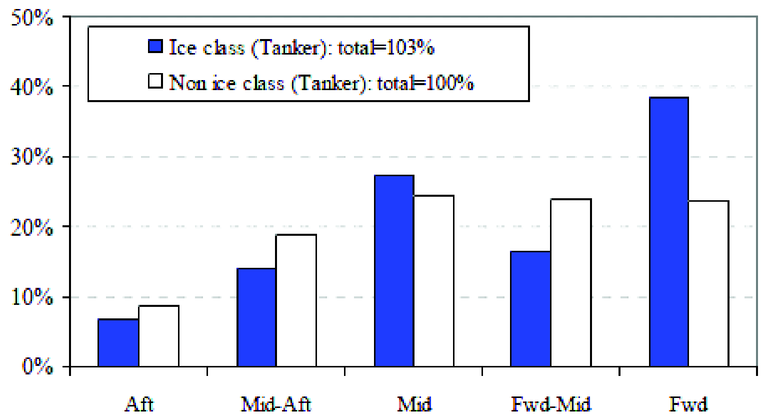


Figure 38. Damage distribution of side shell structures of ice-going and non ice-going vessels (Zhang et al., 2011).

Fatigue assessment of structural details of ships or offshore structures is usually performed by means of a local stress approach. Herein, the local stress acting at a position at which fatigue crack growth might initiate is used to estimate the life by inserting it into a SN design curve of, i.e., a classification society. However, the difficulty lies with the definition of an appropriate load scenario, especially since ice conditions vary significantly. For this purpose an example FLS assessment study for an ice-going ship will now be presented.

The reference ship is MT Uikku is a double hull ice breaking tanker, which is currently transporting oil from an oil terminal in the Ob Bay to a FSO in the Kola Bay near Murmansk, with an approximate distance of 2170 km (Bambulyak and Frantzen, 2009). In order to find a load spectra for this route a Monte Carlo based method suggest by Zhang et al. (2011) may be used to estimate the frequency of impacts due to crushing of level ice per travelled meter. The local stress acting at a critical weld detail in the ice belt of the ship can then be found by applying classic beam theory assuming the ice load to be acting at the mid span of the frame. Based on the so obtained local stress it is possible to estimate the lifetime of the transverse stiffener in the forward region of MT Uikku by means of linear damage calculation. Using, i.e., FSICR to obtain the stiffener scantlings this procedure results in an expected fatigue damage of 0.0241, which corresponds to a lifetime estimate of 41.6 years. However, we must keep in mind, that this estimate is only based on the damage accumulated in ice-covered areas. According to Zhang et al. (2011) it is feasible to assume that a ship will experience half the damage in open water and half the damage due to ice impacts. A reasonable estimate of the lifetime would therefore be equal to 20.8 years, which is nearly half the time MT Uikku is already in service. However, this is example is just an estimate using the minimum scantling requirements from FSICR. Given a 7% larger section modulus is installed in the reference ship, the ice load based lifetime estimate increases to 54.1 years.

For narrow fixed structure, the dynamic ice-structure interaction known as frequency lock-in can occur when level ice acts continuously on a vertical structure at a moderate ice speed. This phenomenon may lead to fatigue. Based on field experience, structures with an Eigen frequency in the range of 0.4 Hz to 10 Hz have experienced self-excited vibrations, if their total structural damping was lower than about 3%. Figure 39 illustrates the three primary modes of interaction in terms of ice force, F(t), and the corresponding displacement, u(t), as measured in full-scale structures in the Bohai Sea. These measurements suggest that a conical waterline geometry of the structure reduces the magnitude of ice-induced vibrations.

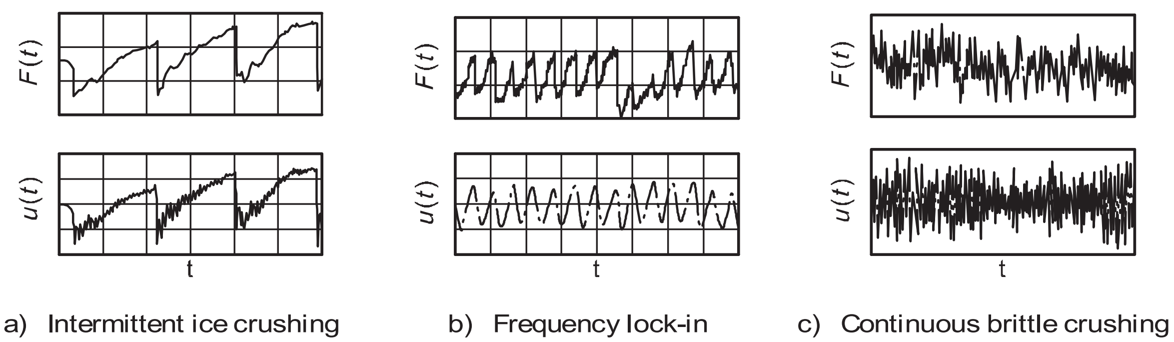


Figure 39. Modes of time-varying action due to ice crushing and corresponding dynamic component of structure response (ISO, 19906).

6. SUMMARY AND RECOMMENDATIONS

This report presented current design methods for ships and offshore structures followed by first principle-based pressure and occurrence determination methods to obtain design ice loads. Further, it was shown that these first principle-based methods can contribute to the design of structures beyond the current minimum requirements as well as for new operational areas in the arctic region and thus to the further development of the present design methods.

The second chapter presented the current developments for ships and offshore structures as well as the underlying rules and regulations. For ships, the essential rules are: the FSICR for first year ice, the IACS polar classes and the RMRS covering also multi-year ice, besides the IMO Polar Code. The corresponding design ice loads are based on experience from specific types and sized vessels operating in corresponding ice conditions. Offshore rules are based on target safety levels which than translate into design ice loads. Their underlying design load, load combination and structural design considerations and assumptions are presented in depth in the Annex of this report. A rational way forward and a possibility to analyse existing design ice pressures is presented based on probabilistic methods. Here extreme design events are identified as well as the model uncertainty. Additionally, different limit states for ships and offshore rules are provided. Ship rules typically use some kind of elastic limit state and allow for a certain amount of plastic deformation, offshore limit states comprise elastic, plastic, ultimate and serviceability, fatigue and accidental limit states, also corresponding to ELIE and ALIE and may also use Load and Resistance Factor Design and probabilistic analysis. The performance based design approach of ISO19903 is big step forward. Target reliability levels are established based on consequence of damage including risk of loss of life and environmental damage. Subsequent designs must satisfy the established targets directly. The approach considers both Extreme Level (10^{-2} annual exceedance probability) and Abnormal Level (10^{-4} annual exceedance probability) ice loads events. For structural design, these events would correspond with elasti –limited plastic designs and ultimate limit state plastic designs respectively. This robust approach to design gives the designer a clear understanding of the performance of the system for certain loading conditions. Mode of failure should also be considered.

The design load obtained with the probabilistic approach presented in the NSR case study confirms that multi-year ice results in the design driving load even if it is only encountered at a fraction of the route. Furthermore, the comparison to IACS polar code confirms the general suitability of the approach to define ice loads on a route, respectively mission, basis. In other words, the presented approach allows for the identification of the design driving conditions, which is also presented for the floating offshore structure case.

In conclusion, the report motivates for a more mission-based design methodology in addition to the present design methods using the presented first principle-based methods. The contents of the mission-based design are presented and an outlook to possible future contents of such design approach for arctic ships and offshore structures is presented. In addition, the current developments in numerical methods are presented, which may be used to understand underlying phenomena better and to simulate processes. Finally, an example on how to assess fatigue damage for structural details was presented.

In view of future research needs, it can be noted that more and more ships are going to operate in the marginal ice zone or close to the ice edge. In those areas, small ice floes can be accelerated by waves and reach substantial impacts speeds when the ship is advancing with relatively high speeds. The resulting damage of such collision event can be extensive and similar approaches as for bergy bits may be applied (Fuglem, 1998). Thus, it is advisable to consider ice in the presence of waves as a possible design scenario for the bow structures. Furthermore, investigation for stern ice loads on vessels, especially DAS, as well as load in compressive ice should be investigated. As a result of the high lateral thrust from azimuthing propulsion systems, ice loads on the aft shoulder might be larger than suggested by the present design methods. Valkonen et al. (2007) observed lateral movement of the ship in model scale. However, the stern of a DAS may experience similar loading as a regular ice strengthened bow in forward motion. Nevertheless, there is no publically available information on the ice loads on the aft of a DAS. Further, the mid-ship section can experience significant ice loads when the ship gets stuck or operates in a compressive ice field, see, e.g., Suominen and Kujala (2012). These aspects, among others, generally indicate the need to investigate the influence from the type of operations in ice on the design considering also human factors. In view of offshore operations, ice management and the loads expected from unmanaged, managed and over-managed ice should be investigated as well as disconnection operation and resulting consequences. A clear definition of extreme load events and specific links between ice conditions and ice induced load levels that could, i.e., lead to a transparent link between measured ice pressures and ship design ice pressures would be very practical. The latter may also help to develop more reliable stochastic models for ice-induced loads in various ice conditions and for selected routes. As for numerical simulations of ice, reliable numerical ice pressure simulations are needed to evaluate structures under target ice conditions and to study load carrying mechanism under spatially and temporally varying loads. For the evaluation of structures, the base material and weld compliance to arctic conditions, i.e., in terms of ductile to brittle transition behaviour should be in investigated.

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REFERENCES

Aari. 2014. *Arctic and Antarctic Research Institute* [Online]. http://www.aari.nw.ru.

Aggarwal, R. & D'souza, R. 2011. Deepwater Arctic-Technical Challenges and Solutions. *Arctic Technology Conference.* Houston, Texas, USA.

Akerarctic 2013. Aker Arctic brings heavy duty Oblique Ice Breaker to market. http://www.akerarctic. fi/news.htm: Aker Arctic.

Baan, D. 2011. *ASSEMBLY OF TURRET AND DISCONNECTABLE BUOY*.

Bainbridge, J., Christensen, H., Hensel, W., Sames, P. C., Skjong, R., Sobrino, M. P., Strang, T. & Vassalos, D. Design, Operation and Regulation for Safety–SAFEDOR. PRADS2004, 2004 Travemünde, Germany.

Bambulyak, A. & Frantzen, B. 2009. Oil transport from the russian part of the barents region, status per January 2009.

Barentsobserver. 2013. Available: http://www.barentsobserver.com/en/arctic/three-new-nuclear-icebreakers-pipeline-14-11.

Bauduin. 2011. *DISCONNECTABLE RISER-MOORING SYSTEM*.

Bergström, M., Ehlers, S. & Erikstad, S. O. A framework for risk-based design of arctic ships. Submitted to OMAE2015, 2015.

Blanchet, D. 1998. Ice loads from first year ice ridges and rubble fields. *Canadian Journal of Civil Engineering,* 25, 206–219.

C-Core 2012. Sea Ice Loads Software (SILS)–Version 1.6–Theory Manual. C-CORE.

Carter, J. E., Daley, C., Fuglem, M., Jordaan, I. J., Keinonen, A., Revill, C., Butler, T., Muggeridge, M. & Zou, B. 1996. Maximum Bow Force for Arctic Shipping Pollution Prevention Regulations–Phase II. *In:* Memorial University of Newfoundland, O. E. R. C. (ed.) *Canadian Coast Guard Arctic Ship Safety.*

Carter, J. E., Frederking, R., Jordaan, I. J., Milne, W. J., Nessim, M. A. & Brown, P. W. 1992. Review and Verification of Proposals for the Revision of the Arctic Shipping Pollution Prevention Regulations. Memorial University of Newfoundland Ocean Engineering Research Centre.

Chnl. 2013. Available: http://www.arctic-lio.com/node/207.

Choi, J., Park, G., Kim, Y., Jang, K., Park, S., Ha, M., Yu, H., Iyerusalimskiy, A. & John, J. S. 2009. Ice load monitoring system for large Arctic shuttle tanker RINA. *Royal Institution of Naval Architects International Conference–International Conference on Ship and Offshore Technology: Ice Class Vessels–Papers.*

Cole, D. M., Johnson, R. A. & Durell, G. D. 1998. The cyclic loading and creep response of alligned first-year sea ice. *Journal of Geophysical research,* 103, 21751–21758.

Daidola, J. C. & Sheinberg, R. Procedure for the Structural Design of Icebreakers and Other Ships Navigating in Ice. 1988. SNAME.

Dnv 2012. What is on the regulatory agenda? Recently adopted and coming rules and regulations from IMO, IACS and DNV. http://www.dnv.ee/binaries/Estonia_presentation1_Regulatory_agenda_tcm172-531755.pdf.

Dnv_Canada 1986. Probability-based design criteria for ice loading on fixed offshore structures in the Beaufort Sea. Final report, Vol. 1–Study Description. Calgary, Alberta, Canada.

Dsme. 2014. Available: http://www.dsme.co.kr/.

Ehlers, S. 2010. A procedure to optimize ship side structures for crashworthiness. *Proceedings of the Institution of Mechanical Engineers, Part M: Journal of Engineering for the Maritime Environment,* 224, 1–11.

Ehlers, S. 2012. High strength steel in crashworthy ship structures. *Journal of Ship production and Design,* 28, 1–9.

Ehlers, S., Benson, S. & Misirlis, K. Ultimate strength of an intact and damaged LNG vessel subjected to sub-zero temperature. Collision and Grounding of Ships and Offshore Structures, 2013 Trondheim. CRC Press, 289–296.

Ehlers, S., Erceg, B., Jordaan, I. & Taylor, R. Structural analysis under ice loads for ships operating in arctic waters. MARTECH2013, 2014a.

Ehlers, S., Kujala, P., Veitch, B., Khan, F. & Vanhatalo, J. Scenario based risk management for arctic shipping and operations. Proceedings of the ASME 2014, 33rd International Conference on Ocean, Offshore and Arctic Engineering OMAE2014, 2014b San Francisco, California, USA. ASME.

Ehlers, S. & Østby, E. 2012. Increased crashworthiness due to arctic conditions–The influence of sub-zero temperature. *Marine Structures,* 28, 86–100.

Frederking, R. & Sudom, D. Local Ice Pressure Distributions during 1990 Hobson's Choice Ice Island Multi-Year Ice Indentation Tests. Proceedings 19th IAHR Symposium on Ice, 2008 Vancouver, B.C., Canada. 815–827.

Fuglem, M. Design Load Calculations for Iceberg impacts. Proceedings of the Eighth International Offshore and Polar Engineering Conference, 1998 Montreal, Canada.

Hänninen, S. 2004. Incidents and Accidents in Winter Navigation in the Baltic Sea, Winter 2002–2003. Winter Navigation Research Board.

Heinonen, J. 2004. *Constitutive modeling of ice rubble in first-year ridge keel.* Doctoral degree, TKK.

Ilo. 2014. *Mission and objectives* [Online]. Available: http://www.ilo.org/global/about-the-ilo/mission-and-objectives/lang--en/index.htm.

Imo 2014a. Goal based New Ship Construction Standards.

Imo 2014b. Implementation, Control and Coordination.

Imo 2014c. Port State Control.

Iso 19906. Petroleum and natural gas industries–Arctic offshore structures. ISO.

Iyerusalimskiy, A., Choi, J., Park, G., Kim, Y., Yu, H. & St.John, J. The interim results of the long-term ice loads monitoring on the large arctic tanker. Proceedings of the 21st International Conference on Port and Ocean Engineering under Arctic Conditions, POAC'11, 2011.

Jordaan, I. 2005. *Decisions under uncertainty. Probabilistic Analysis for Engineering Decisions,* Cambridge, Cambridge University Press.

Jordaan, I. Ice crushing, damaged layers, and pressure-area relationships. POAC2009, 2009.

Jordaan, I., Li, C., Sudom, D., Stuckey, P. & Ralph, F. Principles for local and global ice design using pressure-area relationships. POAC2005, 2005 Potsdam, N.Y., 375–385.

Jordaan, I., Nessim, M., Ghoneim, G. & Murray, M. A Rational Approach to the Development of Probabilistic Design Criteria for Arctic Shipping. Proceedings of the 6th International Offshore Mechanics and Arctic Engineering Symposium, 1987.

Jordaan, I., Stuckey, P., Liferov, P. & Ralph, F. Global and local iceberg loads for an arctic floater. OTC paper 24628. Arctic Technology Conference, 2014 Houston, Texas, USA.

Jordaan, I. J. Numerical and Finite Element Techniques in Calculation of Ice-Structure Interaction. IAHR Ice Symposium, 1986 Iowa, USA.

Jordaan, I. J., Matskevitch, D. M. & Meglis, I. Disintegration of ice under fast compressive loading. Proceedings of the Symposium on Inelasticity and Damage in Solids subject to Microstructural Change

Extended version in the International Journal of Fracture 1999, 97(1–4), 279–300, 1997 Memorial University of Newfoundland. 211–231.

Juurmaa, K., Mattsson, T. & Wilkman, G. The Development of the New Double Acting Ships for Ice Operation. Proceedings of the 16th International Conference on Port and Ocean Engineering under Arctic Conditions, POAC01, 2001. 719–726.

Kaldasaun, J. & Kujala, P. Risk-Based Approach for Structural Design of Ice-Strengthened Vessels Navigating in the Baltic Sea. Proceedings of the 21st International Conference on Port and Ocean Engineering under Arctic Conditions, 2011 Montréal, Canada.

Korlie, M. S. 2007. 3D simulation of cracks and fractures in a molecular solid under stress and compression. *Computers and Mathematics,* 54, 638–650.

Krupina, N. A., Likhomanov, V. A., Chernov, A. V. & Gudoshnikov, Y. P. Full-scale ice impact study of icebreaker Kapitan Nikolaev. General description. Proceedings of the International Offshore and Polar Engineering Conference, 2009. 614–620.

Kujala, P. 1991. Safety of ice-strengthened ships in the Baltic Sea. London: Royal Institution of Naval Architects.

Kujala, P. 1994. *On the statistics of ice loads on ship hull in the Baltic.* Dissertation, Helsinki University of Technology.

Kujala, P. & Arughadhoss, S. 2012. Statistical analysis of ice crushing process. *Cold Regions Science and Technology,* 70, 1–11.

Kujala, P. & Ehlers, S. A risk-based evaluation ice-strengthened hull structures. ICETECH2014, 2014.

Kujala, P., Montewka, J. & Filipovic', A. 2014. Risk management for Arctic shipping. *SORTA.* Baska, Croatia.

Kujala, P., Valkonen, J. & Suominen, M. Maximum ice induced loads on ships in the Baltic Sea. The 10th International Symposium on Practical Design of Ships and Other Floating Structures, PRADS, 2007 Houston.

Kujala, P. & Vuorio, J. 1986. Results and statistical analysis of ice load measurements onboard icebreaker Sisu in winters 1979 to 1985. Winter Navigation Research Board.

Lau, M., Lawrence, K. P. & Rothenburg 2011. Discrete element analysis of ice loads on ships and structures. *Ships and Offshore structures,* 6, 311–221.

Laxon, S. W., Giles, K. A., Ridout, A. L., Wingham, D. J., Willatt, R., Cullen, R., Kwok, R., Schweiger, A., Zhang, J., Haas, C., Hendricks, S., Krishfield, R., Kurtz, N., Farrell, S. & Davidson, M. 2013. CryoSat-2 estimates of Arctic sea ice thickness and volume. *Geophysical Research Letters,* 40, 1–6.

Liferov, P. 2005. Ice rubble behaviour and strength: Part II. Modelling. *Cold Regions Science and Technology,* 41, 153–163.

Liferov, P., Le Marechal, G. & Albertini, M. M. Approach to Performance, Operability and Risk Assessment of the Shtokman Floating Platform in Ice. Arctic Technology Conference, 2011.

Loenhout, V. 2012. *MOORING SYSTEM.*

Masterson, D. & Tibbo, S. Comparison of Ice Load Calculations using ISO 19906, CSA, API and SNIP. Proceedings of the 21st International Conference on Port and Ocean Engineering under Arctic Conditions, 2011 Montreal, Canada.

Meglis, I. L., Melanson, P. M. & Jordaan, I. J. 1999. Microstructural change in ice: II. Creep behavior under triaxial stress conditions. *Journal of Glaciology,* 45, 438–448.

Mejlænder-Larsen, M. & Nyseth, H. 2007. Ice load monitoring RINA, Royal Institution of Naval Architects. *International Conference - Design and Construction of Vessels Operating in Low Temperature Environments–Papers.*

Melanson, P., Meglis, I., Jordaan, I. J. & Stone, B. S. 1999. Microstructural change in ice: I. Constant deformation-rate tests under triaxial stress conditions. *Journal of Glaciology,* 45, 417–437.
Moan, T., Das, P., Friis-Hansen, P., Gu, X., Hovem, L., Parmentier, G., Shigemi, T. & Spencer, J. 2006. Reliability based structural design and code development. *16th Int. Ship and Offshore Structures Congress.* Southampton University Press.
Moore, P. F., Jordaan, I. J. & Taylor, R. S. Explicit finite element analysis of compressive ice failure using damage mechanics. Proceedings of the 22nd International Conference on Port and Ocean Engineering under Arctic Conditions, 2013 Espoo, Finnland.
Mulmule, S. V. & Dempsey, J. P. 1998. A viscoelastic fictitious model for fracture of sea ice. *Mechanics of time-dependent materials,* 1, 331–356.
Niini, M., Kaganov, S. & Tustin, R. D. 2007. Development of Arctic double acting shuttle tankers for the Prirazlomnoye project. *TSCF 2007 Shipbuilders Meeting.*
Nsr. 2013. *NSR rules–Rules of navigation in the Northern Sea Route water area* [Online]. Available: http://www.mintrans.ru/documents/detail.php?ELEMENT_ID=19481, English translation available at: http://www.arctic-lio.com/docs/nsr/legislation/20130425185806en-Rules_unof.pdf.
Nsr. 2014. *Northern Sea Route Administration Office* [Online]. Available: http://asmp.morflot.ru/en/celi_funktsii.
Nyseth, H. 2006. Strain measurements on board KV Svalbard with respect to ice loading. Høvik, Norway: Det Norske Veritas.
Overland, J. E. & Wang, M. 2007. Future regional Arctic Sea ice declines. *Geophys. Res. Lett.,* 34.
Paavilainen, J., Tuhkuri, J. & Polojärvi, A. 2009. 2D combined finite–discrete element method to model multi-fracture of beam structures. *Engineering Computations,* 26, 578–598.
Paavilainen, J., Tuhkuri, J. & Polojärvi, A. 2011. 2D numerical simulations of ice rubble formation process against an inclined structure. *Cold Regions Science and Technology,* 68, 20–34.
Parsons, M. G. & Singer, D. A Fuzzy Logic Agent for Design Team Communications and Negotiations. COMPIT2000, 2000 Potsdam, Germany. 14.
Pedersen, R. A., Molnes, D. A., Stokkeland, L. S. & Ehlers, S. Structural optimisation for ice-strengthened vessels. MARTECH2014, 2014.
Polojärvi, A. & Tuhkuri, J. 2008. 3D discrete numerical modelling of ridge keel punch through tests. *Cold Regions Science and Technology,* 56, 18–29.
Popov, Faddeyev, Kheysin & Yakoviev 1967. Strength of Ships Sailing in Ice. US Army Technical Translation.
Ragner, C. 2000. Northern Sea Route Cargo Flows and Infrastructure–Present State and Future Potential. Lysaker, Norway: FNI.
Ralph, F. & Jordaan, I. Probabilistic Methodology for Design of Arctic Ships. Proceedings of the 32nd International Conference on Ocean, Offshore and Arctic Engineering (OMAE), 2013 Nantes, France.
Ranta, J., Tuhkuri, J., Paavilainen, J. & Polojärvi, A. Statistical reconstruction of peak ice load data based on 2D combined finite-discrete element method simulations of ice interactions against inclined wall. Proceedings of the 22nd IAHR International Symposium on Ice, 2014 Singapore.
Riska, K. 1995. Models of ice-structure contact for engineering applications. *Mechanics of Geomaterial Interfaces*, 77–103.
Riska, K. & Kämäräinen, J. 2012. A Review of Ice Loading and the Evolution of the Finnish-Swedish Ice Class Rules. *SNAME Transactions*.
Ritch, R. S. J., J. 1994. Ice load impact measurements on the CCGS Louis S. St. Laurent during the 1994 Arctic Ocean crossing–A trip report and data summary. *Report to Fleet Systems, Canadian Coast Guard.*
Rmrs 2010. Rules for the Classification and Construction of Sea-going ships.
Rmrs 2014. Russian Maritime Register of Shipping–Rules for the Classification Surveys of Ships in Service.
Romanov, I. P. 1995. *Atlas of Ice and Snow of the Arctic Basin and Siberian Shelf Seas*.
Rosa 2014. Rosatomflot.
Sain, T. & Narasimhan, R. 2011. Constitutive modeling of ice in the high strain rate regime. *International Journal of Solids and Structures,* 48, 817–827.
Sawamura, J., Riska, K. & Moan, T. Finite Element Analysis of Fluid-Ice Interaction during Ice Bending. 19th IAHR International Symposium on Ice, 2008 Vancouver, B.C., Canada. 12.
Schapery, R. A. 1997. Linear elastic and viscoelastic deformation behaviour of ice. *Journal of Cold Regions Engineering,* 11, 271–290.
Shi, W. B. 1992. In-Service Assesment of Ship Strctures: Effecto of General Corrosion on Ultimate Strength. *RINA Spring Meeting.*
Stroeve, J. C., Kattsov, V., Barrett, A., Serreze, M., Pavlova, T., Holland, M. & Meier, W. N. 2012. Trends in Arctic sea ice extent from CMIP5, CMIP3 and observations. *Geophysical Research Letters,* 39, 28.
Stuckey, P., Ralph, F. & Jordan, I. Iceberg Design Load Methodology. ICETECH08, 2008 Banff, Canada.
Su, B., Riska, K. & Moan, T. 2011. Numerical study of ice-induced loads on ship hulls. *Marine Structures*, 1–21.
Suominen, M., Karhunen, J., Bekker, P., Kujala, P., Elo, M., Von Bock, R.F., Polach, R., Endlund, H. & Saarinen, S. Full-scale measurements on board PSRV S.A. Agulhas II in the Baltic Sea. Proceedings of the 22nd International Conference on Port and Ocean Engineering under Arctic Conditions (POAC), 2013 Espoo, Finnland.
Suominen, M. & Kujala, P. Ice Model Tests in Compressive Ice. Proceedings of the 21st IAHR International Symposium on Ice, 2012 Dalian, China.

Suominen, M., Kulovesi, J., Lensu, M., Lehtiranta, J. & Kujala, P. A Comparison of Shipborne Methods for Ice Thickness Determination. 22nd IAHR International Symposium on Ice, 2014 Singapore.

Suominen, M. K., P. 2014. Variation in short-term ice-induced load amplitudes on a ship's hull and related probability distributions. *Cold Regions Science and Technology,* 106, 131–140.

Taylor, R. S., Jordaan, I. J., Li, C. & Sudom, D. 2010. Local design pressures for structures in ice: Analysis of full-scale data. *Journal of Offshore Mechanics and Arctic Engineering,* 132, 1–7.

Tõns, T., Freeman, R., Ehlers, S. & Jordaan, I. Probabilistic design load method for the Northern Sea Route. submitted to OMAE2015, 2015a.

Tõns, T., Ralph, F., Ehlers, S. & Jordaan, I. Probabilistic Design Load Method for the Northern Sea Route. submitted to OMAE2015, 2015b St. Johns, Canada.

Valkonen, J. Uncertainty of a methodology to estimate global ship loads during interaction events with ice features. Proceedings of the 22th International Conference on Port and Ocean Engineering under Arctic Conditions, POAC'13, 2013.

Valkonen, J., Izumiyama, K. & Kujala, P. Measuring of ice induced pressures and loads on ships in model scale. Proceedings of the 10th International Symposium on Practical Design of Ships and Other Floating Structures, PRADS2007, 2007. 1206–1213.

Van Der Nat, R. R. 2012. Developing a turret mooring system for arctic FPSO units. *Arctic Technology Conference.* Houston, Texas, USA.

Von Bock Und Polach, R. F. & Ehlers, S. 2013. Model Ice as Material B: Numerical Modeling. *Cold Regions Science and Technology,* 94.

Von Bock Und Polach, R. F. & Ehlers, S. On the scalability of model-scale experiments. Proceedings of the 33rd International Conference on Ocean, Offshore and Arctic Engineering. OMAE 2014, 2014 San Francisco, CA, USA.

Von Bock Und Polach, R. F., Ehlers, S. & Erikstad, S. O. 2014. A Decision-based Design Approach for Ships Operating in Open Water and Ice. *Journal of Ship Production and Design,* 30, 1–11.

Von Bock Und Polach, R. F., Ehlers, S. & Kujala, P. 2013. Model Ice as Material A: Experiments. *Cold region Science and Technology,* 94.

Yu, B., Wu, W., Xu, N., Yue, Q. & Liu, S. Numerical Simulation of Dynamic Ice Forces on Conical Structures. Proceedings of the 19th International Conference on Port and Ocean Engineering Under Arctic Conditions, 2007 Dalian, China. 277–285.

Zhang, S., Bridges, R. & Tong, J. Fatigue design assessment of ship structures induced by ice loading–an introduction to the shipright fda ice procedure. Proceedings International Offshore and Polar Engineering Conference, ISOPE, 2011 Maui, USA.

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COMMITTEE V.6

ARCTIC TECHNOLOGY

Annex

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.

COMMITTEE MEMBERS

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F. Cheng, *UK*
I. Jordaan, *Canada*
W. Kuehnlein, *Germany*
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KEYWORDS

Ship and offshore structures in ice, rule-based and first principal-based ice loads, mission-based design

CONTENTS

1. BRIEF OFFSHORE STRUCTURES CODE SUMMARIES

This section summaries the different offshore codes including International (ISO), American (API), Canadian (CSA), Russian (SNIP and VSN), Norwegian (NPD and NORSOK), as well as Class Society (DNV and LR) in a Table 1 to 14 (see also Allan et al. 2000). The CSA and ISO Standards have many similarities with care taken in writing the ISO standard to consider methods used in the SNiP code.

Table 1. CSA S471-04.

Design loads:

- Performance based reliability approach to design as with ISO. Two key safety classes (1 and 2) considered based on risk of loss of life and environmental damage. Annual reliability targets set in each case
- Probabilistic and deterministic methods.
- Offshore environment data has considerable detail.
- Loads based on full scale data and actions.
- Full range of ice models and ice types considered.

Structural design:

- Structural design based on Limit State method–load factors and material resistance factors used to achieve safety targets.
- Two limit states include Ultimate Limit State (two safety Classes depending on risk to personnel and environment) and Serviceability Limit State (interruption to operations).

Loads and Load Combination:

- Load categories include: dead (G_D), deformation (G_R), operational (Q), and Accidental (A) and Environmental (E_f & E_r for ***freq***–wind/waves–and ***rare***–iceberg/earthquake) loads.
- Load combinations are illustrated in Table 10.

Table 2. ISO19906.

Design loads:

- Performance based approach to design–overall safety targets set and guidance to achieve targets. Target reliability levels reflect consequence of failure through loss of life, and severity of environmental loading considering Extreme Level and Abnormal Level Ice load Events (ELIE and ALIE).
- Both probabilistic and deterministic calculations are considered.
- Offshore environment has considerable detail.
- Loads are based on full scale data and actions from monitoring of offshore structures not small scale data–Beaufort Sea, Cook Inlet, Baltic Sea, Gulf of Bohai, Sea of Okhotsk.
- Full range of modern ice load models.
- Full range of ice conditions considered (FY level, FY ridges, MY floes, MY ridges, icebergs).

Structural design:

- Structural design based on Limit State method–load factors and material resistance factors used to achieve safety targets.
- Limit states correspond to ELIE and ALIE allowing robust design.
- limit states considered include Ultimate Limit State (plastic design without loss of life or environmental damage) and Serviceability Limit State (elastic design with limited plasticity where operations may be interrupted), Fatigue Limit State and Accidental Limit State.

Loads and Load Combination:

- Where data are available, joint probability distributions of the principal (i.e. ELIE and ALIE) and relevant companion actions should be used to determine magnitude of combined EL or AL environmental actions.
- In absence of joint probability data, companion EL and AL factors are recommended depending on whether companion actions are stochastically dependant or independent of the principal action
- Principal and companion factors are given in Table 8.
- Action factors and combinations are listed in Table 9. Load categories include: permanent action dead (G_1) and, deformation (G_2), variable action long duration (Q_1) and short duration (Q_2), Environmental action Extreme Level (EL) and Abnormal Level (AL) and Accidental (A).

Table 3. API RP 2N.

Design loads:
- Probabilistic and deterministic methods.
- Do not explicitly define safety classes or reliability targets although annual probability of failure for structure designed to API RP 2A is approximately 1.5×10^{-5} (Nevel, 1997).
- Consideration given to personnel safety compliance with existing regulations and pollution prevention
- Offshore environment has considerable detail.
- Loads based on full scale data and actions.
- Full range of ice models and ice types considered.
- Doesn't consider the effect of aspect ratio on global pressures on wide structures.
- Doesn't account for reduced pressure for increased thickness.
- No provision for pack ice driving force.

Structural design:
- Structural design has option for using Load and Resistance Factor Design (LRFD) based on API RP 2A Working Stress Design (WSD)–calibration based on component design practices in the GoM; waves being the predominant environment hazard.
- Two specified load cases for ice loads: 1) frequent events; and 2) infrequent events.

Loads and Load Combination:
- Load categories include: Gravity dead (permanent D_1 and semi-permanent D_2 changing from one ops mode to another), Gravity live (consumables, L_1 and short duration, L_2 loads e.g. crane loads), Wind, Wave and Current (extreme W_e, operating W_o, inertial D_n), ice operational (I_{OP}), ice frequent (I_F), Ice rare (I_R), Earthquate (E) and Fabrication.
- Combinations are illustrated in Table 11.

Table 4. SNiP & VSN.

Design loads:
- Offshore is extension of methods for bridge and port infrastructure design in rivers.
- Offshore environment not specifically addressed.
- Only two types of ice loads considered: level ice and ridges.
- Loads based on small scale tests and factored to obtain global ice pressures.
- Provision of loads use semi-probabilistic methods.
- Return period for extreme environmental loads is not specified.
- Target level for structural reliability is not clear.
- No provision for driving forces which may limit ultimate loads on facility (i.e. loads may be quite conservative).

Structural design:
- Structural design considers two limit states: whether the limit state leads to 1) cessation in operations–Loss of platform and operation due to foundation sliding, or structural collapse, or 2) no cessation–no loss of normal operations due to loss of local strength.

Loads and Load Combination:
- Constant permanent loads (e.g. self-weight, and soil pressure), and Temporary loads a) Long Term operational, b) Short Term Environmental, and c) Special (extreme environment, earthquake or explosive)
- Combinations are illustrated in Table 12.

Table 5. NPD.

Design loads:
- Do not distinctively specify safety classes. Requirements are stipulated to maintain and further develop an adequate level of safety for people, environment, assets, and financial interests. Three reliability levels representing degree of exposure include Low (10^{-3}), Medium (10^{-5}), and High (10^{-7}).

Structural design:
- Four categories of limit states: Serviceability Limit State, Fatigue Limit State, Ultimate Limit State, Limit State for Progressive Collapse.

Loads and Load Combination:
- Loads classified as permanent loads, variable functional loads, environmental loads, and accidental loads.
- Combinations are summarized in Table 13.

Table 6. NORSOK.

Design loads:
- Standards include as far as possible provision of teh NPD.
- Loads defined and classified according to ISO 13819-1.
- Limit states or Load and Resistance Factor Design (LRFD).

Structural design:
- Principles referenced according to ISO 13819-1.
- May consider reliability design method provided it can be documented that the method is theoretically justified and provision is made for adequate safety in typical known cases. For Norwegian petroleum activities, the decision to use reliability based methods for design sits with the NPD.

Loads and Load Combination:
- Loads and load effects are referenced according to NPD guidelines, DNV Class. Note No. 30.5 and API RP 2N.
- Combinations are summarized in Table 13 and 14.

Table 7. DNV.

Design loads:
- Probabilistic and deterministic considerations.
- Safety classes are not specified. Rules do state that structures are to be designed to maintain acceptable safety for personnel and environment.
- Minimum target reliability levels are to be established based on calibration against well-established cased know to have adequate safety.

Structural design:
- Structural design methods include: Partial Coefficient Method, Allowable Stress Method, Reliability/Probabilistic Analysis, design by testing or observation of performance.

Loads and Load Combination:
- Loads and load effects are referenced according to NPD guidelines.

Table 8. ISO Combination factors for Companion EL environmental processes.

Principal Action	Factor for EL companion environmental action	
	Companion action stochastically dependent of principal action	Companion action stochastically independent of principal action
EL Action	0.9	0.6
AL Action	0.5	0.4

Table 9. ISO Exposire levels L1 and L2–ULS and ALS action factors and action combinations.

Action Combination	Limite State Action Factors						
	Permanent		Variable		Enviornmental		Accidental
	G_1	G_2	Q_1	Q_2	EL	AL	A
			Ultimate Limite State				
1 Gravity and deformation–short and long duration	1.3^a or 0.9	1	1.5^a	1.5^a	0.7	-	-
2 Extreme environ-	1.1^a or 0.9^b	1	1.1^a or 0.8^b	-	1.35 (L1)^{cd}	-	-

mental					0.9 (L2)[cde]		
3 Damaged condition[f]	1.1[a] or 0.9[b]	1	1.1[a] or 0.8[b]	-	1	-	-
			Abnormal (accidental) Limite State				
4 Abnormal environ-mental	1	1	1	-	-	1[c]	-
2 Accidental	1	1	1	-	-	-	1

a. For the gravity and deformation action combination, a partial action factor of 1,20 may be used for permanent hydrostatic pressure and for physically limited variable actions.

b. The lower partial action factor applies for permanent G_1 actions when the permanent action resists overturning or uplift, and for variable Q_1 actions when there is a reversal of variable action effects.

c. The representative value of the environmental action to which the action factor applies shall be calculated as described in 7.2.3.

d. The limit state partial action factor for the extreme-level seismic action (ELE) shall be as defined in ISO 19902 for steel structures and shall be as defined in ISO 19903 for concrete structures. The partial action factor for the ELE shall be 1,0 for all other structures.

e. For L2 exposure level, all action factors for all action combinations are as for L1 except for the EL factor in the extreme environmental action combination.

f. Damaged condition or progressive collapse limit states are defined generally for structures in ISO 19900 and for particular types of structures in ISO 19902, ISO 19903 and ISO 19904-1.

Table 10. CSA–S471 Load Combinations.

Loads:		Permanent Dead	Deform	Live	Environmental Freq.	Rare	Accidental
Safety Class 1	ULS1	1.25	1	0.7	-	-	-
	ULS2	1.05/0.9	1	1	1.35	-	-
	ULS3	1.05/0.9	1	1	-	1	-1
	ULS4	1.05/0.9	1	1	-	-	1
Safety Class 2	ULS5	1.05/0.9	1	1	0.9	-	-
	ULS6	1.05/0.9	1	1	-	1	-
Section Strength (concrete)	ULS7	1.05/0.9	1	1	-	1.35	-
Fatigue (steel)	ULS8	1	1	1	1	-	-
Fatigue (concrete)	ULS9	1	1	1	0.7	-	-
Servicability limited state		1	1	1	0.7/1	-	-

Table 11. SNiP Load Combinations.

Limite State/ Load Combination	Constant	Temporary long term	Temporary short term	Special	T1	T2	T2
Main Comb. 1	1	0.95	0.9	-	-	-	-
Main Comb. 2	1	1	-	-	-	-	-
Main Comb. 3	1	1	-	-	1	0.8	0.6
Special Comb.	1	0.95	-	0.8	-	-	-

Table 12. NPD Load Combinations.

Limite State	Permanent	Variable functional loads	Environmental loads	Deformation loads	Accidental loads
Ultimate a	1.3	1.3	0.7	1	-

Ultimate b	1	1	1.3	1	-
Serviceability	1	1	1	1	-
Fatigue	1	1	1	1	-
Progressive Collapse	1	1	1	1	1

Table 13. NORSOK Load Combinations–in addition to NPD (m- mean water level; m*–mean water level including storm flood).

Limite State	Wind	Waves	Current	Ice	Snow	Earthquake	Sea Level
Ultimate	10^{-2}	10^{-2}	10^{-1}	-	-	-	10^{-2}
	10^{-1}	10^{-1}	10^{-2}	-	-	-	10^{-2}
	10^{-1}	10^{-1}	10^{-1}	10^{-2}	-	-	m
	-	-	-	-	10^{-2}	-	m
	-	-	-	-	-	10^{-2}	m
Progressive	10^{-4}	10^{-2}	10^{-1}	-	-	-	m*
	10^{-2}	10^{-4}	10^{-1}	-	-	-	m*
	10^{-1}	10^{-1}	10^{-4}	-	-	-	m*
	-	-	-	10^{-4}	-	-	m
	-	-	-	-	-	10^{-4}	m

Table 14. API Load Factors and Combinations.

Limite State/ Load Combination	D_1	D_2	L_1	L_2	D_n	W_0	W_e	I_{OP}	I_F	I_R	E
Case 1 Operating Wave	1.3	1.3	1.5	1.5	1.5	1.2	-	-	-	-	-
Case 2 Operating Ice	1.3	1.3	1.5	1.5	1.5	-	-	1.2	-	-	-
Case 3 Extreme Wind, Wave, and Current	1.1 0.9	1.1 0.9	1.1 0.8	-	1.7	-	1.35	-	-	-	-
Case 4 Design ice load, frequent events	1.1 0.9	1.1 0.9	1.1 0.8	1	1.7	-	-	-	1.35	-	-
Case 5 Design ice load, rare events	1.1 0.9	1.1 0.9	1.1 0.8	1	1.7	-	-	-	-	1	-
Case 6 Earthquake load	1.1 0.9	1.1 0.9	1.1 0.8	1	-	-	-	-	-	-	-

2. FULL SCALE ICE LOAD MEASUREMENT CAMPAIGNS

This section seeks to summarize the full scale measurement campaignes carried out world wide in the past in Table 15 to 18 without any claim to be complete.

Table 15. Baltic Sea.

Project	Possesion of data	Sea Area	Content of the data
IB URHO, 1976	VTT	Baltic Sea	Stresses during ice trials
IB SISU, 1978-85	VTT, AALTO	Bay of Bothnia	Stresses, loads and pressures during service; bow and bow shoulder areas
References: Kujala and Vuorio (1986)			
MT IGRIM, 1978	VTT	Bay of Bothnia	Stresses and ice pressures on ship bow and bow shoulder during ice trials
References: Korri and Varsta (1979)			

MS KEMIRA and1985-91	AALTO, VTT	Baltic Sea	Stresses and loads during service; bow, mid aftship frame
References: Kujala (1989), Muhonen (1992)			
MT KASHIRA 1984-90	VTT, AALTO	Gulf of Finland	Stresses and loads during service; bow areas
References: Kujala (1994), Lensu and Hänninen (2003)			
MS ARCTURUS 1983-88	VTT, AALTO	Gulf of Finland	Stresses and loads during service; bow areas
References: Kujala (1994), Lensu and Hänninen (2003)			
MT UIKKU 2001, 2003	AALTO, Arcdev	Gulf of Finland	Stresses and load during service and ice trials; mid, aft, continuous time series
References: Lensu (2002), Kujala et al. (2009)			
NEUWERK 1999	HSVA, FHK	Gulf of Bothnia	Stress and ice loads during ice trials and transits; aft shoulder area
IB OTSO, 2005	AALTO	Bay of Bothnia	Ice loads during service; bow, continuous time histories
SA AGULHAS II	AALTO	Bay of Bothnia	Stresses and ice load on ship bow, bow shoulder and stern shoulder during ice trials
References: Suominen et al. (2013)			

Table 16. Arctic Sea (1/2).

Project	Possesion of data	Sea Area	Content of the data
WERDERTOR loads measurements, 1977	GL	Spitsbergen	Stresses and ice loads during ice trials; bow ice shoulder area
RV AKADEMIK FEODOROV, 1991, 1994	VTT, AARI	Russian Arctic	Ice loads on ship bow and mid-body
CANMAR KIGORIAK, 1979 Reference: Dome (1982)	VTT, AALTO	Canadian Arctic	Ramming trials where local bow loads were measured
MV ARCTIC 1984, 1981	CCG, VTT	Canadian Arctic	Total ice load in ramming and local forces on ship bow
MT KASHIRA 1984–90	VTT, AALTO	Russian Arctic	Stresses and loads during service; bow areas
USCGC Polar Sea 1982, autumn Reference: Daley et al. (1990)	NRC, USCGC	Beaufort Sea	Bow, 167 events
USCGC Polar Sea 1983, March Reference: Daley et al. (1990)	NRC, USCGC	South Bering Sea	Bow, 172 events
USCGC Polar Sea 1983, March-April Reference: Daley et al. (1990)	NRC, USCGC	South Bering Sea, North Bering Sea, South Chukchi Bering Sea, North Chukchi	Bow 1225 events Bow
USCGC Polar Sea 1985 September and October Reference: Minnick et al. (1990)	NRC, USCGC	Beaufort Sea	40 Global ram events with MY ice
USCGC Polar Sea 1986, March Reference: Daley et al. (1990)	NRC, USCGC	Bering Sea	Bow, 653 events

POLARSTERN 1984	GL	Labrador	Stress and ice loads during ice trials and transits; bow shoulder area, nozzle ring; superstructure
POLARSTERN 1984	HSVA	Labrador	Loads on ca. 1m^2 pannel in bow area during ice trials and transits, load statistics
POLARSTERN 1985	GL	Spitzbergen	Stress and ice loads during ice trials and transits; bow shoulder area, nozzle ring; superstructure
POLARSTERN 1985	HSVA	Spitzbergen	Loads on ca. 1m^2 pannel in bow area during ice trials and transits, load statistics
MUDZUG (Thyssen/Waas) strain and acceleration, 1987	GL	Spitzbergen	Stress and ice loads during ice trials and transits; bow area
MUDZUG (Thyssen/Waas) strain and acceleration, 1987	HSVA	Spitzbergen	Loads on ca. 0.25m^2 pannel in bow area during ice trials and transits, load statistics
KAPITAN SOROKIN (T/W) strain and acceleration measurements, 1991	GL	Kara Sea, Yenessey Esturary	Stress and ice loads during ice trials and transits; bow area

Table 17. Arctic Sea (2/2).

Project	Possesion of data	Sea Area	Content of the data	References
Louis S. St. Laurent, 1980	NRC	Labrador Sea, Davis Straight, Baffin Bay		
Reference: Glen et al. (1981)				
Louis S. St. Laurent, 1994	NRC	Polar transit	Bow; 30 subpanels, 1730 events. Shoulder; 12 subpanels, 1289 events Bottom; 11 sub-panels over area, 48 events	
References: Ritch and St.John (1994), Frederking and Collins (2005)				
Oden, 1991	NRC	North Pole Voyage	Bow and bow girder 786 events	
References: St. John and Minnick (1993), Frederking and Collins (2005)				
Oden, 1996	NRC	North Pole Voyage	Bow, 1172 events and side, 1135 events	
References: St. John and Minnick (1993), Frederking and Collins (2005)				
MT UIKKU, 1998	AALTO, Arcdev	Russian Arctic	Stresses and load during service and ice trials; bow, mid, aft	
Reference: Kotisalo and Kujala (1999)				
IB Teshio 1998, February	NMRI, JCG	Sea of Okhotsk	Stress and ice load measurements at 5 locations along the hull	
IB Teshio 1999, February	NMRI, JCG	Sea of Okhotsk	Stress and ice load measurements at 5 locations along the hull	
USCGC HEALY 2000	AALTO	Baffin Bay Davis Strait	Loads during ice trials; bow shoulder 1800 events; transom, 1660 events	
Reference: Hänninen et al. (2001)				
POLARSTERN 2002 ff	Laeisz, FHB	Arctic	Stress and ice loads during service bottom area	
Large tanker 2010		Russian Arctic		
Reference: Iyerusalimskiy et al. (2011)				
KV Svalbard	DNV, NTNU	Spitsbergen		
Reference: Mejlænder-Larsen and Nyseth (2007)				

Table 18. Antarctic Sea.

Project	Possesion of data	Sea Area	Content of the data	References
RV AKADEMIK FEODOROV, 1991, 1994	VTT, AARI	Antarctica	Ice loads on ship bow and midbody	
POLARSTERN 2002 ff	Laeisz, FHB	Antarctica	Stress and ice loads during service bottom area	
SA AGULHAS II 2013, 2014	AALTO	Antarctica	Stresses and ice load on ship bow, bow shoulder and stren shoulder during ice trials	
USCGC Polar Sea 1984 References: Daley et al. (1990), Frederking and Collins (2005)		Antarctica	Bow, 310 events	

3. REFERENCES

Daley, C., St.John, J. W., Brown, H. & Glen, I. 1990. Ice forces and Ship Response to Ice–Consolidation Report. Report for Ship Structures Committee.

Dome 1982. Full Scale Measurements of the Ice Impact Loads and Response of the Canmar Kigoriak. August and October, 1981. Prepared by Dome Petroleum Limited.

Frederking, R. & Collins, A. 2005. NRC Catalogue of Local Ice Pressures (CLIP). Canadian Hydraulics Centre Technical Report.

Glen, I., Blount, H., Comfort, G. & Tam, G. 1981. Measurement of Ice Impact Pressures and Loads Onboard CCGS Louis S. St. Laurent during a 1980 Fall Arctic Probe. Report for Canadian Coast Guard by ARCTEC Canada Ltd.

Hänninen, S., Lensu, M. & Riska, K. 2001. Analysis of the Ice Load Measurements During USCGC Healy Ice Trials. Spring 2000. Helsinki University of Technology, Espoo, Ship Laboratory.

Iyerusalimskiy, A., Choi, J., Park, G., Kim, Y., Yu, H. & St. John, J. The interim results of the long-term ice loads monitoring on the large arctic tanker. Proceedings of the 21st International Conference on Port and Ocean Engineering under Arctic Conditions, POAC'11, 2011.

Korri, P. & Varsta, P. 1979. On the ice trial of a 14500 DWT tanker on the Gulf of Bothnia.

Kotisalo, K. & Kujala, P. Ice load measurements onboard MT Uikku during the Arcdev voyage. POAC'99, 1999 Espoo, Finland. 974–987.

Kujala, P. 1989. Results of Long-Term Ice Load Measurements on Board Chemical Tanker Kemira in the Baltic Sea during the Winter 1985 to 1988. Winter Navigation Research Board.

Kujala, P. 1994. *On the Statistics of Ice Loads on Ship Hull in the Baltic. Dissertation.* Dissertation, Helsinki University of Technology.

Kujala, P., Suominen, M. & Riska, K. Statistics of ice load measured on MT Uikku in the Baltic Sea. POAC2009, 2009 Luulaja, Finnland.

Kujala, P. & Vuorio, J. 1986. Results and statistical analysis of ice load measurements onboard icebreaker Sisu in winters 1979 to 1985. Winter Navigation Research Board.

Lensu, M. 2002. Short Term Prediction of Ice Loads Experienced by Ice Going Ships. Espoo, Finnland: Helsinki University of Technology, Ship Laboratory.

Lensu, M. & Hänninen, S. Short Term Monitoring of Ice Loads Experienced by Ships. 17th International Conference on Port and Ocean Engineering under Arctic Conditions, POAC'03, 2003 Trondheim, Norway. 535–544.

Mejlænder-Larsen, M. & Nyseth, H. 2007. Ice load monitoring RINA, Royal Institution of Naval Architects. *International Conference–Design and Construction of Vessels Operating in Low Temperature Environments–Papers.*

Minnick, P., St.John, J., Cowper, B. & Edgecombe, M. 1990. Global Ice forces and Ship Response to Ice. *Report for Ship Structures Committee.*

Muhonen, A. 1992. Ice Load Measurements on Board MS Kemira. Winter 1991. Espoo, Finnland: Helsinki University of Technology, Ship Laboratory.

Ritch, R. & St.John, J. 1994. Ice load impact measurements on the CCGS Louis S. St. Laurent during the 1994 Arctic Ocean crossing–A trip report and data summary. *Report to Fleet Systems, Canadian Coast Guard.*

St. John, J. & Minnick, P. 1993. Swedish icebreaker Oden ice impact load measurements during International Arctic Ocean Expedition 1991; Instrumentation and measurement summary. *STC Technical Report 2682 to U.S Coast Guard Headquarters.*

Suominen, M., Karhunen, J., Bekker, P., Kujala, P., Elo, M., Von Bock Und Polach, R. F., Endlund, H. & Saarinen, S. Full-scale measurements on board PSRV S.A. Agulhas II in the Baltic Sea. Proceedings of the 22nd International Conference on Port and Ocean Engineering under Arctic Conditions (POAC), 2013 Espoo, Finnland.