18th INTERNATIONAL SHIP AND
OFFSHORE STRUCTURES CONGRESS

09-13 SEPTEMBER 2012
ROSTOCK, GERMANY

VOLUME 2

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 infested 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

Chairman: George Wang
        Alexie Bereznitski
        Wim C. de Boom
        Claude Daley
        Frank W. DeBord
        Shunyin Ji
        Joong K. Kang
        Per R. M. Lindstrom
        Per O. Moslet
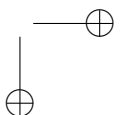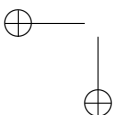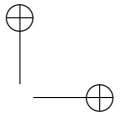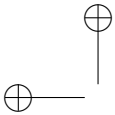   Jukka Tuhkuri
        Akio Usami
        In S. Yoo

KEYWORDS

Arctic structures, ice loads, ice class rules, arctic environment.

CONTENTS

1   INTRODUCTION

During the late 1970's and early 1980's, the interest in Arctic research and development was very high due to anticipated resource development. In the late 1980's, the interest in Arctic development dropped and consequentially the volume of related R&D declined to a minimum. This trend changed in the late 1990's and early 2000's when global warming became a global topic of interest. Evidence reveals that the ice cap in the Arctic has been shrinking year by year. The Northern Sea Route (NSR), which was historically impassable, has been opened up for a small number of commercial ships during summer time. Recently, the USA government announced permitting further drilling in certain areas offshore Alaska. All these may imply the coming of another boom of Arctic development.

These recent demands resulted from interest in exploring for oil and gas in the Arctic and the potentials of commercial shipping using the Arctic routes. Figure 1 shows the Arctic ice cap that has been found to be retreating year by year. Accompanying this trend, research on ice-going ships and Arctic structures has also been revived.

Of particular importance to the R&D community are:

- Development of ice class rules and recommendation: Finnish-Swedish Ice Class Rules (FSICR), IACS Polar Class Rules, ISO 19906 Arctic Offshore Structures
- Application of risk assessment to supplement rules
- Ice loads measurement, prediction, and simulation
- Design and innovation of ice-going ships and Arctic structures
- Expanded scope of research to include winterization, escape, evacuation and recovery (EER), recovery of spilled oils, ice management

This Committee intends to cover recent R&D activities that are directly related to hull structural designs. Emphasis is therefore placed on:

- Design of ice-going ships and Arctic structures
- Rules, regulations and design guidance
- Ice loads and simulation of ice
- Application of structural reliability approaches (SRA)

This committee report concludes with recommendations for future research.

Figure 1: Arctic   ice   cap   (http://mapas.owje.com/maps/10540_arctic-satellite-map.html)

2   ENVIRONMENT AND CLIMATE CHANGE

As far as structural safety of ice-going ships and Arctic structure is concerned, climate change (or global warming) would cast the following questions related to the current design practice:

- Are the existing rules, regulations and guidance adequate to address the structural design at time of changing climate?
- What changes will climate change bring to current design practice? Specially, will design ice loads increase or decrease?
- Are we prepared for the potential risks associated with the increased number and frequency of ships navigating in the Arctic region due to the extended navigational season and also the risk associated with cruise vessel visiting remote areas in the Arctic?
- What must be done to minimize and mitigate potential environmental impact of Arctic shipping and Arctic structures on the pristine environment in the Arctic?

2.1   Changing Sea Ice in the Arctic

According to the National Snow and Ice Data Center, Arctic sea ice extent is declining at a rate of 3.5% per decade. The five lowest December extents in the satellite record have occurred in the past six years (Figure 2). Particularly, the Arctic ice cap in summer 2007 was $4.2 \cdot 10^6\,km^2$, which marked the lowest record (23% less than the high record of September 2005). Some studies estimate that the Arctic could become ice-free during the summer months in a few decades (Wang *et al.*, 2009). Reports also suggest increasing variability in ice extent than before.

In-situ measurements have reported that ice of the Arctic has been thinning (Rothrock *et al.*, 1999). Substantial amounts of older perennial ice have been observed drifting out of the Arctic through the Fram Strait (Rigor and Wallace, 2004).

These environmental changes may result in a need for re-evaluation of ice loads that are the basis of structural design. So far, there is only very limited research on the potential changes in ice loads based on the long-term decreasing trend in measured peak ice loads (Matsuzawa *et al.*, 2010). Melting ice gives rise to the likelihood of iceberg collision (Hill, 2006), which has not been adequately addressed in the existing design codes or safety regulations.
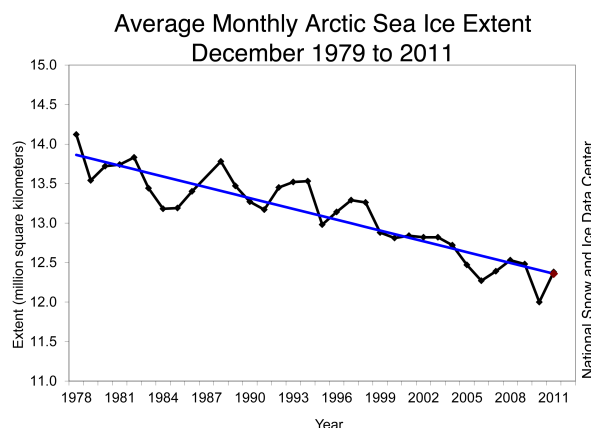

Figure 2: Decline of Arctic sea ice extent (http://nsidc.org/arcticseaicenews/)

2.2 Environmental Concerns

Commercial shipping and offshore rigs in the Arctic also raise significant concerns over oil spillage. Ice and cold temperature will make it very difficult to contain and recover spilled oil as most of current technologies will not be effective in cold water. The current MARPOL Convention Annex I does not designate the Arctic Sea as "*Special Area*" where un-conventional means of oil spill protection are required. This may become an issue for Arctic shipping and Arctic exploration.

3 ARCTIC SHIPS

3.1 Overview

The diverse range of activities in the Arctic and Antarctic, like increased shipping and oil and gas developments, requires (will require) operation of a wide range of vessel types and sizes. Operational experience to date has primarily been limited to escort and research icebreakers and relatively small cargo ships, coastal tankers and bulk carriers. Recently built icebreaking tankers have deadweight capacities less than 100,000 tonnes even though much larger sizes have been proposed for tankers, LNG carriers and bulk carriers since the early 1970s. Commercial resource developments will also require supply vessels, tugs, and dedicated icebreakers. Finally, governments intending to enforce laws and provide emergency response will need a year-round presence in all areas with commercial development and along proposed shipping routes. A variety of different vessels will be required to satisfy these needs.

Because these vessels are (will be) designed to operate in a wide range of ice conditions and climates, some operators will elect to operate year-round and others will choose seasonal operations. Depending on the specific geographic area of operation and season, design ice conditions could include:

- Open water with occasional small, thin ice floes
- First year ice with coverage from 5 to 100 % and thicknesses from several centimetres to two meters
- Compact first-year ice with large pressure ridges and rafting
- Thick multi-year ice with weathered consolidated pressure ridges

Other possible operating conditions would include open water with occasional large ice features such as icebergs, bergy-bits, growlers or ice floes.

3.2 Research and Development of 1990's and 2000's

The last time ISSC had a committee on Arctic technology was more than 20 years ago. Since then, IACS Polar Class Rules have been developing and the Finnish-Swedish Ice Class Rules have been refined. The development of these rules was supported by the results of the projects HELCOM, SAFEICE, BARENTS 2020 and others. In addition, commercial organizations have invested significant resources in research and development projects related to oil and gas exploitation in ice-infested seas in Russia and Alaska.

3.3 Arctic Vessel Design

This section uses an example to illustrate the design of Arctic vessel. The focus is placed on the design basis including selection of ice class and comparison between different ice classes.

Figure 3 shows the concept of a modern Arctic tanker design. A variety of issues must be addressed during design, including but not limited to ice-breaking bow design, ice-strengthening of hull structures, propulsion system designs, winterization of hull and
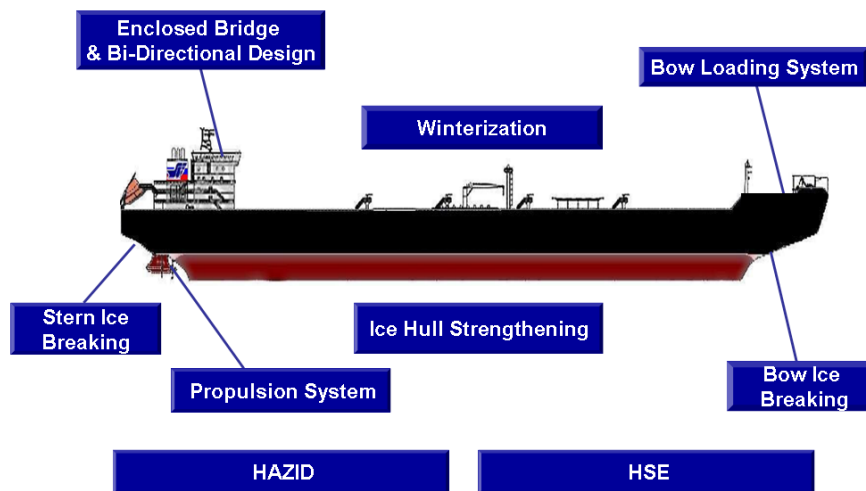
Figure 3: Concept of an Arctic tanker (modified from Kwak *et al.*, 2010)

machinery systems, bridge design, comfort of crew and passenger, and operation in cold environment (Kwak *et al.*, 2010; Dolny *et al.*, 2010). This section only addresses structural design.

3.3.1 Ice Class

The tanker shown in Fig. 3 was intended for year-round operations in the Barents Sea without ice breaker support. According to RMRS Ice Class Rules (see also Section 5.4), the ice class was selected to be ARC 6. The corresponding ice class in IACS PC (see also Section 5.3) is PC 4. Therefore, this tanker was also re-designed to satisfy IACS Polar Class rule PC 4.

3.3.2 Ice Loads

Table 1 shows the ice pressure that PC 4 and ARC 6 specify for design of plating/stiffeners (or local pressure as discussed in Section 7.1). The ice pressure of PC 4 is slightly higher than that of ARC 6, while the ice loads (patch load) of PC 4 are much smaller than ARC 6. This was not fully expected as normally it is believed that ice loads levels for ARC 6 and PC 4 are the same.

Table 1: Design ice loads of PC 4 and ARC 6 (Kwak *et al.*, 2010)

(a) IACS Polar Rule

Ice strengthening structure areas by side depth		Ice strengthening structure area by hull length			
		B	BI	M	S
ice pressure [MPa]	Icebelt	6.70	5.36	3.58	3.91
	Lower	6.70	4.02	2.28	1.95
	Bottom	6.70	2.68	0.00	1.63
The vertical distribution of ice pressure b [m]		b_B	b_BI	b_M	b_S
		0.90	0.90	1.24	1.24
Horizontal distribution of ice pressure lp [m]		w_B	w_BI	w_M	w_S
		4.24	4.24	4.45	4.45

(b) RMRS Rule

Ice strengthening structure areas by side depth		Ice strengthening structure area by hull length			
		p_A	p_A1	p_B	p_C
ice pressure [MPa]	I	6.55	5.77	3.27	3.27
	II	4.26	3.75	1.64	1.64
	III	4.26	3.75	1.47	1.14
	IV	3.28	2.89	0.00	0.49
The vertical distribution of ice pressure b [m]		b_A	b_Ai	b_B	b_C
		1.10	1.20	1.65	1.32
Horizontal distribution of ice pressure lp [m]		l_A	l_Ai	l_B	l_C
		11.09	10.73	9.87	7.90
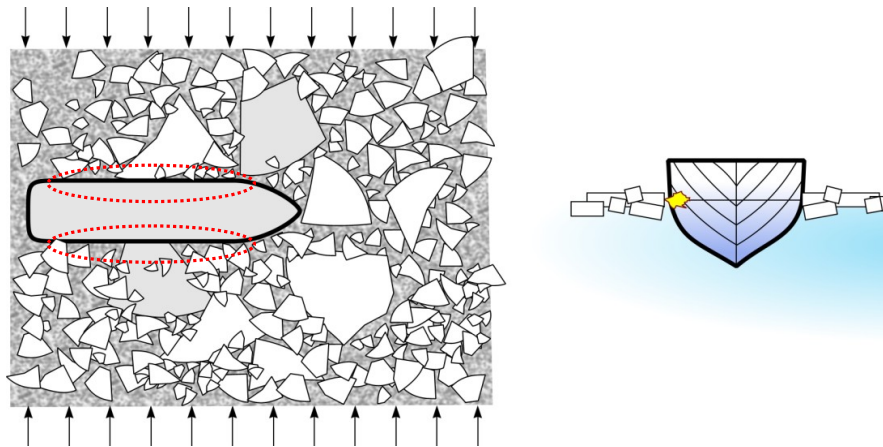
Figure 4: An example of ship-ice collision scenarios not addressed in ice class rules

3.3.3   Structural Design

The bow is designed to be capable of breaking ice (Figure 3). It is transversely framed because transverse framing systems are more efficient in resisting high ice loads. In order to investigate the impact on steel weight and labour costs, three structural designs were considered for the mid-body region. FEM was used to evaluate the structural responses for the rule-based ship-ice interaction model and also many other scenarios.

3.3.4   Scenario-based Evaluation

In addition to the basic rule check, the design team decided to evaluate the structural responses against ship-ice collision scenarios that are likely to take place but not covered in the ice class rules. Additional scenarios include head-on ramming collisions, thick ice flow oblique bow glancing collisions, ice compression in alternate patterns (Figure 4), and thick level ice oblique mid-body glancing collisions.

4   ARCTIC OFFSHORE STRUCTURES

4.1   Overview

The extensive offshore exploration activities in Canada and Alaska during the 1960's through the 1980's were mostly land based. In 1983, a specially designed drilling unit, Kulluk, was put into operation, drilling in limited level ice. In addition, oil and gas has been produced in approximately $50\,m$ water depth using jacket wellhead platforms and jack-up based production.

Along the Canadian East Coast oil, Hibernia, Terra Nova and White Rose fields use production facilities that are either bottom-founded, "iceberg proof" or disconnectable FPSO's which can leave their locations when threatened by icebergs.

In the Russian Arctic region, the northern oil and gas activities are also mainly onshore. The Varanday field includes an offshore loading facility approximately $21\,km$ from shore in $17.5\,m$ water depth. Oil is loaded to shuttle tankers with icebreaking capacity.

The Prirazlomnoye Oil Field will adopt a square ice-resistant gravity platform (Velikhov *et al.*, 2010). This innovative platform will be built at SEVMASH of Severodvinsk, towed to the field and ballasted down to sit on the seabed. It combines all functions of drilling, production, storage and offloading.

The Sakhalin offshore field development in the Sea of Okhotsk uses concrete gravity-base platforms. Field development is progressing but no further offshore structures have been installed in the reporting term of this report.

Research and development work has been reported for the Shtokman development, which is awaiting a go-ahead decision. This project will use a floating production unit, moored by a turret (Marechal *et al.*, 2011). The design will be capable of resisting significant ice loads and will be disconnected in cases where a threat may exceed the design limit.

4.2 Recent Activities

Current research and development into arctic offshore structures focuses primarily on exploration drilling and floating production units.

Arctic floating structures normally remain at a certain operating site for months. Their operation window can be 3 to 9 months long per year. Production units will have to stay on location year round. This means that these offshore floating structures will have to be heavily reinforced against ice loads. This also means that the station keeping will have to be ensured by utilization of extremely high capacity mooring systems, possibly, still supported by the ice management when the ice conditions become too severe.

The direction of the ice drift is difficult to predict and the offshore arctic unit must be prepared to meet ice coming from any direction. One of the design solutions for ship shaped units is the application of a turret. Here a care should be taken that the ship will be always keeping the bow (or stern) against the drifting ice (Zhou *et al.*, 2011; Hidding *et al.*, 2011). Another solution is utilization of a circular shape unit. A good example is the existing drilling unit Kulluk (Gaida *et al.*, 1983; Loh *et al.*, 1984; Wright *et al.*, 1999; Wright *et al.*, 1998). Additionally, circular shape units (i.e. SEVAN concept) are being proposed (Dalane *et al.*, 2009; Loset *et al.*, 2009; Bezzubik *et al.*, 2004; Bereznitski *et al.*, 2011; Bereznitski 2011).

Doelling *et al.* (2010) presented the design of the Aurora Borealis, an icebreaking research vessel, developed under a grant from the European Commission. This vessel features interesting novel concepts to keep station in level ice based on dynamic positioning (DP). The drilling capabilities, however, are designed for scientific coring, not for oil/gas exploration drilling. The vessel is in the design stage.

A number of Arctic drillship designs have been introduced for year-round operation in ice-covered waters. Due to confidentiality restrictions, only a few publications about these developments are available in literature.

Concepts for floating production systems have been presented in recent literature. Figure 5 shows some of the proposed Arctic floating structures. The afore-mentioned vessel shaped FPU planned for Shtokman is probably most progressed. Sablok *et al.* (2011) presented an Arctic Spar. The unit has a disconnectable keel buoy (bottom part of the Spar body) which carries the risers when the Spar has to be moved out of location in case of an ice threat exceeding the ice design conditions. Srinivasan and Sreedhar (2011) proposed a circular FPSO for Arctic Deepwater. The unit has sidewalls designed to provide adequate ice-breaking capabilities.

4.3 Mooring and Structural Designs

The ISO 19906 standard gives a general basis for design of Arctic offshore structures. The design has to be further developed by following the design standards from classi-
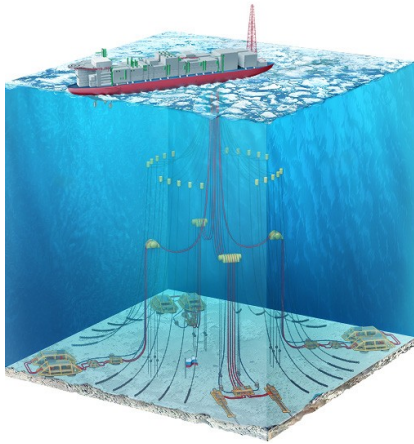
(a) Shtokman field (Marechal *et al.*, 2011)
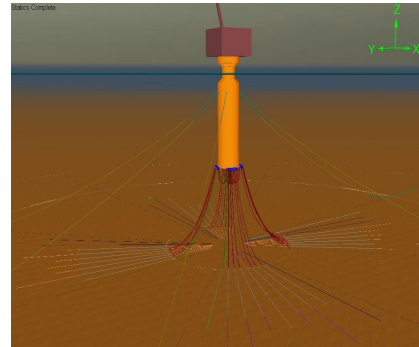
(b) Disconnectable spar (Sablok *et al.*, 2011)
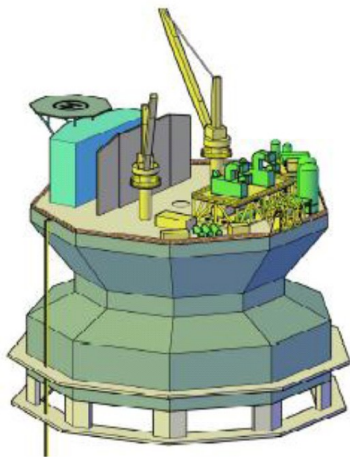
(c) Circular FPSO (Srinivasan *et al.*, 2011)

(d) Alternative circular FPSO (SEVAN concept) (Dalane *et al.*, 2009)
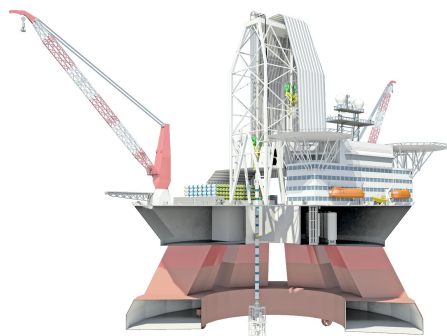
(e) Circular MODU (Bereznitski, 2011)

Figure 5: Some proposed concepts for Arctic floating structures

fication societies. It is also necessary to strike a balance between requirements for ice sea environment during winter and open sea environment during the summer.

4.3.1 Mooring System in Ice

The holding capacity of the mooring systems designed for Arctic ice conditions will be typically much higher than the open water mooring. A disconnection procedure may be needed at the time of emergency, e.g., when a severe ice condition is forecast to exceed the capacity of the mooring system. The drilling units connected to the seabed with riser can have a very small positional offset, especially in shallow water. This small offset requirement in combination with high ice loads makes the design of mooring system extremely challenging.

A number of codes can be applied for the design of mooring system such as API-PR-2SK, DNV-OS-E301, ISO-19901. However, the safety factors are not clearly defined.

4.3.2 Ice Loads

The ice class rules for ships can be directly applied to ship shaped floating structures. API and ISO19906 can be referred to for floating structures. Challenges remain to define ice loads on non-ship shaped structures.

4.3.3 Ice Management

Ice management (IM) normally includes a system to detect large ice features in advance and employ standby ice-breakers to assist in diverting or destroying dangerous large ice features (e.g. by supply vessels towing icebergs). IM has been found to be effective in extending a rig's operating season, ensuring station-keeping and increasing the operability of floating structures (Wright, 2000, Coche *et al.*, 2011). IM should be considered during design of floating structures.

5 RULES AND REGULATIONS FOR ICE-GOING SHIPS

5.1 Ice Class Rules for Ships

Ice class rules play a central role in the design of ice-going ships. The most important ice class rules are:

- Finnish-Swedish Ice Class Rules (FSICR)
- IACS Polar Class Rules (IACS PC)
- Ice class rules of classification societies (ABS, BV, CCS, DNV, GL, LR, NK, RMRS)

Ice class rules specify requirements based on ice conditions and operation of vessels. Details of structural requirements appear to be based on a combination of experience, empirical data and structural analyses.

The FSICR have been adopted widely and have been incorporated by most classification societies as the basis of first-year ice conditions. The exception is RSMS Ice Rules for vessels navigating in the Russian Arctic waters. Other than FSICR and RSMS Ice Rules, few existing ice class rules have actually been used to design ships. The IACS PC Rules are becoming more and more accepted, especially for multi-year ice conditions. To supplement FSICR and IACS PC Rules, some classification societies have rules for icebreakers and guidance on winterization for operation in cold environment. See Table 2 for a summary of some existing ice class rules.

As far as structural requirements are concerned, the following are the key components of ice class rules:

Table 2: Ice class rules for ships (Most classification societies except RSMS have aligned their first-year ice class, ice-strengthening requirements with FSICR, and are implementing IACS PC)

Ice class rules	Multi-year ice	First-year ice	Ice-strengthening	Ice breaking	Notes
FSICR	-	×	×	-	*De-facto* standard for 1st year ice
IACS PC	×	×	×	×	PC 6, 7 aligned with FSICR 1A+, 1A
RSMS	×	×	×	×	Russian region
ABS	×	×	×	×	Supplemental guidance on winterization, ice load monitoring, enhanced PC class
DnV	×	×	×	×	Supplemental requirements on winterization
LR	×	×	×	×	Supplemental requirements on winterization, ice-induced fatigue
NK	×	×	×	×	

- Ice classes that correspond to ice conditions and vessel operations in ice-infested seas
- Areas of ice strengthening that are normally divided into bow, parallel body and aft regions in general
- Ice loads that are associated with various ice-ship interaction scenarios
- Scantling requirements that are dependent on elastic or plastic responses of structures
- Corrosion/abrasion allowance

One of the issues currently facing owners and designers is selection of the appropriate design standards (Daley *et al.*, 2007). A significant amount of experience has been developed for government and escort icebreakers, icebreaking oil field work vessels and small cargo vessels. However, very little information has been published related to the adequacy of design standards used for these vessels. Currently, experience with larger tank vessels is being accumulated and industry is developing designs to support oil and gas exploration in several Arctic regions. Large state-of-the-art icebreaking tankers have recently been constructed and are now providing year round service to the Varanday gravity based production platform offshore in the Russian arctic (Iyerusalimsky and Noble, 2008). This project includes much needed collection of full-scale ice loads data for application to the design of larger vessels anticipated for future commercial developments.

5.2   Finnish-Swedish Ice Class Rules (FSICR)

FSICR were primarily intended for merchant ships trading in the winter Baltic. The rules are based on the premise that icebreaker assistance is available when required. FSICR define four ice classes, which are IA Super, IA, IB and IC (Table 3). Requirements are specified for minimum propulsion power, hull and machinery scantlings.

Over the time, FSICR has become the de-facto global standard for designing ice-strengthened ships for first-year ice condition. The latest update in 2010 streamlined the hull rules (Riska and Kamarainen, 2011).

Table 3: Ice classes of FSICR (TRAFI, 2010)

Ice class	Ice condition and vessel operation
IA Super	ships with such structure, engine output and other properties that they are normally capable of navigating in difficult ice conditions without the assistance of icebreakers;
IA	ships with such structure, engine output and other properties that they are capable of navigating in difficult ice conditions, with the assistance of icebreakers when necessary;
IB	ships with such structure, engine output and other properties that they are capable of navigating in moderate ice conditions, with the assistance of icebreakers when necessary;
IC	ships with such structure, engine output and other properties that they are capable of navigating in light ice conditions, with the assistance of icebreakers when necessary;
II	ships that have a steel hull and that are structurally fit for navigation in the open sea and that, despite not being strengthened for navigation in ice, are capable of navigating in very light ice conditions with their own propulsion machinery;
III	ships that do not belong to the ice classes referred to in paragraphs 1-5;

The scenario considered in FSICR is that a ship collides with a level ice edge while sailing in the ice channel at a speed of about 4 knots. The ice channel is created by the escort icebreaker.

The ice load on hull is a patch that is narrow in height, which is often simplified as a line load. The design ice loads were defined and updated based on ice loads measurements and observed damages to ships.

Recent statistical studies of ice load measurements suggested (Figure 6) that the FSICR design ice loads have a return period of 3.5 to 14.6 days. Measurement data on real ships have revealed that the FSICR design ice loads have been repeatedly exceeded. In comparison, modern commercial ships (such as the IACS Common Structural Rules) are designed for environmental loads with a return period of about 25 years.

FSICR uses formulation of initial yielding for shell plates and formulation of elastic response for frames (i.e. shell stiffeners).
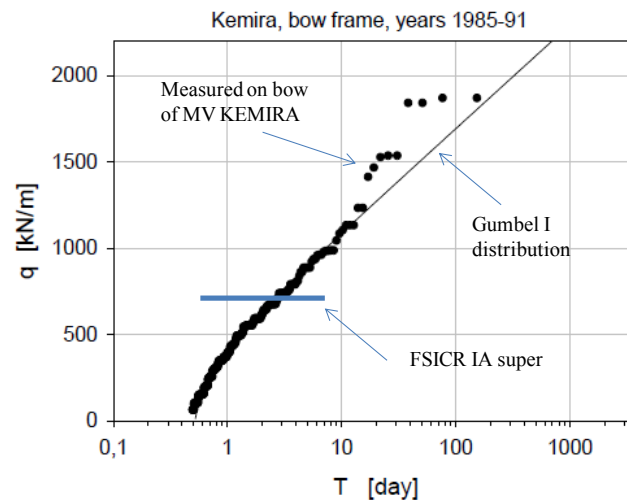

Figure 6: Measured ice pressure and design ice loads of FSICR (according to Riska and Kamarainen, 2011)

Table 4: Ice classes of IACS PC Rules

Polar class	Ice condition
PC 1	Year -round operation in all Polar water
PC 2	Year -round operation in moderate multi-year ice conditions
PC 3	Year -round operation in second-year ice which may include multi-year ice inclusions
PC 4	Year -round operation in thick first-year ice which may include old ice inclusions
PC 5	Year -round operation in medium first-year ice which may include old ice inclusions
PC 6	Summer/autumn operation in medium first-year ice which may include old ice inclusions
PC 7	Summer/autumn operation in thin first-year ice which may include old ice inclusions

5.3   IACS Polar Class Rules (IACS PC)

The IACS PC Rules define seven ice classes (Table 4), PC 1 to PC 7 with the lowest ice class PC 7 approximately aligned with FSICR IA class. IACS PC is intended to cover the full range of ships operating in multi-year and first-year ice conditions.

A notable feature of IACS PC 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.

The considered scenario is that a ship strikes an angular ice edge at the design speed (Figure 7). The ship penetrates the ice and rebounds. The assumption is that the ice loads are determined by the ice's crushing and flexural strength.

In addition, global hull-girder loading due to ramming operation is also specified.

The return period of IACS PC ice loads is not documented.

The IACS PC rules use plastic response formulation for plate and stiffeners (Daley, 2002a, 2002b). The interaction between bending and shear is considered in calculation of stiffener's load-carrying capacity.

5.4   Russian Maritime Register of Shipping Ice Rules (RMRS IR)

The RMRS IR is also important because of Russia's proximity to the Arctic.

The current RMRS IR has a total of 12 ice classes: three for non-Arctic ice conditions, six for Arctic operations, and three for ice-breakers (Table 5). The rules specify requirements for permissible operation condition that are based on permissible vessel speed and ice conditions (Table 6), which are contingent upon operation areas, seasons, navigation severity and availability of an escort ice-breaker.

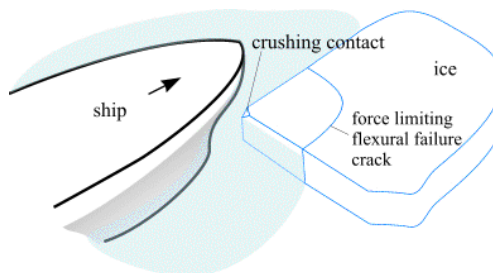The basis of ice load in RMRS IR is said to be a hydrodynamic model of solid body - ice interaction.

Figure 7: Ice-ship interaction scenario of IACS PC Rules (Daley, 2002a)

Table 5: Ice class category by RMRS IR

Ice class	Ice condition, operation
ICE 1, ICE 2, ICE 3	Non-Arctic ice condition
ARC 4, ARC 5, ARC 6, ARC 7, ARC 8, ARC 9	Arctic operation
Ice breaker 6, Ice breaker 7, Ice breaker 8, Ice breaker 9	Ice breaker

Table 6: Permissible service area for ships of Arctic classes by RMRS IR

Ice class	Ice operation tactics	Winter – spring navigation					Summer – fall navigation				
		1	2	3	4	5	1	2	3	4	5
		EHML	EHML	EHML	EHML	EHML	EHML	EHML	EHML	EHML	EHML
ARC 4	IO	---+	----	----	----	----	++++	--++	---+	---+	--++
	PO	-*++	---+	----	----	---*	++++	*+++	--++	--++	-*++
ARC 5	IO	--++	---+	----	----	----	++++	-+++	--++	--++	--++
	PO	*+++	--*+	---+	---+	--*+	++++	*+++	*+++	*+++	*+++
ARC 6	IO	*+++	---+	---+	---+	---+	++++	++++	-+++	-+++	-+++
	PO	++++	**++	-**+	-**+	-*++	++++	++++	++++	++++	++++
ARC 7	IO	++++	--++	---+	---+	--++	++++	++++	++++	++++	++++
	PO	++++	++++	*+++	*+++	*+++	++++	++++	++++	++++	++++
ARC 8	IO	++++	++++	-*++	-*++	*+++	++++	++++	++++	++++	++++
	PO	++++	++++	++++	++++	++++	++++	++++	++++	++++	++++
ARC 9	IO	++++	++++	++++	++++	++++	++++	++++	++++	++++	++++
	PO	++++	++++	++++	++++	++++	++++	++++	++++	++++	++++

Legend:
IO — independent operation
PO — icebreaker pilotage operation;
+ — service is permissible;
- — service is impermissible;
* — service is connected with increase of risk to be damaged;
E — extreme navigation (with average reoccurrence one time per 10 years);
H M, L — heavy, medium, light navigation (with average reoccurrence one time per 3 years).

The RMRS IR adopts plastic capacity limit for the stress criteria.

5.5 IMO Guidelines for Ships Operating in Polar Waters

The International Maritime Organization (IMO) adopted Guidelines for Ships Operating in Polar Waters in December 2009. These guidelines augment the Safety of Life at Sea (SOLAS) and Prevention of Pollution from Ships (MARPOL) International Conventions. They include provisions related to vessel construction, equipment, operations, environmental protection and damage control. The current IMO guidelines are in the process of further revision and are due to become mandatory in the near future.

These guidelines refer to the IACS Polar Class Rules for the detailed hull and machinery requirements.

5.6 Canadian Arctic Shipping Pollution Prevention Regulations (CASPPR)

The CASPPR was established in 1972 as one of the sub-laws required under Arctic Water Pollution Prevention Act (AWPPA), which is a basic act put in force in 1970 to prevent marine pollution from offshore resources development in Canadian Arctic waters.

The CASPPR defines five "Canadian Arctic Class" for ice breakers, and four Types for ice-strengthened ships (Table 7). While not specifying structural requirements

Table 7: CASPPR ice classes

Ice class	Max. allowable ice type	Ice thickness (cm)
CAC1	No limit	No limit
CAC2	Multi year	No limit
CAC3	Second year	No limit
CAC4	Thick first year	> 120
Type A	Medium first year	$70 - 120$
Type B	Thin first year (Stage 2)	$50 - 70$
Type C	Thin first year (Stage 1)	$30 - 50$
Type D	Grey white	$15 - 30$
Type E	Open water / Grey	$10 - 15$

for Type A to D ships, the CASPPR accepted equivalency of ice classes by major classification societies, and consequentially established equivalency with FSICR.

A "Shipping Safety Control Zones" scheme has been long implemented under AWPPA, under which the whole area is split into 16 zones based on the sea ice statistics. AWPPA forces ships attempting to enter into these zones to comply with the requirements on ship construction, propulsion system, equipment and crew competence, etc. The details of these requirements are stipulated in CASPPR that translates the scheme into "Zone/Date system" (Z/DS) in which the operable period for each zone and ice class combination is specified for easy reference.

The Z/DS, however, is founded on statistics from the 1970s which do not necessarily reflect the present conditions. Therefore, conflicts have been reported between the data and the actual ice conditions.

In response to this situation, the "Arctic Ice Regime Shipping System" (AIRSS) has now been put in place to supplement the existing Z/DS. AIRSS is a regulatory standard currently in use only outside Z/DS and it emphasizes the responsibility of the ship owners and captains while providing a flexible framework for decision-making.

5.7   Supplemental Guidance

Supplemental requirements have also been developed to address issues generally not covered by ice class Rules. These include guidance on temperature and ice thickness of selected areas, vessel operation under low temperature, ice load measurement, ice-induced fatigue, propulsion system, additional machinery requirements, analysis of structures for ship-ice interaction scenarios that are not addressed in existing ice class rules (i.e., ABS, 2010, 2011, 2012; DNV, 2011; LR, 2008).

Low temperature environments present numerous challenges related to operation of equipment, systems, structure, vessel maintenance and safety equipment. Vessels designed and constructed without addressing the effects of low temperatures may experience increased structural and equipment failures and non-functioning systems.

The technical developments that led to the IACS PC also allow for extended structural evaluation for additional ice/ship interaction scenarios (see also Section 5.2 and 3.3). Guidance has been developed to describe supplementary loading scenarios and associated structural analysis (ABS, 2012). Procedures for grillage analysis have been developed for analyzing side structures of wider extent (ABS, 2012). Non-linear FEM analyses have also been accepted for evaluation of these additional cases.

6   GUIDANCE FOR ARCTIC STRUCTURES

6.1   ISO 19906 Arctic Offshore Structures

ISO 19906 Petroleum and Natural Gas Industries - Arctic Offshore Structures specifies requirements and provides guidance for the design, construction, transportation, installation, and decommissioning of offshore structures, related to the activities of the petroleum and natural gas industries, in arctic and cold regions environments. The objective is to ensure that arctic and cold regions offshore structures provide an appropriate level of reliability with respect to personal safety, environmental protection and asset value to the owner, to the industry and to society in general. ISO 19906 does not contain specific requirements for the operation, maintenance, service life inspection or repair of arctic offshore structures.

This ISO does not apply specifically to mobile offshore drilling units (see ISO 19905-1). The procedures relating to ice actions and ice management contained herein may be applicable to the assessment of such units. Mechanical, process and electrical equipment and any specialized process equipment associated with arctic or offshore operations are not covered except insofar as the structure needs to sustain safely the loads imposed by the installation, housing, and operation of such equipment.

6.2   API Recommended Practice for Planning, Designing, and Constructing Structures and Pipelines for Arctic Conditions (API RP)

This API RP contains recommended practice to those involved in the design of Arctic systems. The systems covered in this recommended practice for the Arctic environment include:

- Offshore concrete, steel, and hybrid structures, sand islands, and gravel islands used as platforms for exploration drilling or production;
- Offshore ice islands used as platforms for exploration drilling;
- Near shore causeways
- Offshore pipelines;
- Shore crossing for pipelines.

7   ICE LOADS

Ice loads may be conveniently categorized as local ice loads and global ice loads (ABS, 2011). Local ice loads are often defined as ice pressure acting on local areas (on shell plates and stiffeners). Global ice loads on ships are typically (vertical) bending moment on hull girder. With the recent progress of research, vibratory loads, iceberg impacts and cyclical ice loads are also being discussed.

7.1   Local Ice Loads

All ice class rules define local ice pressures. Design ice loads are determined based on field measurement and model tests. Simulations may eventually be used for deriving ice loads once the technology becomes matured.

In general, local ice pressures depend on ice type, ice thickness, ice-structure interaction, dominant ice failure modes. The load is on a small contact area, which forms where ice fails. Lab tests (Wells *et al.*, 2011) have shown that the ice most likely fails in either crushing mode or bending mode.

The average ice pressure is considered to be proportional to the contact area to the power of n. This constant n is found to be −0.52 from a study on data measured at ships (Figure 8). It is taken as −0.5 in DNV Rules and −0.3 in IACS PC.
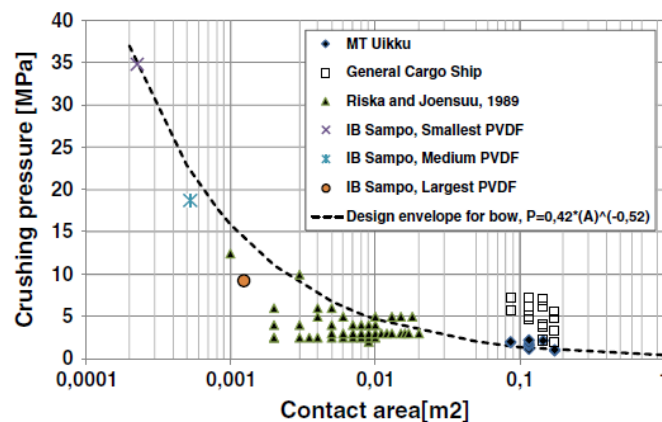
Figure 8: Ice pressure versus contact area (Kujala and Arughadhoss, 2011)

Probabilistic analysis of local ice loads has attracted some attention (Taylor *et al.*, 2009; Li *et al.*, 2010).

7.2   Global Ice Load on Ships

Some ice class rules (IACS PC) also specify global ice loads. The ice-induced vertical bending moments were derived from stresses measured at the deck of ships sailing in ice water (e.g. Chernov, 2009). The global bending moment is dependent on ship operation (ship speed and power), ice conditions (ice concentration, thickness and floe size), and ship-ice interaction.

Simulation approaches have also been applied to calculating global ice loads on ships and ship motion in ice-infested seas (Valanto, 2009; Su *et al.*, 2010a; Sayed and Kubat, 2011).

The peak ice-induced bending moments on MT Uikku were found to follow the Weibull distribution (Kujala *et al.*, 2009). The mean and standard deviations of the peak ice loads were said to be dependent on ice thickness.

7.3   Iceberg-Ship Collision

Simulation technique has been used to analyse iceberg-ship collision. Non-linear FEM tools are often applied (Kim *et al.*, 2011) to simulate such a collision. A major challenge is modelling of ice properties, which are highly variable depending on many parameters that are yet to be fully understood. Simplified analytical approaches were applied in some cases where the mechanisms of iceberg crushing are modelled in simplistic manners (Kierkegaard, 1993; Liu and Amdahl, 2010; Liu *et al.*, 2011c).

7.4   Ice Loads on Fixed Offshore Structures

Measurements taken in Bohai Sea (Yue *et al.*, 2009) revealed that ice may fail in ductile, ductile-brittle or brittle modes. These failure modes correspond to quasi-static loads, steady-state loads and vibratory loads, respectively.

Measurement data has been the basis of rule development. For example, data taken from Molikpaq has been instrumental in the development of ISO 19906.

To supplement the design codes and model tests, analytical and simulation tools are more and more used to assist in determination of ice loads. A major challenge is that different approaches result in different ice loads. A revisit of Molikpaq ice load

data suggested that "Historical Case" ice loads were about twice the level of the "Best Estimate Case" (Jordaan *et al.*, 2011; Frederking *et al.*, 2011). An analysis of Norströmsgrund lighthouse concluded that predicted dynamic ice loads on this lighthouse could be about 110 % higher than ISO/DIS 19906-2009 design code.

7.5 Ice Loads on Moored Floating Structures

Model tests have been relied on determination of ice loads on moored ships. The physical failure mechanisms of ice being pushed against a structure are quite complicated and include: crushing (or bending) failure of ice, ice accumulation, and ice movement around the structure. Attempts have been made to describe level ice sheets breaking against a structure (Croasdale *et al.*, 1994; Ralston, 1979; Nevel, 1992; Maattanen *et al.*, 1990), some of which have been incorporated into ISO 19906. The calculated global ice forces on conical structures are in some cases much lower than those measured in ice tank tests (Bereznitski, 2011). While the results of ice tank tests are well accepted, it is not recommended to base ice load predictions purely on ice tank tests.

Model basin tests have been reported for moored Spar (Evers and Jochmann, 2011; Bruun *et al.*, 2009, 2011), ice ridges (Dalane *et al.*, 2009), level ice (Wille *et al.*, 2011), moored FPSO (Chernetsov *et al.*, 2009), and interaction between ice and ship's bow (Aksenes, 2011).

Analyses have been conducted to investigate mooring force in drifting ice (Aksnes and Bonnemaire, 2009; Aksnes, 2010, 2011b), pack ice loading and ice-hull friction coefficient (Woolgar and Colbourne, 2010), iceberg impact (Karlinsky and Chernetsov, 2010), time history of ice and mooring forces (Zhou *et al.*, 2011), and behaviour of a moored tanker (Karulin and Karulina, 2011).

8 STRUCTURAL RESPONSE

8.1 Elastic, Plastic Behavior of Plate and Stiffener

Ice damages to hull structures are in the form of dent, tripping, buckling, and rupture in some extreme cases (ice damage reports of e.g., Kujala, 2007). Limited plastic deformation to hull structures has been considered inevitable in ice-going ships.

Design of local structural members of shell, stiffeners and main support members is a key component in ice class rules. As shown in Table 8, the basis of scantling requirements in ice class rules varies to a great degree. A recent paper attempts to shed light on the various structural formulations using the concept of "design point" (Riska and Kamarainen, 2011), which includes a definition of the limit state of the structure and the frequency of the ice loads.

Extensive studies have been conducted to investigate the structural responses of shell plate and stiffeners subject to ice loads (Varsta *et al.*, 1978; Kendrick *et al.*, 2007;

Table 8: Basis of structural scantlings requirements of ice class rules

Ice rules	Ice loads	Limit state for plate failure	Limit state for stiffener failure
FSICR	Frequent ice load	Slight yielding	Initial yielding under bending
IACS PC	Extreme ice load	Plastic collapse	Collapse under both bending and shear
RSMS	?	Plastic collapse	Plastic collapse under bending

Daley, 2002a, 2002b; Wang *et al.*, 2004, 2005, 2006). Recent studies tend to apply the non-linear FEM (e.g., Liu, 2011). This is partially encouraged by a tentative acceptance of the Finnish Maritime Administration to use such advanced tool to evaluate structural scantlings.

8.2   Ice-Induced Vibration

Dynamic structural response has been observed in fixed structures of lighthouses, bridge piers, jackets, caissons or multi-leg structures (Peyton, 1968; Blenkarn, 1970). Reported damages to jacket structures in the Bohai Bay include global structural collapse and local damage like pipe failures due to fatigue damage and on channel markers (Ji and Yue, 2011).

Research on ice-induced vibration has also been a topic of interest. As an effective means of reducing ice-induced vibration, ice-breaking cones have been installed on offshore structures such as the Finnish Kemi-I lighthouse in the Gulf of Bothnia, the piers of Confederation Bridge in the Southern Gulf of Lawrence, offshore wind turbines foundations in Denmark, the conical narrow jacket platforms in the JZ20-2 field of the Bohai Bay, China, the Single Point Mooring system in the Sakhalin Field, and a large faceted cone at Varandey in north Russia. The advantage of cone-shaped structures is that the ice force on a conical structure is small, and that a well-designed cone can change the ice failure mode from crushing to bending.

8.3   Ice-Induced Fatigue

Ice loads are cyclic in nature. ISO 19906 specifies that fatigue limit state shall be considered in the design of Arctic offshore structures. How to assess fatigue during ice season remains un-determined.

On the basis of measurements of a chemical tanker sailing the Baltic, Bridges *et al.* (2006) concluded that fatigue may become an issue in severe winter season. On the contrary, a recent study on the measured data for large LNG carriers concluded that ice-induced fatigue damages would be negligibly smaller than that induced by wave.

Investigations into the fatigue behaviour of welded joints under low temperature (Bridges *et al.*, 2011) have been completed to develop guidance on predicting ice-induced fatigue (Zhang *et al.*, 2011).

9   NUMERICAL SIMULATION OF ICE

Numerical simulation is considered useful in studying the physical behaviour of ice failure process (Daley *et al.*, 1998). The increased computational capability has made it feasible to model larger volumes of ice using fine mesh, and thus to analyse the complicated failure mechanics of ice ridges.

This section reports recent numerical modelling efforts on constitutive modelling and failure of ice, failure of ice against offshore structures and ships, ice ridges, ridge strength and ridge loads. The focus is placed on sea ice related to design of ships and offshore structures. Modelling used in geophysical studies on large sea areas is therefore not reviewed.

9.1   Constitutive Modelling and Failure of Ice

As a material, ice creeps when loaded slowly, and fractures when loaded rapidly. The behaviour of ice depends on grain structure, loading direction, temperature, salinity and so on (Schulson and Duval, 2009; Weeks, 2010; Timco and Weeks, 2010). It is challenging to consider all of these properties in one single ice model.

A practical way is to apply different models for different ice behaviour. The following approaches have been studied. Some have been implemented in commercial FEM codes.

- A rheologal model with springs and dashpots is often used to represent the visco-elastic ice behavior (Jordaan and Taylor, 2011).
- A model based on the continuum damage mechanics was developed for the brittle failure of isotropic ice (Kolari, 2007; Kolari *et al.*, 2009; Kuutti and Kolari, 2010).
- The ice is modelled as an elasto-plastic or foam material. The ice failure criterion is left to the user to define. Commercial FM codes support user-defined failure criteria.

Many papers have been published on modelling ice failure processes, with focus placed on: material non-linearities, friction and contact between ice and a structure (Sand, 2008), a multi-surface failure criterion (Wang and Derradji-Aouat, 2009), ice fracture and propagation (Liu *et al.*, 2011), and modelling of ice as a crushable foam (Gagnon, 2007, 2011).

9.2   Ice-Structure Interaction and Discrete Element Method (DEM)

Simulation of ice failure against offshore structures or ships also needs to be taken into account:

- Accumulation and clearing of broken ice
- Shape and stiffness of the structure

Often, it is not known in advance what ice failure modes will be dominant. Therefore, a range of ice models must be attempted before sensible conclusions can be drawn. Studies on ice-structure interactions include those by Gürtner (2009), Konuk *et al.* (2009), Kolari *et al.* (2009), Kuutti *et al.* (2010).

The discrete element method (DEM) has found extensive application in ice-structure interaction problems (Ji and Yue, 2011). The ice floes are modelled with spherical and cubic particles, and the ice cover can be modelled in one layer or two layers of these in regular or random packing. DEM has demonstrated its capability in qualitatively describing the mechanism of rotating and sliding of ice pieces, and seems to have high potential for estimating submerged components (Sawamura and Tachibana, 2011; Zhan *et al.*, 2010; Lau *et al.*, 2011; Kioka *et al.*, 2010; Paavilainen *et al.*, 2009, 2011).

Simplified ice models are often favoured in studies on water-ice interaction during ice bending (Sawamura *et al.*, 2008), ship performance in level ice (Valanto, 2009), simulation of ship-ice interaction (Su *et al.*, 2010; Lubbard and Løset, 2011), level ice actions on moored ships (Aksnes, 2011).

9.3   Ice Ridges

The recent research on ice ridges is concentrated on:

- Ridge loads on structures
- Deformation, failure, and strength of a ridge

Various material models have been attempted, including a shear cap material model (Heinonen, 2009), Drucker-Prager model and the arbitrary Lagrangian-Eulerian (ALE) FEM for rubble failure against a conical structure (Ranta *et al.*, 2010).

The challenges are material parameters for ice. Punch-through tests have been used to measure the ridge and rubble strength both in full scale and in laboratories. Derivation of the material properties from the experimental data is not straightforward and usually requires assistance of numerical simulation (Serré, 2011a, 2011b; Polojärvi and Tuhkuri, 2009, 2010).

10 STRUCTURAL RELIABILITY ANALYSIS

One challenge to the Arctic development is the lack of experiences. Ship design has traditionally relied on operational experience for the development of design methods and design codes. In the absence of this experience, alternative methods are required. Structural reliability analysis (SRA) may have been a useful role to play in this regard.

SRA holds, in principal, the promise of more rationalized structural designs that achieve consistent safety levels. The reliability methods are attractive since they provide a framework to properly account for the uncertainty associated with the relevant design variables.

10.1 Structural Reliability Approach (SRA)

Several recent surveys of SRA literature provide good overview of the theoretical development and practical applications. ISSC had a Specialist Committee on "Reliability based structural design and code development" (ISSC, 2006). This ISSC committee work was performed at the time when the IACS was developing Common Structural Rules (CSR). A recent trend is to apply SRA to hull integrity management (Wang *et al.*, 2010). However, there is only limited coverage on SRA applications to ice-going ships and Arctic offshore structures.

A major challenge for practical application of the SRA is the proper selection of uncertainty models (Guedes Soares, 1988, 1997; Moan *et al.*, 2006; Wang *et al.*, 2010). The apparent disparities in SRA results presented by different research groups can be attributed to the differences in uncertainty modelling and the formulations of the limit state functions (Guedes Soares and Teixeira, 2000; Wang *et al.*, 2010; VanDerHorn and Wang, 2011).

10.2 Probabilistic Ice Loads

The ISO 19906 (2009) recommends a probabilistic approach that takes into account the high uncertainty of the ice geometric, kinetic, and mechanical characterics, and various possible interaction scenarios in addition to those related to the ice, structure, soil, and mooring parameters.

As usual, the challenge is to determine the relative importance of these parameters and to concentrate on the significant interaction scenarios to increase the reliability of the calculated ice loads.

The ice loads are random in nature like other environmental loads. A large number of variables are needed to characterize ice failure phenomena and the resulting ice loads. This includes, among others, ice thickness, salinity, flexural strength, compressive strength. In addition, the ice loads on a ship also depend on the vessel's characteristics such as power, hull form of the entire vessel, and the location of interest. Virtually all ice load models are based on measurements in full- or model-scale tests. Short-term and long-term full-scale measurements have been made on ships travelling in the Polar regions, and these remain the most reliable sources of information.

Three limit mechanisms define the net imposed ice load on a structure (Wang *et al.*, 2011):

- Limit strength: An ice floe cannot sustain itself and crushes when the applied stress exceeds the material strength of ice. This strength corresponds to crushing and bending failures in the ice floe.

- Limit momentum: This is the load imposed by ice due to the floe moving with acceleration and impinging on a structure to impart its momentum as a load on the structure. The CSA code (CSA, 2004) indicates that the limit momentum can be neglected compared to the limit strength if the ice floe diameter is less than $5\,km$.
- Limit force: The ice load caused by the moving ice floe, where the movement is due to wind or current force, or due to movement of surrounding ice pack.

The ice load on the structure is limited by the force necessary to fail the ice feature and by the force driving the ice feature against the structure. In the absence of sufficient environmental driving force, the ice failure force cannot be generated. Therefore, the minimum value of the environmental driving force (limit force) and the ice failure force (limit strength) is taken as the critical ice load on the structure.

Figure 9 (Wang *et al.*, 2011) summarizes the methodology for calculating the annual maximum ice load on an Arctic offshore structure. For an arbitrary year, the number of ice floes that would interact with the offshore structure is first calculated. This number depends on parameters such as ice season length, ice concentration, floe velocity, floe size, and the structure geometry.

For each floe interacting with the structure, the two force components calculated include the limit strength and the maximum ridge force across all ridges in the floe. The limit strength is calculated based on ice floe size, wind velocity, ocean current velocity, and pack ice force. The maximum ridge force is calculated by finding the maximum of each individual ridge force on the floe. Each ridge force is calculated based
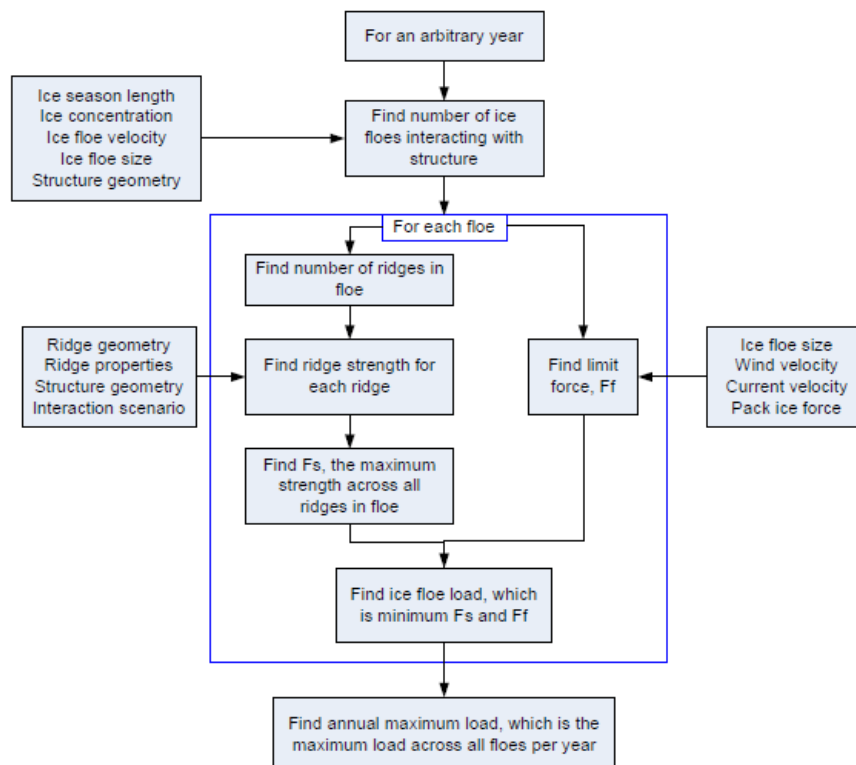

Figure 9: Derivation of probabilistic ice loads

Table 9: ISO 19906 maximum acceptable annual failure probability

Exposure Level	Maximum Acceptable Annual Failure Probability
L1 (high consequence/manned non-evacuated)	$1.0 \cdot 10^{-5}$
L2 (Medium consequence/manned evacuated or unmanned or Manned Evacuated with low consequence)	$1.0 \cdot 10^{-4}$
L3 (low consequence unmanned structures)	$1.0 \cdot 10^{-3}$

on ridge geometry and other ridge properties, structure geometry and the interaction scenario assumed between the ridge and the structure. The overall ice floe load on the structure is the smaller value of the limit strength and the maximum ridge force. Such floe loads are calculated for all floes during the year and from these the annual maximum floe load is calculated.

10.3 Implied Reliability Levels in Ice Class Rules

There are studies on the implied reliability level in the Finnish-Swedish Ice Class rules (Wang *et al.*, 2007). The plate thickness requirements of ice belt were investigated, and the influence of ship size and ice belt region was considered. The ice loads were assumed to follow type I extreme value distribution with a mean of 1.0 and a COV of 0.2, based on an existing statistical study on measurement data (Kujala, 1990). The calculated reliability indices were considerably lower than typical values for marine structures. The primary reason was the low level of applied ice loads in FSICR (see also section 5.2 of this Committee report). The acceptance criteria are correspondingly conservative when compared with the ultimate capacity of plate panels. As a result, the limit state for the FSICR thickness requirements has some features of a serviceability limit state.

If the FSICR is re-cast in an ultimate limit state, the ice loads need to be the extreme values and the resistance of the plate panels must represent the ultimate capacity. Assuming that the design ice loads have a 5 % probability of exceedance, the type I extreme value distribution would have a mean of 0.73 and a COV of 0.2. The resulting reliability level is significantly different.

The ISO DIS 19906 standard on Arctic Offshore Structures is a timely document that encompasses many aspects of Arctic and sub-Arctic Development. It employs the same principles of the other ISO standards such as ISO 19902 and ISO 19903 for fixed steel and concrete structures, respectively, and ISO 19904-1 for floaters. The ISO 19906 standard employs the Limit State design methodology that applies load and resistance factors to arrive at the target reliability levels as shown in Table 9.

11 SUMMARY AND RECOMMENDATIONS

The Committee strongly recommends that ISSC continues this committee. The revived demand for Arctic shipping and Arctic development will continue driving research and development of Arctic technologies.

11.1 Ice Class Rules

The ice class rules are the corner stone of ship design. The Committee attempted to survey literature that supports the development of ice class rules, and we realized that our coverage is rather limited.

The Committee noted that various differences exist in technical basis between ice class rules. This may offer opportunities of future research on, but not limited to:

- Concept of ice class rules (limit states, target failure probability)
- Definition of ice belt
- Ship-ice collision scenario
- Ice load (probabilistic feature, extent of ice patch, pressure versus area relationship)
- Structural analysis models for the response of plate and stiffener/frame – elastic versus plastic methods, including application of linear and non-linear FEM
- Materials for Arctic application
- Corrosion/abrasion

For Arctic structures, the following topics may need to be improved:

- Definition of operating parameters for each "class" of ice strengthening
- Evaluation of feasibility of applying ship design practice to Arctic structure

11.2   Tests, Analysis

Numerical and analytical tools will continue to be extensively applied in explaining ice behaviour, ice failure mechanisms, ice-structure interaction and the resulting ice loads. The Committee believes that there is room for developing and improving these tools, and comparisons with field measurement and model tests will be important.

Techniques of numerical simulation are advancing rapidly, but face a major difficulty in verification due to lack of data. Traditional ice models need information on compressive and bending strengths, but the more advanced models need more data about ice properties (i.e., shear strength, particle-particle bonding strength within a ridge). This will in turn lead to needs for additional tests and sharing of test results.

11.3   Structural Reliability

Structural reliability approaches deserve more research and development attention. SRA adds values to the understanding of the ice mechanics, and may potentially lead to refinement of design rules that are mostly based on limited experiences.

A very important task of SRA is probabilistic modelling of ice loads. Additional studies of this topic are needed.

11.4   Risks of Arctic Shipping and Arctic Development

Arctic shipping and Arctic development face a variety of risks (Tikka *et al.*, 2007). Existing ice class rules have focused on vessel performance and responses of hull and machinery. These rules only provide a minimum set of requirements that must be supplemented by more comprehensive considerations of a wider range of topics, including but not limited to:

- Propulsions
- Winterization of vessels and equipment
- Ice management
- Ergonomics
- Crew training
- Ice forecasting, ice management
- Oil spill behaviour and recovery

The Committee encourages increased applications of risk assessment in all these areas.

12 ABBREVIATION

CASPPR   Canadian Arctic Shipping Pollution Prevention Regulations
ISO   International Standard Organization
FPSO   Floating Production Storage Unit
FPU   Floating Production Unit
FSICR   Finnish-Swedish Ice Class Rules
IAHR   International Association of Hydraulic Research, Ice Symposium
IACS PC   IACS Polar Class Rules
NSR   Northern Sea Route
POAC   Port and Ocean Engineering under Arctic Condition
RSMS   Russian Society of Maritime Register of Shipping
SRA   Structural Reliability Approach

13 REFERENCES

ABS (2010). *Guide for Vessels Operation in Low Temperature Environment*, ABS, Houston, TX.

ABS (2011). *Guide for Ice Load Monitoring System*, ABS, Houston, TX.

ABS (2012). *Guidance Notes on Ice Class*, ABS, Houston, TX.

Aksnes, V. and Bonnemaire, B. (2009). Analysis of the behaviour of a moored ship in variable ice drift, *20th International Conference on Port and Ocean Engineering Under Arctic Conditions*, Luleå, Sweden, 9-12 June 2009.

Aksnes, V.A. (2011a). Panel method for modelling level ice actions on moored ships, Part 1: Local ice force formulation, *Cold Regions Science and Technology*, 65:128-136.

Aksnes, V.A. (2011b). Panel method for modelling level ice actions on moored ships, Part 2: Simulations, *Cold Regions Science and Technology*, 65:137-144.

Aksnes, V.A. (2010). Simplified interaction model for moored ships in level ice, *Cold Regions Science and Technology*, 63:29-39.

Bereznitski, A. (2011). A novel design of mobile offshore drilling unit for arctic conditions, *30th International Conference on Ocean, Offshore and Arctic Engineering*, Rotterdam, the Netherlands, 19-24 June 2011.

Bereznitski, A. and Roodenburg, D. (2011). JBF Arctic - A mobile offshore drilling unit with high performance in ice covered waters and in open seas, *Offshore Technology Conference*, 2011.

Bezzubik, O.N., Bitsulya, A.V., Karulin, E.B., Karulina, M.M., Klementyeva, N., Sazonov, Y., K.E., Chernetsov, V.A., Kulakov, A.V. and Kupreev, V.V. (2004). Experimental investigation of interaction of moored platforms with drifting ice features, *17th International Symposium on Ice*, 2004.

Bridges, R., Riska, K. and Zhang, S. (2006). Preliminary results of investigation on the fatigue of ship hull structures when navigating in ice, ICETECH 2006.

Bridges, R., Riska K., and Zhang S. (2011). Experimental investigation on the effect of low temperatures on the fatigue of welded steel joints, *International Journal of Ships and Offshore Structures*, 2011.

Bruun, P.K., Husvik, J. and Le-Guennec, S. (2009). Ice model test of an Arctic SPAR, *20th International Conference on Port and Ocean Engineering under Arctic Conditions*, Luleå, Sweden, 9-12 June 2009.

Bruun, P.K., Loset, S. and Gurtner, A. (2011). Ice model testing of structures with a downward breaking cone at the waterline JIP; presentation, set-up & objectives, *30th*

International Conference on Ocean, Offshore and Arctic Engineering, Rotterdam, The Netherlands, 19-24 June 2011.

Chernetsov, V.A., Karlinskiy, S.L. and Malyutin, A.A. (2009). Arctic FPSO environmental resistance, *20th International Conference on Port and Ocean Engineering under Arctic Conditions*, Luleå, Sweden, 9-12 June 2009.

Chernov, A.V. (2009). Measuring total ship bending with a help of tensometry during the full-scale in situ ice impact study of icebreaker "kapitan nikolaev", *20th International Conference on Port and Ocean Engineering under Arctic Conditions*, Luleå, Sweden, 9-12 June 2009.

Croasdale, K.R. and Cammaert, A.B. (1994). An improved method for the calculation of ice loads on sloping structures in first-year ice, *Power Technology and Engineering*, 1994.

Dalane, O., Aksnes, V., Løset, S. and Aarsnes, J.V. (2009). A moored arctic floater in first-year sea ice ridges, *28th International Conference on Ocean, Offshore and Arctic Engineering*, Holululu, HI, 31 May-5 June 2009.

Daley, C., Tuhkuri, J. and Riska, K. (1998). The role of discrete failures in local ice loads, *Cold Regions Science and Technology*, 27: 197-211.

Daley, C. (2002a). Derivation of plastic framing requirements for polar ships, *Marine Structures*, 15, 544-559.

Daley, C. (2002b). Application of plastic framing requirements for polar ships, *Marine Structures*, 15: 533-542.

DNV (2011). *Classification Notes No. 51.5, Ice Strengthening of Propulsion Machinery*, Det Norske Veritas.

Doelling, W., Delius, A. and Lembke-Jene, L. (2010). Aurora Borealis – A new European combined research icebreaker and drilling vessel, *ICETECH*, Anchorage, Alaska, 2010.

Dolny, J., Liu, S. W., Won, D., Lee, J. Y., Choi, J. H., and Kwak, M. J. (2010). Structural integrity assessment for a Polar Class Arctic tanker under Ice Loads, *ICETECH*, 20-23

Evers, K.U. and Jochmann, P. (2011). Experiences at HSVA with model testing of moored structures in ice-covered waters, *21th International Conference on Port and Ocean Engineering under Arctic Conditions*, Montréal, Canada, 10-14 July 2011.

Frederking, R., Hewitt, K. and Jordaan, I.J. (2011). Overview of the Molikqaq multi-year ice load reanalysis 2007 JIP, *21th International Conference on Port and Ocean Engineering under Arctic Conditions*, Montréal, Canada, 10-14 July 2011.

Gagnon, R.E. (2007). Results of numerical simulations of growler impact tests, *Cold Regions Science and Technology*, 49:206-214.

Gagnon, R.E. (2011). A numerical model of ice crushing using a foam analogue, *Cold Regions Science and Technology*, 65:335-350.

Gaida, K.P., Barnes, J.R. and Wright, B.D. (1983). Kulluk - An Arctic exploratory drilling unit, *Offshore Technology Conference*, 1983.

Gürtner, A. (2009). Experimental and numerical investigation of ice-structure interaction, PhD thesis, *Norwegian University of Science and Technology, Dept. of Civil and Transport Engineering*, 2009.

Hidding, W., Bonnaffoux, G. and Naciri, M. (2011). Advanced weathervaning in ice, *30th International Conference on Ocean, Offshore and Arctic Engineering*, Rotterdam, the Netherlands, 19-24 June 2011.

Hill, B.T. (2006). *Ship Iceberg Collision Database*, National Research Council of Canada.

Iyerusalimsky, A.V. and Noble, P. (2008). Design challenges for a large arctic crude oil tanker, *ICETECH*, Banff, Canada, 2008 .

Ji, S. and Yue, Q. (2011). *Numerical Modeling of Ice and Engineering Applications* (in Chinese), Since Publisher, Beijin, China.

Jordaan, I.J. and Taylor, R.S. (2011). Viscoelasticity, damage and ice behaviour in compression, *21th International Conference on Port and Ocean Engineering in Arctic Conditions*, Montreal, Canada, 10, 2011.

Jordaan, I., Bruce, J., Hewitt, K. and Frederking, R. (2011). Re-evaluation of ice loads and pressures measured in 1986 on the Molikpaq structure, *21th International Conference on Port and Ocean Engineering under Arctic Conditions*, Montréal, Canada, 10-14 July 2011.

Kim, J., Oh, H. and Kim, D. (2011). Safety assessment of cargo containment systems in LNG carriers under the impact of iceberg-ship collision, *30th International Conference on Ocean, Offshore and Arctic Engineering*, Rotterdam, The Netherlands, 19-24 June 2011.

Kioka, S., Yamamoto, Y., Mori, M. and Takeuchi, T. (2009). Medium-scale test and numerical simulation using DEM for the impact load by a high speed ice floe against a structure, *20th International Conference on Port and Ocean Engineering under Arctic Conditions*, Luleå, Sweden, 9-12 June 2009.

Kierkegaard, H. (1993). *Ship Collisions with Iceberg*, PhD thesis, Denmark Technical University, Lingby, Denmark.

Kolari, K. (2007). Damage mechanics model for brittle failure of transversely isotropic solids, *VTT Publications*, 628, 195, Espoo, Finland.

Kolari, K., Kuutti, J. and Kurkela, J. (2009). FE-simulation of continuous ice failure based on model update technique, *20th Int. Conf. on Port and Ocean Engineering Under Arctic Conditions*, Luleå, Sweden, 9-12 June 2009.

Kujala, P. (2007). *Increasing the Safety of Icebound Shipping*, Helsinki University of Technology, Ship Laboratory report, Helsinki, Finland.

Kujala, P.J. (1990). *Safety Of Ice-Strengthened Ship Hulls In The Baltic Sea*, the Royal Institution of Naval Architects, London, UK, 1990.

Kujala, P, and Arughadhoss, S. (2011). Statistical analysis of ice crushing pressures on a ship's hull during hull-ice interaction. *Cold Regions Science and Technology*, doi:10.1016/j.coldregions. 2011.09.009.

Kujala, P., Suominen, K. and Riska, K. (2009). Statistics of ice loads measured on MT Uikku in the Baltic, *20th International Conference on Port and Ocean Engineering under Arctic Conditions*, Luleå, Sweden, 9-12 June 2009.

Kuutti, J. and Kolari, K. (2010). Simulation of ice crushing experiment using FE-model update technique, *20th International Association of Hydro-Environment Engineering and Research*. 11, Lahti, Finland, 2010.

Kwak M., Choi J., Park S. and Kang J. (2010). Strength assessment for bow structure of Arctic tanker (107K) under ship-ice interaction, *Journal of Offshore and Polar Engineering*.

Lau, M., Lawrence, K.P. and Rothenburg, L. (2011). Discrete element analysis of ice loads on ships and structures, *Ships and Offshore Structures*, 6(3):211-221.

Li, C., Jordaan, I.J. and Taylor, R.S. (2010). Estimation of local ice pressure using up-crossing rate, *Journal of Offshore Mechanics and Arctic Engineering*, 132:031501-1-6.

Liu, Z. (2011). *Analytical and Numerical Analysis of Iceberg Collisions with Ship*

Structures, PhD thesis, Norweigan University of Science and Technology, Trondheim, Norway.

Liu, Z., Amdahl, J. and Løset, S. (2011). Plasticity based material model of ice and its application to ship-iceberg impacts, *Cold Regions Science and Technology*, 65:326-334.

Liu, Z. and Amdahl, J. (2010). A new formulation of the impact mechanics of ship collisions and its application to a ship-iceberg collision, *Marine Structures*, 23:360-384.

Liu, Z., Garee, L. and Amdahl, J. (2011c). Analysis of foreship and iceberg impact loads based on Bayesian networks, *30th International Conference on Ocean, Offshore and Arctic Engineering*, Rotterdam, The Netherlands, 19-24 June 2011.

Loh, J.K.S., Stamberg, J.C. and Cusack, K.P.(1984). New generation arctic drilling system: overview of first year's performance, *Offshore Technology Conference*, Houston, TX, 7-9 May 1984.

Løset, S. and Aarsnes, J.V. (2009). Icebreaking buoy in Arctic waters, *9th International Conference and Exhibition for Oil and Gas Resources Development of the Russian Arctic and CIS Continental Shelf RAO/CIS Offshore*, 1, 138-143, 2009.

LR (2008). *Provisional Rules for the Winterisation of Ships*, Lloyd Register.

Lubbad, R. and Løset, S. (2011). A numerical model for real-time simulation of ship-ice interaction, *Cold Regions Science and Technology*, 65:111-127.

Maattanen, M. and Hoikkanen, J. (1990). The effect of ice pile-up on the ice force of a conical structure, *10th International Symposium on Ice*,1990.

Marechal, G. Le, Anslot, P., Mravak, Z., Liferov, P. and Guennec, S. Le (2011). Design of a floating platform hull for arctic conditions in the Barents Sea, *Arctic Technology Conference,* Houston, TX, February 2011.

Matsuzawa, T., Takimoto, T., Shimoda, H. and Wako, D. (2010). Five-year observations of ship hull ice load in the southern sea of Okhotsk, *20th IAHR International Symposium on Ice*, 2010.

Nevel, D.E. (1992). Ice forces on cones from floes, *IAHR Symposium on Ice*, 1992.

Paavilainen, J., Tuhkuri, J. and 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. and Polojärvi, A. (2011). 2D Numerical simulations of ice rubble formation process against an inclined structure, *Cold Regions Science and Technology*, 68:20-34.

Polojärvi, A. and Tuhkuri, J. (2009). 3D Discrete numerical modelling of ridge keel punch through tests, *Cold Regions Science and Technology*, 56:18-29.

Polojärvi, A. and Tuhkuri, J. (2010). Modelling ridge keel freeze bonds in finite-discrete element method simulations, *20th International Association of Hydro-Environment Engineering and Research*, 12, Lahti, Finland, 2010.

Ralston, T.D. (1979). Plastic limit analysis of sheet ice loads on conical structures, *Conference IUTAM*, 1979.

Ranta, J., Santaoja, K. and Tuhkuri, J. (2010). Simulation of ice rubble failure against a conical structure with arbitrary Lagrangian-Eulerian finite element method, *20th IAHR International Symposium on Ice, International Association of Hydro-Environment Engineering and Research, Lahti*, Finland, 2010.

Rigor, I.G. and Wallace, J.M., (2004). Variations in the age of arctic sea ice and summer sea ice extent, *Geophysical Research Letters*, 31.

Riska, K. and Kamarainen K. (2011). A review of ice loading and the evolution of the

Finnish-Swedish Ice Class Rules, *Annual Meeting of the Society of Naval Architects and Marine Engineering*, Houston, TX.

Rothrock, D.A., Yu, Y. and Maykut, G.A. (1999). Thinning of the Arctic sea-ice cover, *Geo-physical Research Letters*, 26, 23, 3469-3472, 1999.

Sablok, A., Ramachandran, M. and Kim, J.W. (2011). Disconnectable arctic spar, *Arctic Technology Conference*, Houston, TX, February 2011.

Sand, B. (2008). Nonlinear finite element simulations of ice forces on offshore structures, PhD thesis, *Luleå Univ. of Technology, Division of Structural Engineering*, Sweden, 2008.

Sawamura, J., Riska, K. and Moan, T. (2008). Finite element analysis of fluid-ice interaction during ice bending, *19th IAHR International Symposium on Ice*, 1, 191-202, Vancouver, Canada.

Sawamura, J. and Tachibana, T. (2011). Development of a numerical simulation for rotating and sliding of the ice floes along a ship hull, *21th International Conference on Port and Ocean Engineering under Arctic Conditions*, Montréal, Canada, 10-14 July 2011.

Sayed, M. and Kubat, I. (2011). Forces on ships transiting pressured ice covers, *21th International Offshore and Polar Engineering Conference*, Hawaii, 2011.

Schulson, E.M. and Duval, P. (2009). Creep and fracture of ice, *Cambridge University Press*, Cambridge, UK, 2009.

Serré, N. (2011a). Mechanical properties of model ice ridge keels, *Cold Regions Science and Technology*, 67:89-106.

Serré, N. (2011b). Numerical modelling of ice ridge keel action on subsea structures, *Cold Regions Science and Technology*, 67:107-119.

Srinivasan, N. and Sreedhar, M.S. (2011). Circular FPSO for arctic deepwater, *Arctic Technology Conference*, Houston, TX, February 2011.

Su, B., Riska, K. and Moan, T. (2010a). A numerical method for the prediction of ship performance in level ice, *Cold Regions Science and Technology*, 60:177-188.

Taylor, R.S., Jordaan, I.J., Li, C. and Sudom, D. (2009). Local design pressures for structures in ice: analysis of full-scale data, *28th International Conference on Ocean, Offshore and Arctic Engineering*, Hawaii, HI, 2009.

Tikka, K., Riska, K. and Liu, S. (2007). Ship design considerations for safety and environmental protection of Arctic waters - learning from past experience, *Int. Symposium on Maritime Safety, Security and Environmental Protection*, Athens, Greece, October 2007.

Timco, G.W. and Weeks, W.F. (2010). A review of the engineering properties of sea ice, Cold Regions Science and Technology, 60:107-29.

TRAFI (2010). Finnish Swedish Ice Class Rules 2010, Transport Safety Agency, Helsinki, Finland.

Valanto, P. (2009). On Computed Ice Load distributions, magnitudes and lengths on ship hulls moving in level ice, *20th International Conference On Port And Ocean Engineering Under Arctic Conditions*, Luleå, Sweden, 2009.

Velikhov, E.P., Kuznetsov, V.P., Makarov, V.I., Mikhailichenko, V.V., Lavkovskiy, S.A. and Glumov, I.F. (2010). What's Going on in the Russian Arctic, ICETECH, Anchorage, Alaska, 2010.

VerDerHorn, E. and Wang, G. (2011). A statistical study on the material properties of shipbuilding steels, *International Congress of International Maritime Association of the Mediterranean (IMAM)*, Lisboa, Portugal, 2011.

Wang, B., Basu, R., Jha, A. and Winterstein, S. (2011). Reliability analysis of ice loads

on Arctic offshore structures, *21th International Conference on Port and Ocean Engineering under Arctic Conditions*, Montréal, Canada, 10-14 July 2011.

Wang, G. and Wiernicki, C.J. (2004). Using nonlinear finite element method to design ship structures for ice loads. *The Society of Naval Architects and Marine Engineering*.

Wang, G., Basu, R., Chavda, D., Liu, S.W., Lee, M.S., Suh, Y.S. and Han, Y.J. (2005). Rationalization of design of side structure of ice-strengthened tankers, *International Journal of Offshore and Polar Engineering*, 15, (3):210-4.

Wang, G., Liu, S. and Riska, K. (2006). Recent advances in structural design of ice-strengthened vessels, ICETECH, Banff, Canada, July 2006.

Wang, G., Chen, N.Z., Guo, J. and Soares Guedes, C. (2010). Application of structural reliability approach to assist hull integrity management, *11th International Symposium on Practical Design of Ships and Other Floating Structures*, Rio de Janeiro, Brazil, 19-24 September 2010.

Wang, J. and Derradji-Aouat, A. (2009). Implementation, verification and validation of the multi-surface failure envelope for ice in explicit FEA, *20th Int. Conf. on Port and Ocean Engineering Under Arctic Condition*, Luleå, Sweden, 2009.

Wang, M. and Overland, J. E. (2009). A sea ice free summer Arctic within 30 years?, *Geo-physical Research Letters*.

Wang, S.H. and Basu, R. (2007). Structural reliability levels in ice class rules, *1st MARSTRUCT International Conference*, Glasgow, UK, 12-14 March 2007.

Weeks, W.F. (2010). On sea ice, University of Alaska Press, Alaska, 2010.

Wells, J., Jordaan, I., Derradji-Aouat, A. and Taylor, R. (2011). Small-scale laboratory experiments on the indentation failure of polycrystalline ice in compression: Main results and pressure distribution, *Cold Regions Science and Technology*, 65:314-325, 2011.

Wille, S.F., Kuiper, G.L. and Metrikine, A.V. (2011). On the dynamic interaction between drifting level ice and moored downward conical structures: a critical assessment of the applicability of a beam model for the ice, *30th Int. Conf. on Ocean, Offshore and Arctic Engineering*, Rotterdam, 19-24 June 2011.

Woolgar, R.C. and Colbourne, D.B. (2010). Effects of hull–ice friction coefficient on predictions of pack ice forces for moored offshore vessels, *Ocean Engineering*, 37:296-303, 2010.

Wright, B. (1998). Moored Vessel Stationkeeping in Grand Banks Pack Ice Conditions, The National Research Council of Canada, 26-189.

Wright, B. (1999). Evaluation of Full Scale Data for Moored Vessel Stationkeeping in Pack Ice, The National Research Council of Canada, PERD/CHC Report 26-200.

Yue, Q., Guo, F. and Tuomo, K. (2009). Dynamic ice forces of slender vertical structures due to ice crushing, *Cold Regions Science and Technology*, 56:77-83, 2009.

Zhan, D., Agar, D. and He, M., Spencer, D. and Molyneux, D. (2010). Numerical simulation of ship maneuvering in pack ice, 29th International Conference on Ocean, *Offshore and Arctic Engineering*, Shanghai, China, 2010.

Zhang, S., Bridges, R. and Tong, J. (2011). Fatigue design assessment of ship structures induced by ice loading – an introduction to the ShipRight FDA ICE procedure, *21th Int. Offshore and Polar Engineering Conference*, Maui, HI, 19-24 June 2011.

Zhou, L., Su, B., Riska, K. and Moan, T. (2011). Numerical simulation of moored ship in level ice, *30th International Conference on Ocean, Offshore and Arctic Engineering*, Rotterdam, the Netherlands, 19-24 June 2011.