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STRENGTH ASSESSMENT OF ICE STRENGTHENED SHIPS

-APPLICATION IN ICE CLASS LNG CARRIER-

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PREFACE

This thesis report marks the conclusion of a two-year master program in interdisciplinary postgraduate programme of “Marine Technology and Science” of National Technical University of Athens (NTUA).

Arctic engineering and shipbuilding are the major topics of this thesis, as well as the rules and regulations beyond Arctic shipping. I would like to thank my supervisor Manolis S. Samuelides for his advises, constant supervision of the topic and for his patient.

Also I would like to thank my fellow students, George G. Tsirigotakis and Daphne Papadaki for the digital diligence of the pictures.

Last but not least, I would like to dedicate this thesis report to my parents with all my respect and gratitude.

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Alexandros A. Gioldasis

ABSTRACT

Climate changes and polar ice melting posed the researches of oil and gas exploration, development and production to Arctic Regions. In 2008, the U.S. Geological Survey estimated that the 13% and 30% of the Earth's undiscovered oil and natural gas respectively, exist in the Arctic region. Meanwhile, a viable marine route emerged and in November 2012, Liquified Natural Gas Carrier (LNGC) 'Ob River' voyaged from Norway to Japan through the Arctic Seas, establishing a new path for LNG transportations. These Arctic passages, known as Northern Sea Route (NSR) diminish the transit from Europe to Asia for approximately 13 days, concluding to fuel savings, CO_2 emission reductions and secure voyages, in contrast to the possibility of a pirate attack while transiting the high risk area of the Indian Ocean.

Due to this increase in oil and gas activities in Polar areas and climate changes, the demand for ice capable vessels has increased. This demand has reached a peak of importance for the proper designing of these ships. Unified rules concerning the structure of ice capable ships have been publiced in accordance with classification societies and maritime authorities. However, these rules are based on semi-empirical methods and as the researches are in an initial stage, more progress for an adequate, safe and efficient design of ships navigating in ice needs to be done.

The aim of this study is to investigate the unified ice class rules used by IACS and Finnish-Swedish Maritime Administration for the design of ice capable ships and the common ship-ice interaction scenarios behind each rule. The design ice loads based on this ship-ice interaction must be calculated in order to extract the required scantlings that ensure an adequate safety of ships.

The scope of the thesis is to describe the Ice Class rules in two basic ways. Firstly, all the appropriate details of the ice conditions, the Northern Sea Route features and the ice capable ship's structures are described. Ice class rules for vessels operating in ice infested waters are reviewed and principles behind the rules are compared. The categories of ice class ships and the equivalencies between the categories are notified in order to be treated in a less risky way.

Secondly, an existing ice capable ship, Liquified Natural Gas Carrier 'Lena River' – sister vessel of the above mentioned 'Ob River' – is considered, in order to estimate the design ice load and understand the structural needs for its design. The scenario for the 'Lena River' LNG Carrier is a real scenario, transiting the Northern Sea Route, in the worst ice conditions with the Administration's permission. A glancing impact on the bow, bow shoulder and midship of the vessel is being assumed and the calculations for these scenarios with the two different approved methods are made as well as with an energy-based collision method.

The calculation of the ice pressure and the design ice loads based on the ice class rules give the opportunity for useful informations to be extracted, regarding the design principles and the theory behind, as well as a great amount of details in refenence to ice characterictics and their treatment from the ice class rules.

In conclusion, the scope is after the completion of this study, the researcher to be able to clarify the basic topics of ice capable ships, the ice conditions in the Baltic, Arctic and Antarctic Seas, as well as the operational scenarios that a ship may face when navigating in ice, in order to be able to understand the methods used in ice class rules. Equivalances and differences between the two ice class rules and the difficulties in the design should be

notified. The calculations of the design ice load for the target vessel 'Lena River' gives the opportunity to identify the way to extract the appropriate scantlings and compare the design loads of the two different ice class rules. Finally, conclusions for the present ice capable ships and proposals for more efficient ship design and risk diminishment are being given as a challenge for the future.

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LIST OF ACRONYMS

ACRONYMS	DESCRIPTION
ACIA	Arctic Climate Impact Assessment
AF	Hull Area Factor
AM_x , AM_y , AM_z	Added Mass Factors in surge, sway, heave
AM_{rol} , AM_{pit} , AM_{yaw}	Added Mass Factors in rolling, pitch, yaw
AR	Aspect Ratio
(B)	Bow region
(BI)	Bow Intermediate region
BOR	Boil-Off Rate
C	Concentration of the ice floes
C_B	Block Coefficient
C_M	Midship Coefficient
C_o	Mass reduction
C_P	Prismatic Coefficient
C_W	Waterline Coefficient
CF_C	Crushing class factor
CF_D	Patch class factor
CF_{DIS} (CF_{Δ})	Displacement Class Factor
CF_F	Flexural class factor
CCS	Cargo Containment System
DAS	Double Acting Ship
DAT	Design Average Temperature
DF	Displacement Factor
DFDE	Dual Fuel Dual Engine
E	Elastic Limit State
ECA	Emission Control Action
EEDI	Energy Efficiency Design Index
F	Form of ice floes
F_n	Normal Force
FEA	Finite Elements Analysis
FEM	Finite Elements Method
FMA	Finnish Maritime Administration
FSICR	Finnish-Swedish Ice Class Rules

FY	First-Year Ice
GCMs	Global Climate Models
I_e	Impulse
IACS	International Association of Classification Societies
IE	Ice crushing Energy (Indentation Energy)
ITRP	Ice Thickness Regression Procedure
KE_n	Normal kinetic energy
LIWL	Lower Ice WaterLine
L_{pp}	Length between Perpenticular
(M)	Midship region
Me	Effective mass
MOHQs	Marine Operational Headquarters
MY	Multi-Year Ice
NSR	Northern Sea Route
NWP	North West Passage
P	Plastic Limit State
PC	Polar Class
PE	Potential Energy
PIOMAS	Pan-Arctic Ice-Ocean Modeling and Assimination System
PPF	Pressure Peak Factor
Q, (q)	Line Load
RMRS	Russian Maritime Register of Shipping
S	Stage of development of ice floes
(S)	Stern region
SPS	Sandwich Plate System
U	Ultimate Limit State
UIWL	Upper Ice WaterLine
URs	Unified Rules
V_{SHIP}	Velocity of the ship
V_n	Normal Velocity of the ship
WMO	World Meteorological Organization
A	Shear Area
A_{wp}	Longitudinal Area in the UIWL
Δ, Δ_{SHIP}, M_{SHIP}, D	Displacement

Z	Frame Section Modulus
Z_p	Net effective plastic section modulus of transverse frame
a	Longitudinal design span
c_d	Factor that depend on the size & engine output (FSICR)
c_p	Factor that depends on the probability that the design ice pressure occurs in a certain region of the hull (FSICR)
c_a	Factor that depends on the ice load length (FSICR)
f_a	Shape Coefficient
ex	Ice exponent
h	Height of the load patch
h_o	Level ice thickness
l	Frame span
l, m, n	Direction cosines
l_a	Load length
p_{avg}, p	Design ice pressure
p_o	Nominal ice pressure
rx^2, ry^2, rz^2	Squared mass radii of gyration
s	Frame space
t_c	Increment of abrasion and corrosion
t_{net}	Plate thickness required to resist ice loads
v_b	Brine volume fraction
w	Width of the load patch
α	Upper ice waterline angle
β	Frame angle in UIWL
β', θ	Normal frame angle (flare angle)
γ	Buttock (sheer) angle at upper ice waterline
δ_m	Maximum penetration depth
μl, λl, nl	Moment arm in pitch, roll, yaw
σ_f	Ice flexural strength
σ_y	Minimum yield strength of the material
φ	Ice edge angle

I. INTRODUCTION

In early November 2012, the Ob River Liquified Natural Gas (LNG) carrier – a ship operated by Dynagas LTD – made a remarkable voyage when she became the world's first LNG Carrier to transit and carry a cargo through the Northern Sea Route (NSR). Built in 2007, the LNG carrier 'Ob River' is properly equipped to operate in low-temperature conditions.

The vessel departed from the Port of Hammerfest (Norway) on November, 7 and arrived at the regasification terminal in the Port of Tobata (Japan), delivering a Gazprom Group-owned LNG cargo to Japanese consumers. When sailing across the Northern Sea Route (NSR), the ship was escorted by atomic icebreakers led by two ice masters. During the voyage between Barent Sea and the Kara Sea (Figure IV-1), not much ice in the waters found, but during the second half of the passage, from the Vikitski Strait to the Bering Strait, the LNG carrier was headed through young ice with the thickness reaching 30 centimeters.

As a result, LNG carrier 'Ob River' via the NSR saved :

- time for delivering cargos (13 days),
- 40% fuels via 40% shorter voyage,
- losses from LNG evaporation - resulting to increase of delivered gas volumes (0.1% to 0.15% boil-off rate per date),
- CO_2 emissions and
- mitigating risks of pirates attack during the voyage .

All these lead to an attractive and reliable solution for the LNG interregional trade [22].

1. GENERAL INFORMATIONS

Global climate changes – especially melting of sea ice– araise opportunities for international marine transportation networks in the Arctic. However, these routes are not without risk and a potential disaster in the Arctic or Antarctic Seas would be considered equivalent to environmental tragedies such as the Exxon Valdez oil spill.

Finnish-Swedish Ice Class Rules (FSICR) [53] and International Association of Classification Societies (IACS) Polar Class Unified Requirements [3] have been introduced to ice-capable ships operating in Baltic and Polar Seas respectively, in order to diminish risk of damages due to ship-ice impacts. Special attention was given to the proper design of the hull of the ship, machinery equipments, propulsion system and winterization of material's choice for both hull and equipment on open deck, important for the proper operation of the ship in severe ice conditions.

The choice of the appropriate ice class vessel influences the timeplan of the shipowners, due to permission or not of the Northern Sea Route during the year-round ice conditions. The emerging market of ice strengthened merchant vessel poses a challenge to the balance of safety and commercial flexibility between low lightship in open waters and efficient operation in harsh ice conditions [7].

In order to choose the appropriate class notation, shipowners, shipbuilders and engine builders, known as the Interested Parties, should be thoroughly informed of the operational spectrum of the ice capable ship, the theory and the steps behind the ice formation and the ice conditions when sailing in particular ice covered seas. The development of the ice shipping is in progress, but nobody can predict with certainty if there is going to be a boost in the construction and the operation of ice capable ships. However, a good understanding of the scientific approach of the topic can be the first step for the Interested Parties.

A ship operating in Baltic or Arctic/Antarctic Seas face different ice conditions. The ice conditions differ regionally and seasonally, leading to soft, medium or severe conditions for navigation. Moreover, depending on the ice class notation, ice capable ships can navigate independently or escorted by icebreakers in ice infested waters.

In order to evaluate the analysis behind the design properties, the design ice load and the ice strengthened hull and propeller should be determined. The determination of the design ice load is the key for the assessment of the scantlings of the ship, the hull structure and the materials that are appropriate for low temperatures.

In the forthcoming chapters, the mandatory requirement of analysing the basic factors of ice navigation is being held, giving special concern to ice characterictics [9], operational requirements when navigating in certain ice infested waters [10] and design rules and regulations, established by Classification Societies and Maritime Administrations [3], [5].

2. OBJECT OF THE THESIS

The topics of major concern for this thesis are the following:

- Ice characteristics in ice-infested seas and new marine transportation routes in northern seas.
- Identification of the basic rules and regulations used by Classification Societies and Marine Administrations, in reference to ice capable ships, as well as the theory beyond them.
- Equivalances and differences between these ice class rules and the consequences in the design of the ice capable vessel.
- The methodology, rules and regulations used in each Ice Class in order to determine the design ice load and the scantlings of an ice capable ship.
- The design ice load and scantlings of the shell plates of a target vessel, LNG – Carrier 'Lena River', – sister vessel of the above mentioned 'Ob River' – as well as the confirmation of the final construction, in accordant with the rules of each ice class rules.
- Challenges that the arctic shipping will face in the future.

The results show that the design scenarios used in FSICR and IACS Polar Rules have similarities, in reference to ship's structure, design ice loads and scantlings, but also many differences either in the shell reinforcement, the design scenarios followed or the final construction. After analysing the basic topics for the construction of ice capable ships, the example of LNG – Carrier 'Lena River' shows that the target vessel is treated by IACS Polar Rules and FSICR equivalently, but also differences found. IACS polar rules derive from an energy-based method that give very similar results to the ones extracted from the IACS equations.

3. LAYOUT OF THE THESIS

Firstly, an introduction to the basic factors for the decision of the appropriate ice class ship and a familiarization with the types and characteristics of ice operation is given, based on ice conditions, operational spectrum and ship design.

Secondly, the ice characteristics and the formation of ice in low temperature are presented in order to give the opportunity to the reader to understand the different types of ice, based on the age and form.

Northern Sea Route can boost the development of shipping industry of ice capable ships and lead to a promising solution for maritime transportation. That is the reason why the Northern Sea Route is described, specifying the different regions that the route is divided to, the periods of the year that different ice conditions are being faced and the requirements that the vessels are obliged to fulfill.

After the description of the general conditions and the geographical areas that the ice capable ship operates, the priority area is the design of ice capable ships. The history and basic informations regarding the design of these ships is presented, emphasizing to the design scenario, the basic meanings and the theory beyond.

Furthermore, in Chapter VII, the two major, ice class rules are analysed: the Finnish-Swedish Ice Class Rules (FSICR) and the IACS Polar Class Rules. Both groups of rules and regulations estimate the appropriate design ice load and the relative load patch, the assessment of the scantlings and the structural differences for each ice class vessel. As the design ice load of IACS Polar class rules derive from a semi-empirical method, based on the impact of the ship with the ice floe, this method is also analysed. Similarities and differences between the methods are extracted and presented.

As the theory of the ice class rules, the design ice load and scantlings have been completed, the next chapter is the application of the theory to the target vessel, LNG-Carrier 'Lena River' and the calculation of the design ice loads and scantlings with the above mentioned methods. The scope is the reader to be able to identify in practise the basic topics of arctic engineering and cope with the differences and similarities of each ice class rules.

Finally, the future challenges and the conclusions from the research are presented in the last two chapters (Chapters X & XI), giving the opportunity to the reader to start a discussion, regarding the major topics about the present and the future of ice capable ships.

II. FAMILIARIZATION WITH ICE CLASS SHIPS

1. INTRODUCTION TO ICE CLASS RULES

Ships navigating in ice, face harsh conditions and should be reinforced properly. This is achieved by a special set of Classification Rules, the Ice Class Rules. Ice Class Rules provide standards for additional strengthening of the hull structure and machinery, and increased engine power to enable force its way through the ice. Ice thickness is the basic factor in order to distinguish ice classes. Nevertheless, ice thickness is not the only factor of high concern. The factors that contribute to the decision of the appropriate ice class may be principally divided into three groups [7]:

- *The environment*
  The environment includes all meteorological and geological features that a ship may face when navigating in ice conditions such as ice thickness, but also ice ridges, winds and sea currents, and weather status.
- *The operational scenario*
  Ships intending to navigate in ice should be familiar with the appropriate National Administration's requirements and request icebreaker assistance or sail on convoys. Safe speed when navigating in ice and ability to manuever in ice are factors for the division of the ship to the proper ice class.
- *The ship design*
  Size of ship, hull form and propulsion are matters that a ship owner should take care of before constructing an ice capable ship for certain ice operation.

The choice of the right ice class vessel is a very important issue for the operational schedule of the ship and the ability or not to navigate in ice in certain periods of the year. For each advancement in ice class, the steel weight, machinery and engine power increase and a subsequent increase in the cost of the ship happens. However, this cost is usually offset by the enhanced operation and/or lower icebreaking fees.

Navigation in Baltic seas differ from navigation in Arctic or Antarctic and these differences have a repercussion in the design of the appropriate ship for the relevant operation. The main difference is the characterictics of ice. First-year ice (FY) and multi-year ice (MY) are the two forms that can be found in ice infested environment. First-year ice is the sea ice that present during the winter only, as in the summer melts entirely. Baltic sea and St Lawrence Seaway are covered in winter with first-year ice. Multi-year is thicker and much stronger than first-year ice and has survived at least one summer. Multi-year ice happens in Arctic and Antarctic seas.

In brief, Finnish-Swedish Ice Class Rules (FSICR) correspond to first-year ice and thus, Baltic Seas, while the Polar Ice Class Rules are related to multi-year ice and Arctic/Antarctic Seas. The ice class requirements can be divided into three parts:

- Hull strengthening

Hull strengthening is the basic way to protect the hull from damages through ice collision. The hull is strengthened along an icebelt. For first-year ice class, this is taken in side shell area between the maximum and the minimun draught waterlines that the ship is intended to navigate in ice. For multi-year ice, this includes the side shell area, as well as the bilge and bottom regions. For each advancement in ice class, steel weight increase approximately 30%.

- Increased engine power

Additional power to navigate through ice is needed in order to face ice conditions and not to delay the operational scenario. Extra power for manuevering as well as ice devices are required.

- Machinery strenghtening

The propeller, shaft and reduction gears are enhanced to provide protection against ice loads. Also, the steering gear, sea water inlets, overboard discharges and fire pumps also require arrangements to protect against ice damage and blockage.

2. CLASSIFICATION OF FACTORS FOR THE CHOISE OF AN ICE CLASS SHIP

The choice of the proper ice class is based on factors, that are divided into three basic categories:

1. The environment

The region where the ship is intended to operate and the environment therein, is one of the major contributing elements for the choise of the right ice class. Although the ice classes are mainly chosen for the maximum ice thickness in the area of operation, there is a variety of different ice obstacles that the ship should overpass.

When sea ice conditions are mentioned, three fundamental features should be described; air temperature, sea conditions and geographical features.

Air temperature

Basic factor for the good operation of the ship's equipments and the strength of the structure is the air temperature. Below zero, the sea ice is expected to start its formation and navigation restriction at the region starts when the weather conditions become harsh.

Sea conditions

Ice characterictics of a specific sea region, such as salinity, sea state and wind currents are included into the sea conditions. The less salinity sea water has, the stronger the ice becomes. Wind currents are responsible for the movement of icebergs and the creation of ice ridges.

Geological features

Geological features include items such as the depth of water (shallow ice is generally more susceptible to temperature) and proximity to land.

2. The operational scenario

The ice class rules cover a vast range of ice conditions and hence, a vast range of operations. Examples of operations include acting in convoys, ramming against ice ridges, manoveuring in channels, all of which have a different ice loading. Additionally, the way ship operates in these ice conditions have a significant impact on the integrity of the ship.

Speed in ice

Navigating in a safe speed in an ice channel independently or escorted by an icebreaker is very important in order to choose the right ice capable ship. A ship with larger engine power will be able to travel faster in ice, navigate into thicker ice conditions and impact the ice at a higher speed. Thus, the ship will be subjected to larger ice forces.

In all ice class rules, the hull strength of the vessel depends on her speed, directly or indirectly. The ice/speed relationship in Finnish-Swedish Ice Class Rules (FSICR) is included in the assessment of the design ice loads by the engine power, while in IACS Polar Class Rules, ship's speed is a factor of the ice crushing/flexural strength for the estimation of ice force.

Duration of the voyage in ice

A ship operating all year round Baltic or Arctic/Antarctic seas, should be chosen for the appropriate operational environment. The design of an ice class ship is detrimental to the open water performance (as the ship becomes heavier and slower). The ice class should be chosen properly, so that the ship is still competitive in open water.

Icebreakers - Escort and Convoys

Navigation in ice can be broadly categorised into five modes of sailing:

- Independent in level ice
- Independent in channel ice
- Icebreaker escort (Singularly)
- Icebreaker escort (In convoy)
- Towed by an icebreaker

The mode of sailing is assumed within the ice class rules and the requirements of the Maritime Administration.

Administration Requirements

The main targets of the Maritime Administration are ensuring safe navigation and protection of marine environment and their territorial waters from pollution. Maritime Administrations require fairway dues to reinforce traffic restrictions. The fairway dues are usually in relation to the ice class. The higher ice class a ship is, the lower fee she pays.

Owner Requirements

The decision for the appropriate ice class vessel is planned by the Owner of the ship. A high ice class vessel is not cost efficient if the operation spectrum is mostly in open waters, while it can be suitable if she operates only in Arctic, e.g. for researches in arctic seas.

4. Design of the Ship

Hull strengthening

The level of hull strengthening in ice class rules is related to the ice conditions and most of the rules use an ice scenario as a design basic. IACS PC rules use a glancing impact to the bow region, while the Finnish-Swedish ice class rules use the contact with level ice, where the process assumes the ship contacts the ice at an angle to create a force which precipicates bending of the ice until breakage. The exact contact loads vary due to ice conditions, ship speeds, hull angles and hydrodynamic components.

Propulsion

An ice-strengthened hull must suit to the appropriate propulsion system. The selection of the propulsion system is an important part in determining the capability of the ship in ice.

The ship speed is relatively slow when navigating in ice, but the demand for manuverability and propulsion in unbroken ice make the strong propulsion systems compulsory for higher ice classes. On the other hand, increasing the ice performance of the propulsion system will usually decrease the open water performance and increase the cost.

Size of ship

Traditionally, ice class ships were small ships and the predominant nature of transportation was limited to feeder service. Nowadays, with the exploration, development and production of oil and natural gas in the Arctic regions, large ice class LNG and oil carriers are needed. The size of the ship is vital for the selection of the ice class. Small ships, except of the icebreakers, have a relatively small engine power and they are more likely to become entrapped in the ice due to absence of enough power to force their way out of the ice. Larger ships are less likely to become trapped in ice, due to the greater inertia, and they have to move through ice ridges and obstacles. However, larger ships are less manoeuvrable, and thus turning in a channel becomes more difficult, exposing the hull to larger ice loads.

3. THE FUTURE OF ICE CLASS

As greater amount of ice capable ships operate in ice infested seas with concern to the above mentioned factors, higher knowledge of the environment, ice operations, ship performance and machinery, and structural analysis are gained and the requirements for ice class will be developed in order to include further fields and diminish the risk of navigation in ice conditions. Classification Societies, Maritime Administrations, research institutes, merchant ship owners and operators involve in the task to make navigation in ice safer. The future of ice class rules is uncertain, but some of the possible avenues of development are under examination.

A unified and detailed description, in terms of ice conditions (ice ridges, ice drift, etc) and operations (ramming, escort, etc) should be developed for the purpose of providing additional consistency to the ice class rules. Furthermore, speed when navigating in ice plays a significant role. Scenarios, such as operations in brash ice, in level ice, ramming against ice and going astern demand a separate set of requirements for engine power and hull reinforcement. Researches in this field of engineering will improve the operations of the ships in ice-infested seas.

In particular, one future challenge is to provide requirements for double acting ships. Double acting ships are able to proceed forwards to thin ice and astern in thick ice, by utilising an azipod system (which acts as a pump to flush the hull). Particular operation modes for double acting ships can be intergrated with individual scenarios.

Another issue is the cold operation or winterisation. Operating at low temperatures effects a number of items on the ship, such as hull material grades, engine air intakes, ballast tank heating, deck equipment, sea chest icing and stability.

The development of these requirements should be incorporated using the same principals that were mentioned above, thus, developing the requirements based on individual scenarios combining environmental, operational and ship design. The ice class rules that exist nowadays for the Baltic, Arctic and Antarctic Seas incorporate some of this scenarios for the construction of the ice class vessels, but exclude many others [7].

The choise of the appropriate ice class is a very complex issue. In the next chapters, a description of the above mentioned factors is planned, in order an amount of details, regarding ice characterictics, operational conditions in ice-infested waters and design properties to be provided.

III. ICE CHARACTERICTICS

In this chapter, the physical and mechanical characterictics of ice are classified in different types, based on macro description. Understanding the ice formation is very important in order to distinguish the ice characterictics.

1. ICE FORMATION AT SEA

Sea ice is a solid sheet, a polycrystalline continuum with sub-structure according to the formation mechanism into congelation ice, snow-ice and frazil ice. Ice formation at sea is completely different from that at rivers and lakes, and the reason is the present of salt in sea water. Sea water has a salinity of 35 parts per thousand (ppt or ‰) and a freezing point of -1.8 °C. The salinity of ocean water in winter period is about 30 – 34 ‰, while in summer, due to the rivers run off and the melting of sea ice, there is a drop to 25 – 30 ‰ .

When the air temperature drops below -1.8 °C, the surface of the sea water is cooled and becomes colder and denser than the sea water below. As a result, the upper cool layer sink and replaced by warmer or less saline water. This process continues until the deep lower layers that are denser and with higher salility (35 ‰) to be unable to replace the cool upper layers. During this period, a layer of 10 – 20 meters of sea water has reached the freezing point. Sea ice has not appeared, yet.

Once these 10 – 20 meters remain cold and the air temperature is at or below -1.8 °C, small crystals of some centimeters start to form and rise up to the surface of the upper layer. These crystals are called *frazil*. At first, a thin layer of *slush* is formed as the crystals link, giving a mat, oily appearance to the sea. If the conditions are proper and surface is calm, ice crystals come together to form ice rind of solid ice. Otherwise, if waves disturb the calmness of the sea, rounded dics are formed, called *pancake ice* [13].

All these different types and formations of ice will be present in the following sections of this chapter.

2. PARAMETERS OF DESCRIPTION

The age and form of the ice are the basic parameters in order to classify the sea ice.

New ice, young ice, first-year ice and old or multi-year ice are categories mainly reflecting the age of the ice. The age of the ice is the main factor for understanding the ice thickness and strength.

However, due to different weather conditions, ice can be compressed and form ice ridges. Numerous forms of ice can be found.

The following descriptions are extracted from a glossary, which was based on the standard definitions published by the World Meteorological Organization [9].

Macro description according to the age of the ice

The age of the ice is an important parameter as it influences the mechanical properties of the ice. In fact, the strength of the ice depends on the volume of salt water in the ice (brine volume). This volume of salt water decreases significantly when the ice partially melts

during the summer/autumn season, as the brine is drained through the porosity of the ice because of the gravity. Thus an old ice contains less brine and that's the reason why multi year ice is notably stronger than young ice.
The classification of ice according to the age comes as follows:
1. New ice

A general term for recently formed ice which includes frazil ice, grease ice, slush, shuga and nilas.

- Frazil ice

Frazil ice formation represents the first stage of sea ice growth. Frazil is the slurry of ice flakes. The frazil crystals are usually suspended in the top few centimeters of the surface layer of the ocean and give the water an oily appearence [13].

Figure III-1:Frazil ice [9]

- Grease ice

A later stage of freezing the frazil ice when the crystals have coagulated to form a soupy layer on the surface. Grease ice reflects little light, giving the surface a matt appearance and behaves in a viscous fluid-like manner.

Figure III-2: Grease ice [9]

- Slush

Snow which is saturated and mixed with water on land or ice surfaces, or as a viscous floating mass in water after heavy snowfall.

- Shuga

An accumulation of spongy white lumps, a few centimeters across, which are formed from grease ice or slush and sometimes from anchor ice rising to the surface.

Figure III-3: Shuga [9]

- Nilas

A thin elastic crust of ice, easily bending on waves and swell, and under pressure, thrusting in a pattern of interlocking «fingers» (finger rafting). Has a matt surface and is up to 10 cm in thickness [13]. May be subdivided into dark nilas and light nilas.

Figure III-4: Nilas [9]

2. Young ice

Young ice is the coalescence of pancake ice and remaining ice rind, forming a solid ice layer of 10-30 cm in thickness. The crystals of ice are approximately 1mm in diameter. Young ice is the stage between nilas and first-year ice. May be subdivided into grey ice and grey-white ice.

- Grey ice

Young ice is 10-15 cm thick and less elastic than nilas and breaks on swell. Usually rafts under pressure.

- Grey-white ice

Young ice is 15-30 cm thick and under pressure more likely to ridge than to raft.

Figure III-5: Grey-White ice [9]

3. First-year ice

Once a solid layer of ice forms, a new freezing procedure starts. The layer of young ice will continue growing from the bottom of the layer, downwards [13]. However, it is the formation of one winter's growth; thickness (typically) 30 cm – 2 m. May be subdivided into thin, first-year ice and thick, first-year ice.

Thin, first-year ice is 30-70 cm thick, medium first-year ice is 70-120 cm thick, and thick, first-year ice is over 120 cm thick. First-year ice may be thicker than 200 cm when it is in the form of ridges.

Figure III-6: First-year ice [9]

4. Second-year ice

Solid ice layer that has survived one summer's melt. As it is thicker and less dense than first-year ice, it stands higher out of the water and due to its less salinity content, it is stronger than first year ice. Second-year ice is the most common form of old ice present in Antarctica and some regions in Arctic.

During summer season, the temperature of the sea water raises and melt the bottom surface of ice, while snow turns to melting pools on the ice cover. Ice floes drift around, due to winds and ice currents. Then, in second winter season, remaining ice with drifting ice floes are the base for the new ice formation that leads to a diversified ice thickness with ridges and rafts [13].

5. Multi-year ice

Old ice up to 3 m or thicker which has survived at least two summers' melts is defined as multi year ice. Compressive stresses cause new ridges to form, while old ridges become smooth from melting processes. These ridges are called *hummocks* and the ice is almost salt-free. Color, where bare, is usually blue [13].

Macro description according to the form of the ice

The form of the ice is also of great importance for the evaluation of the loads due to the ice environment that the ship or the structure is going to evolve in [9].

Brash ice

Accumulations of floating ice made up of fragments not more than 2 m across; the wreckage of the other forms of ice. Brash is common between colliding floes or in regions where pressure ridges have collapsed.

Figure III-7: Brash ice [9]

Fast ice

Sea ice which forms and remains fast along the coast, where it attached to the shore, to an ice wall, to an ice front, between shoals or grounded icebergs. Fast ice may be formed in situ from sea water or by freezing of pack ice of any age to the shore, and it may extend a few meters or several hundred kilometers from the coast. Fast ice may then be prefixed with the appropriate age category (old, second-year, or multi-year).

Figure III-8: Fast ice [9]

Floe

A floe is any continuous piece of sea ice. Floes may be descrided in terms of several size categories:

- Giant: over 10 km across
- Vast: 2-10 km across
- Big: 500-2000 m across
- Medium: 100-500 m across
- Small: 20-100 m across
- Floes less than 20 m across are called cake ice

Figure III-9: Floe [9]

Pack ice

Term used in a wide sense to include any area of sea ice, other than fast ice, no matter what form it takes or how it is disposed.

The pack can be described as very open (with an ice concentracion of 1/10 to 3/10), open (4/10 to 6/10, with many leads and polynyas and the floes mostly in contact), very close (9/10 to less than 10/10), and compact (10/10, with no water visible, called consolidated pack ice if the floes are frozen together).

Figure III-10: Pack ice [9]

Pancake ice

Predominantly circular pieces of ice from 30 cm – 3 m in diameter, and up to 10 cm thickness (unrafted) with raised rims due to the pieces striking against one another. It may be formed on a slight swell from grease ice, shuga or slush or as the result of the breaking of ice rind, nilas or, under severe conditions of swell or waves, of grey ice.

Figure III-11: Pancake ice [9]

Rafting

Due to wind and water currents, one piece of ice overrides another. This compression process is commonly seen in new and yound ice. It is the dominant, dynamic mechanicm whereby floes reach about 0.4 and 0.6 m thick in the early stages of ice development. Beyond this thickness, converging floes are more likely to form ridges than to raft.

Figure III-12: Rafting [9]

Ridging

A ridge is a line or wall of broken ice forced up by pressure. When two ice sheets forced to become one, then ridges are formed. They can divided to pressure and shear ridges, according to the movement of the sheets. May be fresh or weathered. The submerged volume of broken ice under a ridge, forced downwards by pressure, is termed an ice keel.

Figure III-13: Ridging [9]

Iceberg

A massive piece of ice of greatly varying shape, more than 5 m above sea-level, which has broken away from glacier (or an ice shelf), and which may be afloat or aground. Icebergs may be described as tabular, dome-shaped, sloping, pinnacled, weathered or glacier bergs (an irregular shaped iceberg). Icebergs are not sea ice. When they melt they add fresh water to the ocean.

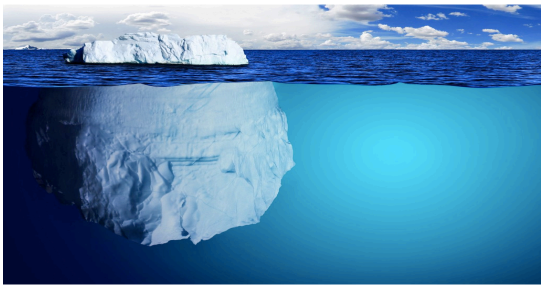


Figure III-14: Iceberg [9]

3. ICE AND WEATHER CONDITIONS

Based on [45], the natural ice cover is commonly dynamic because of the driving forces that are caused by the drag of the winds or currents. The ice motion creates different zones of ice. Close to the shore is the fast ice zone where ice is not broken and stays stationary due to the support of the outer islands or a grounded ridge zone. In some coastlines this zone is extensive (for example in Pechora Sea in Russia) but in steep coastlines without islands, this zone may be negligible (like north-east coast of Sakhalin). Outside of the fast ice zone ice cover is broken and moving. The zone where the effect of the coastline is felt is called the transition zone. Example of this kind of sea is the northernmost Baltic (westerly winds push ice against the Finnish coastline).

In those transition zones where ice cover is often converging, the ice coverage tends to be 100% with heavy ridging. If the ice is diverging in the transition zone (like in many Antarctic seas) the coverage tends to be less and ridging less intense. The ridge size in the transition zone is stochastic. The statistics of ridges has been studied much and most often it is concluded that the ridge size (and density) follow an exponential probability distribution.

Finally, outside the transition zone is the pack ice zone. Some scientists state that the only pure pack ice zone is formed in the Arctic Pack- it is however difficult to see the difference between the transition zone and the pack ice zone and anyhow this difference does not matter for ship design. These different ice zones are illustrated in Figure III-15.

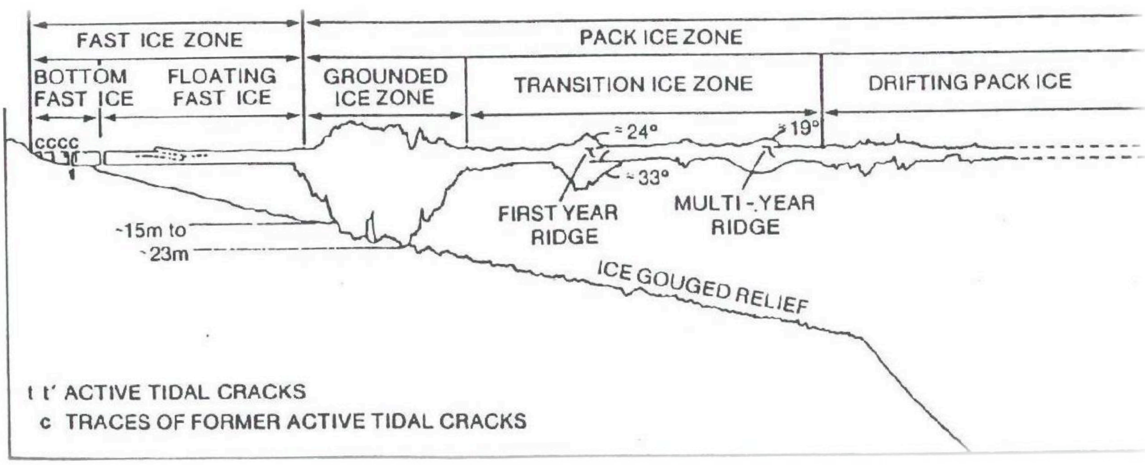


Figure III-15: The ice zones in a sea ice cover [45]

4. ICE PARAMETERS

A ship sailing in first-year ice will not encounter only level ice, but also ice ridges, rafts, open water as well as bergy bits and icebergs. So, an ice pilot and icebreaker captain should be thoroughly informed of the ice parameters needed for safe navigation. The data of the ice cover required are given in Table III-1 [45].

Coverage of ice	C	Portion of sea surface covered by ice (given usually in tenths of ice
Level ice thickness	h_i	If there are several different thicknesses, these are given versus the
Average maximum thickness of ice ridges	H_R	This thickness usually ignores the part above water which is called sail
Density of ridges	μ	Number of ridges sail along a straight route segment (in units of

Table III-1: Ice parameters needed for the navigation in ice [45]

Typical ice coverage in stationary ice is about 90% and maximum level ice thickness typically in first year ice areas is 1 m (Baltic) and 2 m in the Arctic. Average ridge thickness in the Baltic is about 5 m whereas the ridge density varies from 4 to 10 ridges/km. If the average ridge thickness is more than 10 m, the ice conditions can be considered severe.

The basic data concern concentrations, stages of development and form (floes size) of ice are contained in a simple oval form (Figure III-16). The oval and the coding associated with it are referred to as “Egg Code” and is the basic system used by World Meteorology Organization (WMO) for sea ice symbology [54].

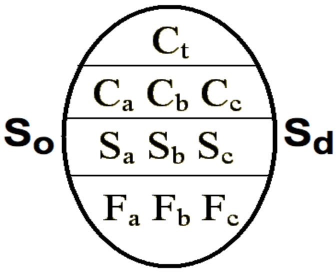


Figure III-16: WMO sea ice symbology [54]

The system encompasses ice elements and features which can be grouped under the following headings [27]:

a. Concentration (C);
b. Stage of development (S);
c. Form of ice (F);
d. Water openings;
e. Topography;
f. Ice thickness;
g. Stage of melting;
h. Surface features;
i. Ice of land origin;
j. Limits
k. Strips and patches

Concentration (C)

C_t – Total concentration of ice in the area, reported in tenths

C_a C_b C_c – Partial concentrations of thickest (C_a), second thickest (C_b) and third thickest (C_c) ice, in tenths.

Stage of development (S)

$S_aS_bS_c$ – Stage of development of thickest (S_a), second thickest (S_b) and third thickest (S_c) ice, of which the concentrations are reported by C_a,C_b,C_c, respectively (Table III-3).

S_o – stage of development of ice thicker than S_a but having a concentration of less than 1/10;

S_d – stage of development of any other remaining class.

Form of ice (F)

$F_aF_bF_c$ – form of ice (floe size) corresponding to S_a, S_b and S_c, respectively (Table III-3).

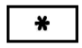
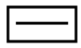
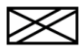
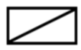
Numerical classification in Volime I	Element	Thickness	Symbol	Alternative symbol
	No stage of development	-	0	
2.1	New ice	-	1	
2.2	Nilas; ice rind	<10 cm	2	
2.4	Young ice	10-30 cm	3	
2.4.1	Gray ice	10-15 cm	4	
2.4.2	Gray-white ice	15-30 cm	5	
2.5	First-year ice	30-200 cm	6	
2.5.1	Thin first-year ice	30-70 cm	7	
2.5.1a	Thin first-year ice, first stage	30-50 cm	8	
2.5.1b	Thin first-year ice, second stage	50-70 cm	9	
2.5.2	Medium first-year ice	70-120 cm	1•	
2.5.3	Thick first-year ice	>120 cm	4•	
2.6	Old ice		7•	
2.6.1	Second-year ice		8•	
2.6.2	Multi-year ice		9•	
10.4	Ice of land origin			
	Undetermined or unknown		x	

Table III-2: Stage of development and thickness (So,Sa,Sb,Sc,Sd) [27].

Element	Symbol	Size
New ice	x	(0-10 cm)
Pancake ice	0	(30 cm -3 m)
Small ice cake; brash ice	1	(<2 m)
Ice cake	2	(3 – 20 m)
Small floe	3	(20 – 100 m)
Medium floe	4	(100 – 500 m)
Big floe	5	(500 m – 2 km)
Vast floe	6	(2 - 10 km)
Giant floe	7	(>10 km)
Fast ice, growlers or floebergs	8	
Icebergs	9	
Undetermined or unknown	/	

Table III-3: Forms of ice [27].

IV. NAVIGATION IN NORTHERN SEA ROUTE (NSR)

The operational scenario is very important for the proper navigation of the vessel and many informations can be extracted from the geographical characterictics of the specific route that the vessel is intended to proceed.

In this chapter, the Northern Sea Route is described. Details regarding the geography, weather conditions and navigation requirements and instructions are presented, giving emphasis to the new paths that are about to open, if this routes are used in a proper way.

1. THE RUSSIAN ARCTIC: GENERAL PARTICULARS

Northern Sea Route (NSR) is established as the Russian national transportation sea route which is suited within a water area adjacent to the northern coast of the Russian Federation. Navigation via the Northern Sea Route should comply with the Russian legislation, administrative procedures and international agreements of the Russian Federation.

Northern Sea Route does not define a single passage, but a number of alternative passages. Novaya Zemlya (Cape Zhelanie) in the east (68º 35’ E), which sits astride the Barents and Kara Seas and the Bering Strait (Cape Dezhnyov) in the west (168º 58’ 37’’ W), which divides Alaska and the eastern-most tip of the Russian mainland, are the physical limits (Figure IV-1). The route is some 2.500 nautical miles long and can be transited by ice-capable merchant vessels. Within this boundaries, all vessels are required to follow special rules known as the ‘Rules of navigation on the water area of the Northern Sea Route’ and comply ‘The Federal Law of Shipping on the Water Area of the Northern Sea Route’ [10].

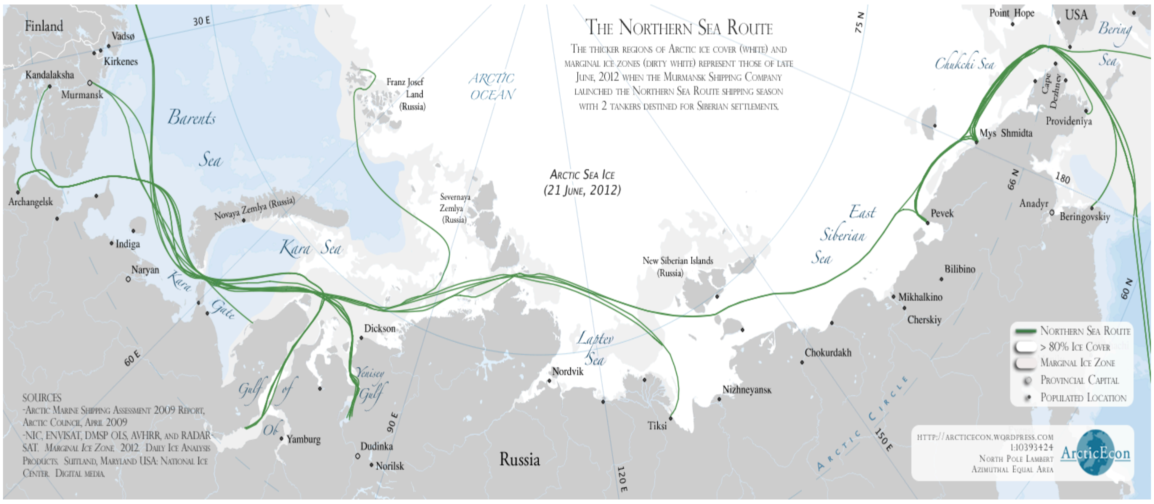


Figure IV-1: Northern Sea Route (NSR) [6].

Several marine route distances are notable: from Murmansk to the Bering Strait is 3,074 nautical miles; and the Northern Sea Route from Kara Gate to the Bering Strait is 2,551 nautical miles. The Dudinka to Murmansk marine route that is maintained year round is 1,343 nautical miles, while it is approximately 500 nautical miles between the offshore region of the Pechora Sea (site of new oil terminals) in the southeast corner of the Barents Sea and Murmansk. The average time spent at Northern Sea Route on autumn/summer period is about 10 – 12 days, while on spring/winter increases to 16 – 20 days, depending on the weather conditions.

Compared with the Canadian Arctic, the Russian maritime Arctic has many more viable ports located along the length of the NSR. Primary NSR ports from west to east include: Amderma, Dikson, Yamburg (Ob' Gulf), Dudinka (north Yenisei River), Igarka (south Yenisei River), Khatanga (Khatanga River on the Laptev Sea), Tiksi (Tiksi Gulf near the Lena River), Zeleny Mys (Kolyma River) and Pevek. There are several options and routes for navigation in the Russian Arctic, Figure IV-2 [37].

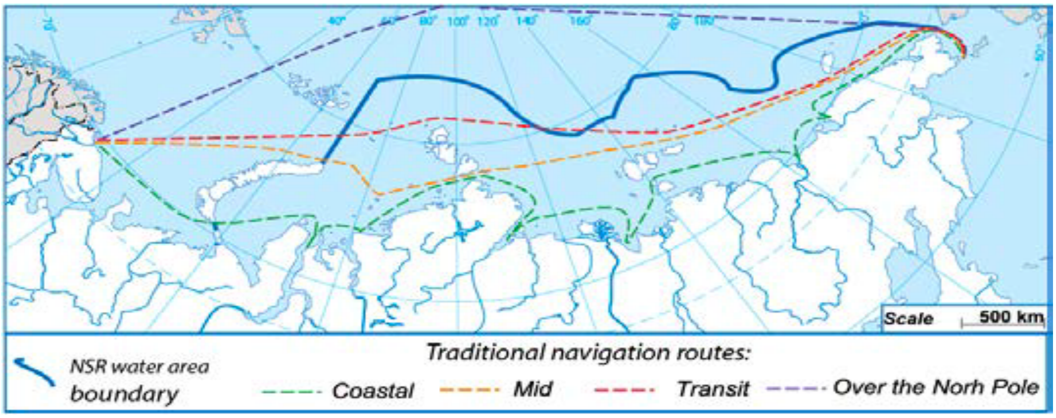


Figure IV-2: Traditional navigation routes in the Russian Arctic and NSR boundaries [32].

The Russian Arctic seas are very similar in nature. All belong to a group of marginal seas, that almost entirely located within the Arctic shelf and lie north of the Arctic Circle. They are delimited by natural boundaries, including the coast of Eurasia to the south. To the north, they widely and freely mix with the Arctic Ocean and are separated from it by conventional boundaries, i.e. lines passing around the edge of the shelf. The seas are separated from each other also by conventional lines and by the archipelagos of the New Siberian Islands, Severnaya Zemlya, and Wrangel Island. [38].

Northern Sea Route Administration was established to organize navigation in the water of Northern Sea Route. This Administration is split in two Marine Operational Headquarters (MOHQs), the division being the 125º east longitude. The western sector is under the responsibility of the Murmansk Shipping Company (MSCO), operating from Murmansk, while the eastern sector is under the responsibility of the Far East Shipping Company (FESCO), operating from Vladivostok. Vessels who request permission for sailing the NSR should comfront to the requirements of the Administration prior to their entering in the Northern Sea Route waters [10].

Any ship going along Northern Sea Route will get navigation, hydrographic, hydrometeorological service, ice-breaking and ice-pilotage support.

Northern Sea Route (NSR): Advantages

Global warming and climate change have brought a new issue in the Arctic sea. The melting of the sea ice and the technological development of the shipping industry gave a new prospect to the Northeast Passage of Arctic Sea. Ships were able to sail from European ports such as Rotterdam, Hamburg, Kirkenes and Murmansk via the northern route to the Bering Strait and on the ports of Nakhodka, Yokohama, Dalian, making this passage a feasible shipping route with tremendous potential and great shipping benefits.

This route is considerably shorter than the corresponding commercial southern routes. Therefore, the merchant ships sailing from Northern Europe to the Asia-Pacific region and contrariwise can diminish into a third of the time required for a transit through the Suez

Canal and the Indian Ocean. For instant, the time spent while sailing 6920 nautical miles from Rotterdam to Dalian via the NSR is 35 days, 13 days faster and 39% shorter than the route via Suez channel (11430 nautical miles), Figure IV-3 [37].

This decrease in distance result to less consumption in fuels and lubricants, as well as less emissions of gases to the environment. Shorter time also result to better transportation and reliability for the delivery of the appropriate cargos.

Furthermore, large LNG Carriers benefit through lower boil-off rate of the load transported and thus, bigger efficiency.

Figure IV-3: Comparison of NSR with the current southern route [37].

Another matter that concern the shipowners when ships navigate from Europe to Asia via the commercial passage is the risk of conflicts and attacks by pirates in high risk areas. This risk results to higher insurance fees and ships manned with securities. Last but not least, avoiding payment of the Suez Canal toll, have made the NSR very attractive and reliable solution for interregional trade, although these savings are offset at least in part by icebreaking fees.

Typical Ice Conditions

The ice conditions along the Northern Sea Routes slightly vary from eastern to western part and a good subdivision of areas with equivalent ice conditions is made by natural borders such as islands and peninsulas. For each area defined in Figure IV-4, the average expected, ice thickness is given in Table IV-1. The ocean areas of the Laptev Sea are fortunate in having a slightly deeper shelf and lighter ice conditions in average than the eastern sector [38].

Sea	Area	Season							
		Winter-spring navigation				Summer-autumn navigation			
		Soft	Medium	Hard	Extreme	Soft	Medium	Hard	Extreme
Kara	North	0.75	1.25	1.75	2.35	0.38	0.63	0.88	1.18
	South	0.45	1.00	1.70	2.20	0.23	0.50	0.85	1.10
Laptev	North	1.00	1.90	2.80	4.00	0.50	0.95	1.40	2.00
	South	0.65	1.50	2.25	3.70	0.33	0.75	1.15	1.85
East Siberian	North	1.00	1.70	2.40	3.20	0.50	0.35	1.20	1.60
	South	0.60	1.34	1.90	2.95	0.30	0.67	0.95	1.50
Chukchi	North	0.85	1.50	2.50	3.75	0.43	0.75	1.25	1.88
	South	0.50	1.18	2.00	3.45	0.25	0.60	1.00	1.73

Table IV-1: Mean ice thickness (m) in the Russian Arctic Seas [10].

The eastern sector lacks this kind of land protection and is more open to the influx of multi-year ice from the Central Arctic Basin. The Barents Sea as well as the Northern east Kara Sea are strongly influenced by Northern Atlantic current. The influence of the Atlantic Sea decrease while going to south-east Kara Sea and Laptev Seas. There is a much smaller effect of the Pacific Ocean on the eastern seas (East Siberian and Chukchi Seas).

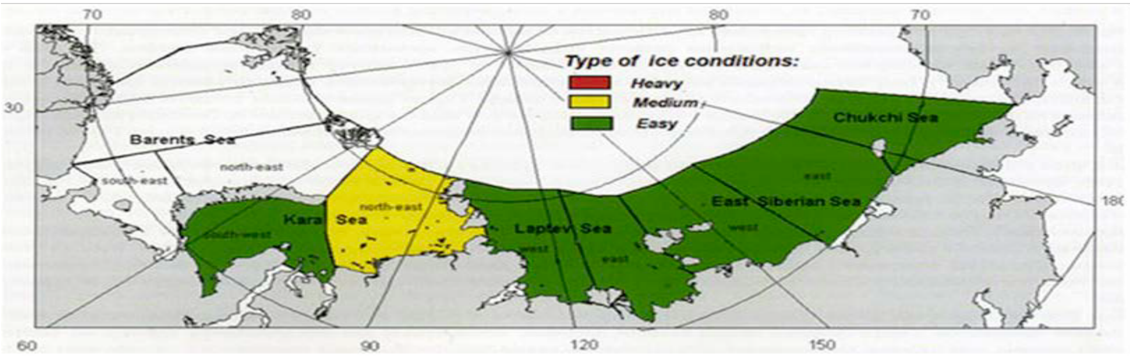


Figure IV-4: Ice conditions in the Arctic sea in the first half (September - October) 2013 navigation period [32].

Navigation is divided and permitted respectively to the appropriate ice class vessels, based on various parameters such as the area of navigation (seas), the period of the year (December to June stands for winter-spring period and January to June for autumn-summer period), the existing ice conditions (from easy to severe) and the operational conditions (independent navigation or navigation with icebreaker support) [10].

In the Tables IV-2 and IV-3, a pros (+) is given, whether the ships are permitted to sail or a con (-), whether are not.

Class	Ice mode	Navigation in the period December to June in the:																				
		Kara Sea						Laptev Sea						East Siberian Sea						Chukchi Sea		
		South-west			North-East			Western			Eastern			South-west			North-East					
		S	M	L	S	M	L	S	M	L	S	M	L	S	M	L	S	M	L	S	M	L
Arc4	IN	–	–	+	–	–	–	–	–	+	–	–	+	–	–	+	–	–	+	–	–	+
	IS	–	–	+	–	–	+	–	–	+	–	–	+	–	–	+	–	–	+	–	–	+
Arc5	IN	–	–	+	–	–	+	–	–	+	–	–	+	–	–	+	–	–	+	–	–	+
	IS	–	–	+	–	–	+	–	–	+	–	–	+	–	–	+	–	–	+	–	–	+
Arc6	IN	–	–	+	–	–	+	–	–	+	–	–	+	–	–	+	–	–	+	–	–	+
	IS	–	+	+	–	+	+	–	–	+	–	–	+	–	–	+	–	–	+	–	–	+
Arc7	IN	+	+	+	–	+	+	–	–	+	–	–	+	–	–	+	–	–	+	–	–	+
	IS	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
Arc8	IN	+	+	+	+	+	+	–	+	+	–	+	+	–	+	+	–	+	+	+	+	+
	IS	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
Arc9	IN	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
	IS	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+

Table IV-2: Ice class ships Arc4-Arc9 for navigation on Russian Arctic in winter-spring periods [10].

IN : Independent navigation
IS : Navigation with icebreaker support
S : Severe ice conditions
M : Moderate ice conditions
L : Easy ice conditions

\+ : Navigation is allowed
– : Impermissible service
Arc4 – Arc9: Russian Classes

Class	Ice mode	Navigation in the period July to November in the:																				
		Kara Sea						Laptev Sea						East Siberian Sea						Chukchi Sea		
		South-west			North-East			Western			Eastern			South-west			North-East					
		S	M	L	S	M	L	S	M	L	S	M	L	S	M	L	S	M	L	S	M	L
Arc4	IN	–	+	+	–	+	+	–	–	+	–	–	+	–	–	+	–	–	+	–	–	+
	IS	–	+	+	–	+	+	–	–	+	–	–	+	–	–	+	–	–	+	–	+	+
Arc5	IN	+	+	+	+	+	+	–	+	+	–	+	+	–	+	+	–	+	+	–	+	+
	IS	+	+	+	+	+	+	–	+	+	–	+	+	–	+	+	–	+	+	–	+	+
Arc6	IN	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
	IS	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
Arc7	IN	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
	IS	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
Arc8	IN	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
	IS	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
Arc9	IN	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
	IS	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+

Table IV-3: Russian classes Arc4 -Arc9 for navigation on Russian Arctic in winter-spring and autumn-summer periods [10].

Additional meteorological parameters

In addition to the ice conditions already quoted, Tables IV-4 and IV-5 describe more precisely the prevailing meteorological conditions of the Russian Arctic. The data, reflecting the extreme conditions that can be encountered during the winter, are given for information only and not for design purpose, calculations being based on averaged values in the whole sea regions and not on local extreme values. Moreover they were built from public data available on the internet and consequently are not consistent enough for calculations [10].

Location	Air T°	Wind force	Waves (height-period)	Current
Barents Sea	-20 °C	22 m/s	2.7 m – 11 sec	0.5 m/s
Pechora Sea	-20 °C	22 m/s	2.5 m – 9 sec	1.2 m/s
Kara Sea	-25 °C	35 m/s	0.8 m – 5 sec	1.0 m/s
Laptev Sea	-30 °C	40 m/s	0.4 m – 3 sec	0.9 m/s
East Siberian Sea	-30 °C	40 m/s	0.4 m – 3 sec	0.9 m/s
Chukchi Sea	-45 °C	40 m/s	7.0 m – 7 sec	0.2 m/s

Table IV-4: Meterorological characterictics and observed conditions in the Russian Arctic [10].

Location	Ice season	Ice thickness	Ridges	Icebergs
Barents	all year	150 cm (FY), 250 cm (MY)	—	0.5 m/s
Pechora	November-July	100 cm (FY)	5-10 ridges/km, (10 m high)	1.2 m/s
Kara	November-September	160 cm	5-10 ridges/km, (12 m high)	1.0 m/s
Laptev	October-July	200 cm	—	0.9 m/s
East Siberian	October-August	140 cm	5-10 ridges/km,(10-15 m high)	0.9 m/s
Chukchi	October-June	140 cm (FY), 230 cm (MY)	5-10 ridges/km, (10-15 m high)	0.2 m/s

Table IV-5: Meteorological conditions observed in the Russian Arctic [10].

NSR Fees & Icebreaking support

Commercial use of the NSR necessitates the consideration of icebreaker fees (tariffs) [24]. From the 1990s until 2011, the NSR fees were much higher than those for Suez Channel. These fees made the route unprofitable. In 2011, the Federal Tariff Service of the Russian Federation introduced a flexible fare for icebreaker services in the NSR, which allows tariffs to be applied below the limits and adjusts tariffs to market conditions. Currently, it is three times more expensive to charter an atomic icebreaker than to charter a cargo ship. This rate is approximately 100 thousand USD per day and non-Russian ship owners claim that the fees are overestimated.

Nevertheless, the Russian State remains interested in the control and development of international transit navigation through the NSR. Five icebreakers worked on the NSR in 2014: three Arktika-type nuclear icebreakers (the *Sovetsky Souz* (1989), the *Yamal* (1992) and the 50 *let Pobedy* (2007), and two Taymar-type icebreakers (the *Taymar* (1989) and the *Vaygaph* (1990)).

In November 2013, construction of the world's largest and most powerful nuclear-powered icebreaker began at the Baltic Shipyard in St. Petersburg. The vessel will be powered by two nuclear reactors and will be 173 meters long and 34 meters wide, which is 14 meters longer and 4 meters wider than the largest current icebreaker *50 let Pobedy*. The new icebreaker is expected to become operational in 2017 and enable the NSR to be used year-round.

The increase in traffic on the NSR necessitates a longer preparation time for convoys. The NSR passage time could easily reach 20-25 days, including the waiting time for icebreakers. Longer waiting time could critically affect trade via the NSR because the competitiveness of the route is based on voyage time being shorter than those for voyages via the Suez Canal. Better planning could significantly shorten the waiting time.

NSR'S Relevance to Arctic Oil, Gas & Mineral Deposits

One of the main reasons why there is an increased demand of ice capable merchant ships and increased interest in the Northern Sea Route is the exploration, devepoment and production of Arctic Oil, Gas and Mineral Deposits.

Russia holds the great majority – about 52% of the assessed total of the Arctic region, in terms of barrels of oil equivalent (Figure IV-5) [24]. The East Barents, South Kara, Laptev, East Siberian and Chukchi are essential Russian hydrocarbon basins. Hydrocarbon development will boost Arctic shipping over the next decades. The commercial viability of Northern Sea Route encourage the LNG projects, including Yamal and Shtokman. Russia's Baltiysky Zavod shipyard and Rosatomflot, the Russian company that maintains the world's only fleet of nuclear-powered icebreakers, came to an agreement for the construction of the largest nuclear-powered icebreakers of its kind on 2017. Inevitable, these signs prove that Russia want to take advantage of the basins and explore, develop and produce the potential LNG and oil deposits.

The following list indicates the sizable and expanding nature of key exploration and production operations in areas accessed by the NSR [24]:

- *Yamal LNG:* This project is intended for the supply of liquid natural gas (LNG) to China and Japan via the NSR. If this goes ahead, it will significantly boost Russia's drive to open up the NSR to increased LNG carrier traffic.

- *Kara Sea oil exploration:* Exploratory seismic survey and drilling campaign in the Prinovozemelsky blocks, led by Rosneft in partnership with Statoil, ExxonMobil and ENI.
- *Pechora Sea exploratory drilling (area is located to west of the Kara Gate):* First commercial offshore development in the Arctic centered on the Prirazlomnaya platform. The field license is held by Gazprom Neft Shelf.
- *Yuzhnoe-Khykchuyu oil field:* Production of 7.5 million tons of very high quality crude oil per year. The field is operated by Lukoil and is linked by 158 km export line to the Varandey Oil Export Terminal on the Siberian coast.

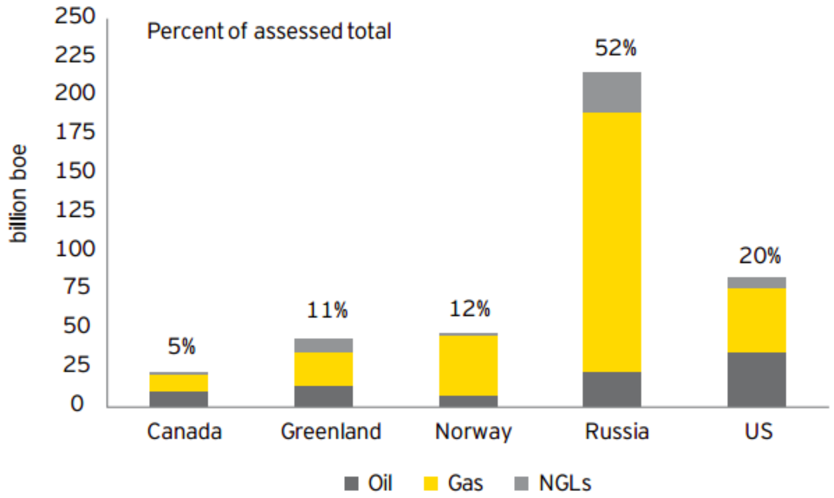


Figure IV-5: : Oil and gas production in arctic regions [24].

Moreover, near the coastal area of Barent and Kara the largest amounts of minerals are found. About 20.000 mineral deposits have been explored and more than 30% have been mined. In Kola Peninsula more than 700 different minerals have been found, while the Murmansk Oblast has more than 200 deposits of 40 types of minerals. In Table IV-6, the deposits as well as the year of estimated depletion are given [28].

Commodity	Year of depletion
Bauxite	Beyond 2025
Chromite	Depleted
Coal	Beyond 2025
Copper	2016
Diamond	Depleted
Iron ore	Beyond 2025
Natural gas	Beyond 2025
Nickel	2015
Oil	2015
Phosphate	Beyond 2025
Platinum group metals	2018
Tin	2015
Tungsten	2016

Table IV-6: Deposits of Hard Minerals in Russian Arctic [28].

2. EQUIVALENT ICE CLASS NOTATIONS & NSR REGULATIONS

In order to have a thorough understanding of the acceptance of ice class vessels in Russian Arctic, equivalances between Russian classes and other ice classes have been made. Except Russian Maritime Register of Shipping (RMRS), rules for navigation in ice have been assigned by Finnish-Swedish Maritime Administrations and International Association of Classification Societies (IACS). The classification of ice capable vessels is made according to the ability to navigate in certain ice conditions. Ships under IACS Unified Rules are divides in seven classes, Polar Class 1 (PC1) to Polar Class 7 (PC7), while under Finnish-Swedish Ice Class, only IA Super, IA classes are permitted [10].

In Table IV-7, ice type descriptions for Polar Class 1 to 7 are those of the IACS Unified Requirements concerning Polar Class, while Ice Class notations stand for FSICR.

Ice Type	Typical ice thickness	Polar Class notation	Ice Class notation	Ice going ships (RMRS)
Year-round operation in all polar waters	>3.0 m	POLAR CLASS 1	–	Arc 9
Year-round operation in moderate mylti-year ice conditions	3.0 m	POLAR CLASS 2	–	Arc 8
Year-round operation in second-year ice with old ice inclusions	2.5 m	POLAR CLASS 3	–	Arc 7
Year-round operation in thick first-year ice which may contain old ice inclusions	>1.2 m	POLAR CLASS 4	–	Arc 6
Year-round operation in medium first-year ice with old ice inclusions	1.2 m – 0.7 m	POLAR CLASS 5	–	Arc 5
Summer/autumn operation in medium first-year ice with old ice inclusions	1.2 m – 0.7 m	POLAR CLASS 6	ICE CLASS IA SUPER	Arc 5
Summer/autumn operation in thin first-year ice with old ice inclusions	0.7 m	POLAR CLASS 7	ICE CLASS IA	Arc 4

Table IV-7: Equivalences with ice class notations other than Russian Maritime Register of Shipping [10].

The ice thickness limitations for ice capable ships related to the different ice/polar class notations of the above mentioned classes, can be distinguished in the diagram of Figure IV-6. It is important to note that equivalences between ice classes are approximate and differences that derive from the class requirements can be distinguished in ice thickness as well as in ice belt regions, design ice load calculations and scantlings [39].

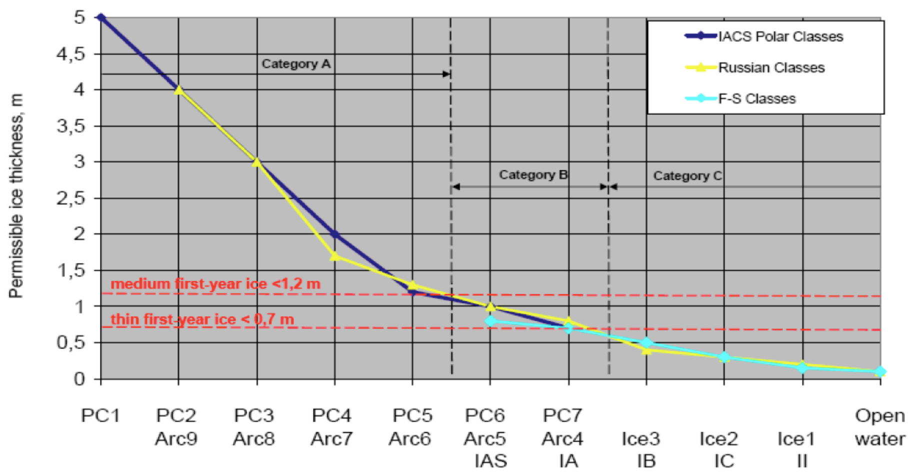


Figure IV-6: Diagram of permissible ice thckness level for ice/polar class ships navigating in ice [39].

To navigate through the Northern Sea Route, an authorization is to be requested to the Russian Ministry of Transports at least four months in advance. The full Regulations for icebreaker assistance and ice pilotage of the NSR are included in the publication *Guide to Navigating through the Northern Sea Route* [10].

This Guide incorporates the following regulations that are in force in the NSR:

- *Regulations for Navigation on the Seaways of the Northern Sea Route*
  These regulations present the general requirements for navigation through the NSR, namely the fact that the Owner or the Master of a ship intending to navigate through the Northern Sea Route is to submit a notification and request for leading through the NSR to the Administration (Marine Operational Headquarters).
- *Regulations for Icebreaker-Assisted Pilotage of Vessels on the NSR*
  The regulations define how to submit requests, the pilotage organisation and the obligations and responsibilities of the Master of the ship, the Master of the icebreaker and the pilot on the waterways of the NSR.
- *Requirements for Design, Equipment and Supply of Vessels Navigating the NSR*
  These regulations give the particular requirements applying to the hull, machinery installations, systems and arrangements, stability and watertight intergrity, navigational and communication facilities, supplies and emergency outfit, and manning.

All ships entering the NSR are to be inspected by the authorities prior to commencing the voyage. It is pointed out that ships not fully complying with the regulations may still be allowed to make the voyage on the condition of further implementation of requirements, such as the use of additional icebreakers, with additional costs for the shipowner.

The Ice Passport, or Ice Certificate, issued by The Arctic and Anarctic Research Institute (AARI) or the Central Marine Research & Design Institute (CNIIMF), is compulsory for ships navigating the Northern Sea Route. It namely includes the following:

- Concise information about the ship and its class,
- assessment of the shipside compression strength,
- main working documents providing the ship's safe speed in ice, i.e. ice performance curves, diagrams fo safe speeds, distances and circular motion radiuses in the channel when following an icebreaker.

In the next section, assessments regarding the ship's safe speed in ice is made, in order the risk of a damage to be diminished.

3. SAFE SPEED IN ICE

Every ice class rule has a different approach to ship's speed in ice. However, navigation in Arctic Seas is allowed in all kind of ships that fulfill some requirements and for this reason, safe speed limitations should be determined, either to ice capable ships or open-water ships.

IMO introduced in 2013 the Polar Operational Limitation Assessment Risk Index System (POLARIS) [39]. POLARIS is an approach to the operation of ships, valid for different ice conditions in Polar Seas, as given in World Meteorological Organization (WMO). Commercial ships are divided into categories and limitations are set in the operation of ships, regarding ice thickness and safe speed.

- Category A: Ships designed to operate in Polar Seas year round, at least in medium, first-year ice. Polar Class 1 (PC1) to Polar Class 5 (PC5) ships are included.
- Category B: Ships designed to operate in Polar Seas in autumn/summer period. Polar Class 6 (PC6), Polar Class 7 (PC7), Ice Class IA Super and Ice Class IA are included.
- Category C: Ships designed to operate in open water or in conditions less severe than those included in categories A and B.

The three categories are also determined in the diagram of Figure IV-7.

For the period of time allowed to operate in Polar Seas and the respective ice thickness defined for each type, a rate of indicative safe speeds are given to ships from Polar Class 1 (PC1) notation to Open Water (OW). This rate is presented in the diagram of Figure IV-7.

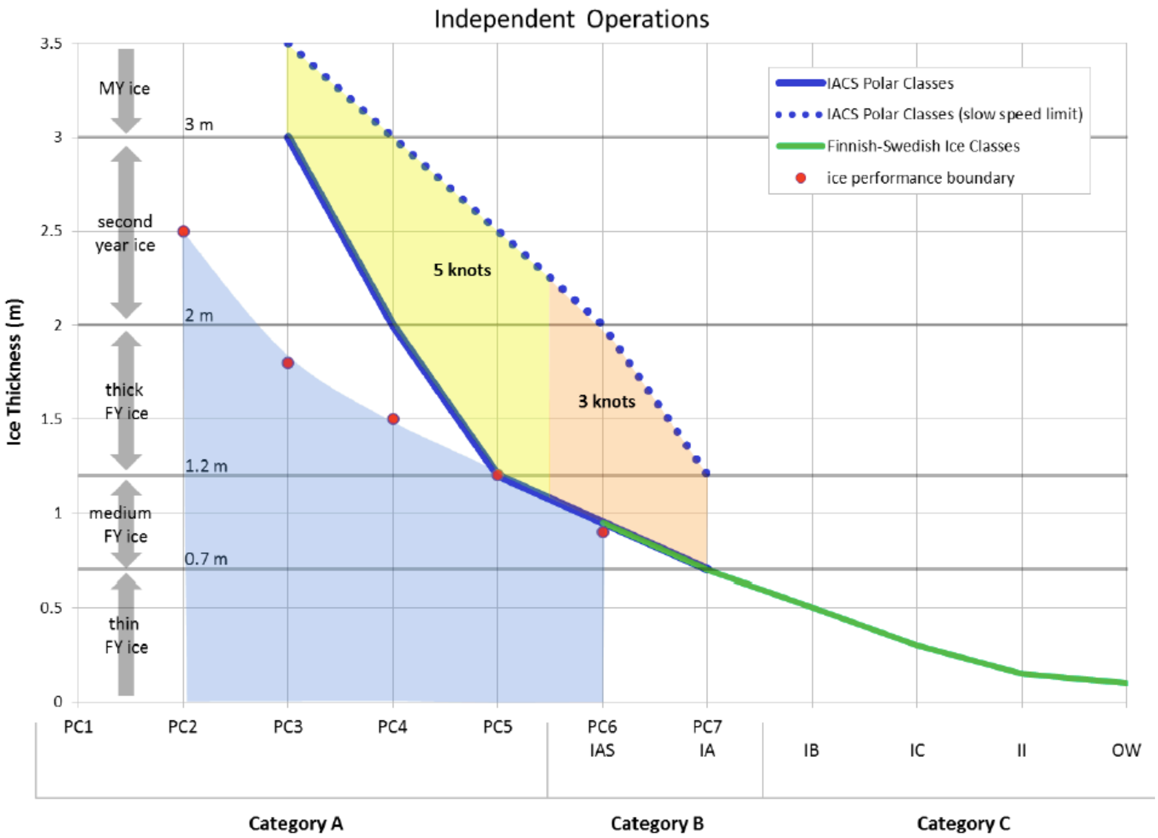


Figure IV-7: Limitations for level ice-low speed limit and ice performance boundary for recently specified ships [39].

Ice performance boundary is an indication of the actual capability of ships designed to meet the Polar Class requirements and is not associated with Polar Class rules.

Limitations in ice thickness should be taken over only in speed limited to:

- 5 knots, for category A ships
- 3 knots, for category B ships
- 0 knots, for category C ships.

V. CURRENT AND FUTURE ARCTIC SEA ICE CONDITIONS

1. SEA ICE EXTENT

Sea ice typically covers about 14 to 16 million square kilometers in late winter in the Arctic. On average, the seasonal decrease is approximately 7 million square kilometers. Over the past several years, Arctic minimum have been only 4 to 6 million square kilometers. Sea ice extent has decreased for all seasons, with the strongest average decline in September (84100 km^2 per year), and a moderate average decline during May of 33100 km^2 per year. Satellite data show that since the late 1970s, September Arctic sea ice extent has decreased by about 12% per decade.

In the Arctic Ocean, north of Greenland and in the Canadian Arctic Archipelago, the ice extent with the higher ice concentration can be found. However, the trend of decrease in the summer ice extent can be noticed also in these regions. From 2005 to 2012 the ice extent was all lower than the minimum between 1979 and 2004. Especially within the East Siberian, Chukchi and Beaufort seas and in the Barents and Kara seas, a pronounced ice retreat is the result of global warming.

The shape of the remaining sea ice cover varies between the different record minimum events. Since the late 1990s the Northeast Passage has been largely free of ice during September, with only small sea ice concentrations occuring, e.g. in September 2007. Even the Northwest Passage was largely ice free during September, starting 2007. Sea ice extent is also decreased during winter, mostly in the northern parts of the Barents Sea and in the northern North Pacific [36].

2. DECLINE IN SEA ICE THICKNESS AND AGE

Likewise, the decrease in multi-year ice is another alarming event. In 1987, 57% of the observed ice pack was at least 5 years old, and around 25% of it was at least 9 years old. In March 1988, thick multiyear ice (4+ years) comprised 26 percent of the Arctic's ice pack. When they surveyed the Arctic again in 2005, multiyear ice dropped to 19 % and in 2007, only 7% of the ice pack was at least 5 years old and the ice that was at least 9 years old had vanished. The 2013 Arctic Report Card showed that only 7 % was thick, multiyear ice. The map of Figure V-1 shows exactly this tremendous drop [42].

Examining 42 years of submarine records (1958 to 2000), and a five years of ICESat records (2003 to 2008), researchers Kwok and Rothrock (2009), observed a decline of 1.75 meters at mean Arctic sea ice thickness from 3.64 in 1980 to 1.89 meters in 2008. Another study published in 2013 compared sea ice volume between two periods: 2003-2008 and 2010-2012. The researchers used data from ICESat, the Pan-Arctic Ice-Ocean Modelling and Assimilation System (PIOMAS) and the European Space Agency CryoSat-2 mission found that sea ice volume descend by 4,291 cubic kilometers at the end of summer, and 1,479 cubic kilometers at the end of winter [36], [21].

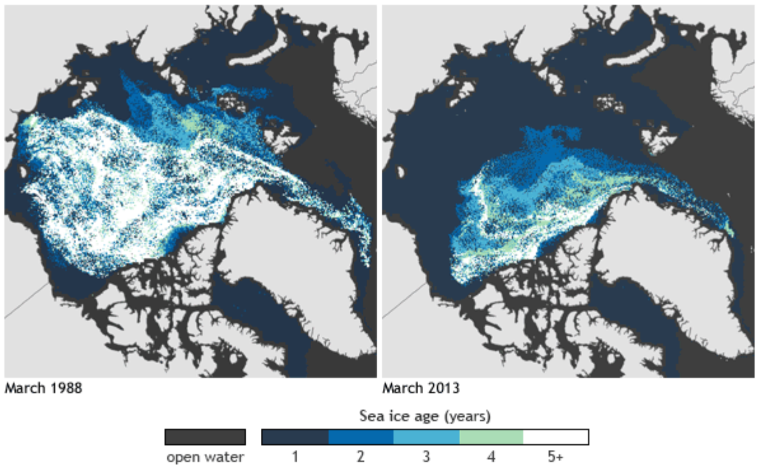


Figure V-1: Old vs. new ice in Arctic, in March 1988 and 2013 [42]

The researchers also, used the Ice Thickness Regression Procedure (ITRP) to evaluate the spatial and temperal patterns of ice. ITRP is a smooth function of space and time that can evaluate at all locations and times to yield a complete time and space record of Arctic Basin ice thickness. However, the fact that different observation systems may have unknown biases relative to each other, needs to be solved. The annual mean basin-average ice thickness for the 2000-2012 period based in ITRP are shown in Figures V-2 and V-3.

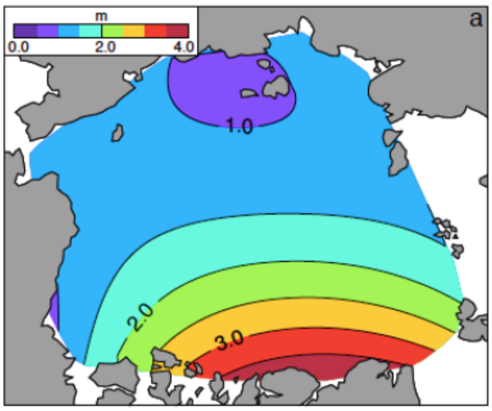


Figure V-2: Mean annual ice thickness from the ITRP for the period 2000-2012 [36]

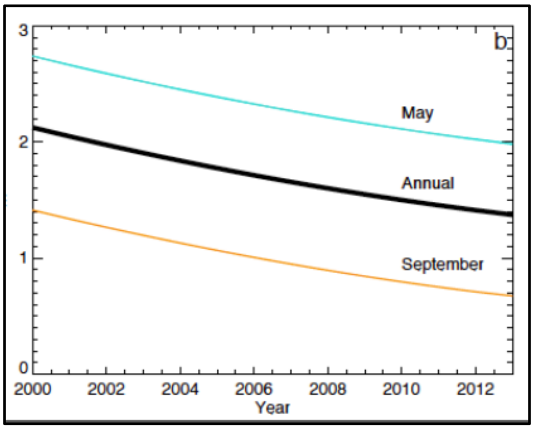


Figure V-3: Mean ice thickness for Arctic Basin in May, in September and for the annual mean [36]

What is easily notified in the map is the extent of maximum ice thickness along the Canadian coast, reaching at the coast of Greenland the four (4) meters and a minimum in the vicinity of the New Siberian Islands with thin first-year. The annual mean basin-average ice thickness has declined from 2.12 m to 1.41 m (34%) with a linear trend of -0.58 ± 0.07 m· decade^{-1}. The September thickness has decline from 1.41 m to 0.71m (50%) [36].

3. MARINE FISHES IN ARCTIC SEAS

Another important issue that is examined through the decades is the survival of the species of fishes in the Northern Atlantic Ocean and the Arctic Seas. The Norwegian Sea has a variety of 204 fish species, followed by the Barents Sea (153) and the Greenland Sea (57)

(Table V-1). The proportions show that more than 85% of the species of the Norwegian Sea are ray-finned fishes, while sharks and their allies (chondrichthyans) compose 9-14 % of the fish fauna. These proportions are similar to those reported for oceans, worldwide [41].

However, because of the global warming and melting of Arctic sea ice, fish stocks, such as Atlantic mackerel (Scomber scombrus), capelin and Atlantic cod (Gadus morhua) are expected to move poleward into Arctic seas. The Atlantic cod in the Barents Sea is presently at a historical high, but industrial fisheries already emerged on several Arctic shelves and the destruction of coral induced by climate change may also affect the fishery resources.

Class	Greenland		Norwegian		Barents		White		Kara		Laptev		E. Siberian	
	N	%	N	%	N	%	N	%	N	%	N	%	N	%
Hagfishes (Myxini)	-	-	1	0.5	1	-	-	-	-	-	-	-	-	-
Sharks &their allies (Chondrichthyes)	5	8.8	28	13.7	19	12.4	4	8	2	3.3	1	2	1	3.8
Ray-finned fishes (Actinopterygii)	52	91.2	175	85.8	133	86.9	46	92	58	96.7	49	98	25	96.2
Total number of fish species	57	100	204	100	153	100	50	100	60	100	50	100	26	100
Fishes targeted by industrial fisheries	7	12.3	24	11.8	21	13.7	8	16	1	1.7	-	-	-	-

Table V-1: Number (N) and proportians (%) of marine fishes and fish-like species in the norhteast Atlantic Ocean & Russian Arctic seas [36].

4. FUTURE SEA ICE CONDITIONS IN THE ARCTIC OCEAN

In accordance with the above-mentioned statements, Arctic Council and the International Arctic Science Committee released the Arctic Climate Impact Assessment (ACIA) in November 2004. The projected climate change and its impacts are very difficult to be stated in certainty. Nevertheless, the rapid and severe climate change faced on earth and especially in the last decades, prove that the near future is not auspicious and this will have an impact to the Arctic environment [8].

The decline in the extent, age and thickness of the Arctic sea ice in all seasons and mainly the Northern Sea Route prove the criticalness of the condition. Five Global Climate Models (GCMs) used in ACIA project a continuous decline in Arctic sea ice coverage throughout the 21st century. One of the models projects an ice-free Arctic Ocean in summer by 2050, a future scenario of great significance for Arctic marine shipping since multiyear (MY) ice could possibly disappear in the Arctic Ocean. All of the next winter's ice would be first-year (FY) ice. GCM projections to 2100 suggest that Arctic sea ice in summer will retreat further and further away from most Arctic coasts, potentially increasing marine access and extending the season of navigation in nearly all Arctic regional seas. The ACIA models, however, could be applied to the more open coastal seas of the Russian Arctic [8].

This great change in the form of ice from multi-year to first-year, as well as the ice free period in summer has a very big impact in the shipping industry. Except of the environmental issues that arise for the protection of life and Arctic seas, shipbuilders, shipowners, Classification Societies and Administrations should conform to the possible changes in ice conditions.

In summary, ACIA confirms that the observed retreat of Arctic sea ice is a real phenomenon. The GCM projects to 2100 shows an extensive ice-free region around the Arctic basin (Figure V-4). Thus, it is highly plausible there will be increasing regional marine access in all the Arctic coastal seas. However, the projections show only a modest decrease in winter Arctic sea ice coverage. There will always be an ice-covered Arctic Ocean in winter, although the ice may be thinner and may contain a small fraction of MY ice.

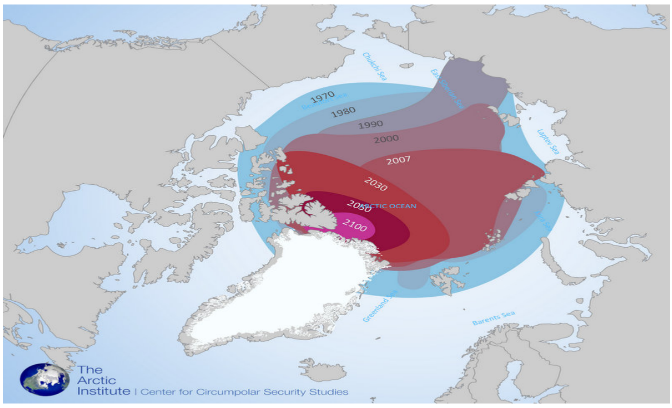


Figure V-4: Arctic sea ice simulation for the 21st century [50]

As noted, the Arctic Institute indicates the possibility of a nearly ice-free Arctic Ocean in summer 2050 with a small ice extent in the northern coast of Greenland and an even smaller in summer 2100 [50]. Recent analyses of GCM sea ice simulations using models for the Fourth Assessment of the Intergovernmental Panel on Climate Change (applying global warming scenarios) show near-complete loss of Arctic sea ice in September for 2040 to beyond 2100. However, research also indicates abrupt reductions in sea ice coverage during the 21st century are a common feature in many of GCM sea ice simulations. Just as important to ship navigation, these simulations show large areas of the coastal Arctic seas to be ice-free for long periods in the spring and autumn months. Arctic marine access continues to increase in nearly all scenarios posed by these global warming assessments [8].

Figure V-5 indicates ice-free passages that appear in the Russian Arctic & Northern Sea Route from Kara Gate to the Bering Strait in summer period as well as in the future Arctic winter. Moreover, the North West Passage (NWP) and the Transpolar Sea Route opened in 2007 to summer shipping traffic. However, these passages will remain covered by ice in winter time, thus will not serve as a substitute for existing shipping routes. In other words, Canadian Archipelago and Greenland will consist their spring/winter ice [34].

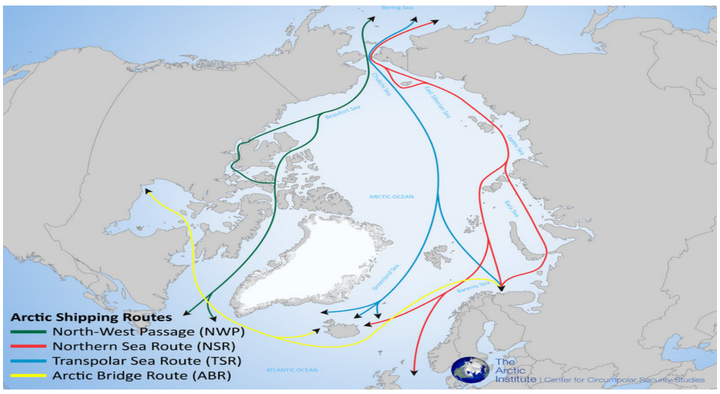


Figure V-5: Arctic shipping Routes in future ice-free conditions [34]

5. CONCLUSIONS CONCERNING THE ARCTIC ICE CONDITIONS

Several conclusions derive from these assessments, observations and studies, that in brief, are classified in the below [8]:

1. Arctic sea ice has been observed to be diminishing in extent and thinning continuously for five decades.
2. Sea Ice decrease will continue through the 21st century.
3. Simulations indicate the possibility of an ice-free Arctic Ocean (for a short period in summer) by 2040.
4. Even a brief ice-free period in summer for the Arctic Ocean would mean the disappearance of MY ice in the central Arctic Ocean; Such an occurance would have significant implications for design, construction and operational standards of all future Arctic marine activities.
5. Longer open water seasons increase the potential Arctic development and transportation, but also coastal problems because of erosion.
6. The observed record of sea ice extent in the Arctic sea is a serious challenge to risk and reliability of Arctic marine transportation systems.
7. Despite a small decrease in the maximum Arctic sea ice extent in March, the Arctic sea ice cover will continue to present unique challenges for all Arctic marine uses including commercial shipping.
8. It is highly plausible that Arctic sea ice will be more mobile and coastal seas may experience increased ridging of seasonal sea ice.
9. The current GCM sea ice simulations are not yet robust enough to provide detailed information on future operating conditions such as the length of the navigation season and duration of ice-free regions that would allow faster ship transits.
10. These is a critical requirement for more real-time sea ice observations, especially ice thickness measurements, to support all future Arctic marine uses.

Inevitably, the demand for multi-year (MY) ice capable ships will grop in the next decades. However, the present of first-year (FY) ice in winter/spring periods shows that the necessity for ice going ships operating in arctic will not cease. A different approach of ice class divisions should be made, giving emphasis to the ship's strength and ability to navigate in ice without judging the specific period of the year that the ship will operate. The higher polar ice class vessels that can be used for year-round operation in all Polar waters should be constructed in the next years with a plan of proper use in less severe ice conditions. In contrast, the lower ice class vessels that are used nowadays, only in summer/autumn operation in thin, first-year ice will have an increased demand through a year-round period.

VI. DESIGN OF ICE CLASS SHIPS

The design of ice capable ships includes reaching an adequate performance, hull and machinery strength and proper functioning of the ship in ice and cold weather. Good ice performance requires hull shape with low ice resistance as well as good manoeuvrability and good propulsion thrust which can be achieved with proper propeller design and hull lines so that propeller-ice interaction minimize. The designer must have some insight about ice loads in order to select the structural arrangement, thus the way how ice is acting on the ship and how this interaction reflects to the ice class rules.

1. DESIGNING AN ICE CAPABLE SHIP

Ship-ice interaction and the mechanicm behind this is the basic aspect in order to understand the design of ice capable ships. The way rules and regulations of ice class ships approach ship design is qualitative rathen than quantitative. The reason is that there is not a developed methodology for all ship operating in all ice infested conditions. Different ship-ice impact in different ice conditions can lead to completely different demands in the design of an ice capable ship.

The design starting point is usually a functional specification outlining the ice performance, as it is given in Table VI-1 for Baltic environmental multipurpose icebreakers [46].

BALTIC ENVIRONMENTAL MULTIPURPOSE ICEBREAKERS

General Ice Performance Requirements:

• **Average escort speed**	The average speed in all normal ice conditions in the operational area must be at least 8-12 knots
• **Level ice ahead**	The ship speed must be at least 13 knots in 50 cm thick level ice proceed with 3 knots speed in 1.5 thick level ice
• **Level ice astern**	The ship must be able to go astern with 7 knots speed in 70 cm thick level ice (flexural strength 500 kPa, thin snow cover)
• **Manoeuvring capability**	The ship must be able to turn on spot (180º) in 70 cm thick level ice in max 2.5 minutes. The ship must be able to turn out immediately from an old channel with 5 m thick side ridges
• **Old channels**	The ship must be able to maintain a high speed in old channels. Especially in a channel corresponding to the requirement of IA Super ships, she has to maintain at least 14 knots speed
• **Ridge penetration**	The ship has to be able to penetrate with one ram (initial speed 13 knots) a ridge of 16m thickness
• **Channel widening**	The ship has to be able to open a 40 m wide channel in 50 cm thick ice (500 kPa, thin snow ice) at speed 4 knots
• **Performance in compressive ice**	The ship must be able to maintain a 9 knots speed in compressive ice of thickness 50 cm
• **Temperatures**	Air temperature -35º-+30º C and sea water temperature -1º-+32º C

Table VI-1: General Ice Performance Requirements for Baltic Environmental Multipurpose Icebreakers [46].

Ships navigating in severe Arctic ice conditions in a year round period, differ from those in Baltic seas. Ships enhanced with certain hull strengthening, double acting propeller with four (4) blades, machinery installations, and navigational and communication facilities can confront harsh ice conditions, indepentently. However, these ships because of the excessive lightship, due to the hull strengthening, are not cost efficient to operate in open waters. All ships designed with winter navigation system should fit into their intended operational spectrum and can be divided into three main types, regarding the ice going capability [46]:

- *Ice strengthened ships*

Ships that have ice strengthening and some ice performance but can not navigate in medium or severe ice conditions without icebreaker escort. The vast majority of ice capable ships belong to this category. The ship is usually designed for open water performance, but they are able to operate also in autumn/summer, first-year, ice conditions. These ships are not designed to ram through ice.

- *Ice going ships*

Merchant ships that can proceed independently in multi-year ice conditions. The hull shape and strength is specially designed for ramming and ice breaking as well as manueving through ice, although they may beach to extreme ice conditions. Machinery power raises above the demand of those in open water ships. Capability to go astern in ice is needed in order to avoid getting stuck in ice. Only a few of this kind of ships exist (Norilsk Nikel, Norilsk-class multipurpose ships, MV Arctic, Umiak I, Lunni-class tankers).

- *Icebreakers*

Ships that are intended to operate in the most extreme ice conditions in the operational area and escort or assist other vessels in all seas. Icebreakers should not stuck in ice and operate in the worst case scenarios.

This division into different types of ships intended to ice operations forms the basis of designing. The operational spectrum of the ship according to her role in the winter navigation system sets all the functional requirements for the project ship.

2. HISTORICAL DEVELOPMENT OF ICE CAPABLE SHIPS

These short notes from the historical development of ice design show how closely the design of ice capable ships is linked with the experience from earlier designs.

The development of icebreakers and ice going ships started in mid 1840's in Hudson River in the US and in the Elbe River in Germany with the development of the first ice breaking ships. The first recorded icebreakers were constructed in 1860's and 1870's in the St. Petersberg and Hamburg harbours. However, merchant ships able to navigate in ice did not appear before the end of 19^{th} century. Express II was one of those sailing across the Baltic sea between the ports of Turku in Finland and Stockholm in Sweden. It is worth mentioning that the icebreakers gave the hull design to this ship as and to many similar. Only the machinery power was larger in icebreakers.

The first ships able to navigate independently in ice infested environment evolved in 1950s in the Soviet with the emergence of the Lena- and Amguema- series of ships (the latter is also called Kapitan Gotskij series). The special feature of these ships were the icebreaking bow shape without bulbous bow, able to endure Arctic seas.

Several series of Arctic ship has been built to Soviet and Russian owners (e.g. Norilsk and Norilsk Nikel-series) and to Finnish owners (Lunni-series) – the Canadian ships MV Arctic and MV Umiak1 should also be mentioned. Since the early times the icebreakers and ice breaking ships have developed much based on several technological innovations.

The principle of hull lines design has been the basic matter for icebreakers and ice breaking ships. The hull shape of the early icebreakers in the 19th century was characterized by a very small buttock line angle φ at the stem; values were usually smaller than 20º (definition of the hull angles, see Figure VI-1). The buttock lines and waterlines were rounded and the sides were inclined (β°> 0). The flare angle ψ° was designed as small as possible. The rounded stem developed quite late (in the 1980's) as a sharp bow was long deemed favourable for ice breaking [46].

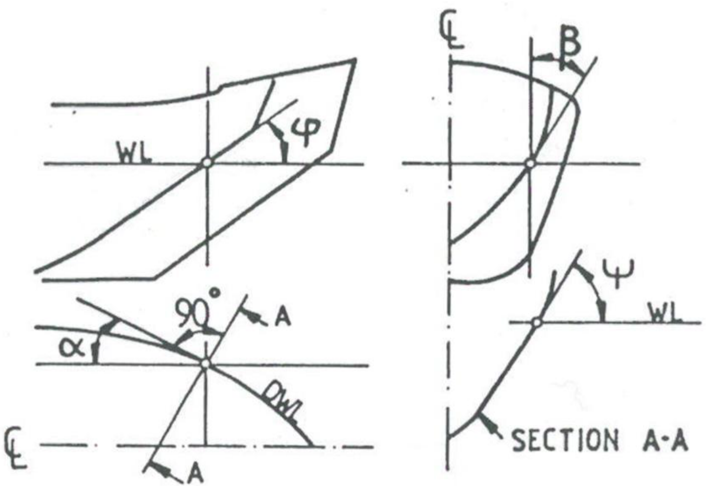


Figure VI-1: Definition of the hull angles [46].

The general arrangements of icebreakers and also ice going ships have slightly changed during the years. The largest chance took place in 1970's when the superstructure was changed into deck house i.e. no accommodation was placed in the hull. The reason for the chance was partly to increase the height of the bridge, to improve the visibility and partly to avoid the noise and vibration caused by ice in the crew accommodation.

Strength of ship hull and machinery is still mostly designed based on experience from earlier ships. When damages caused by ice occurred, strengthening of the structures was indicated. These experiences have been collected into rules by the classification societies and Maritime Administrations and thus most of the strength designs are even nowadays done following these rules. The Baltic is the most active sea area for ice navigation and it is natural experiences from Baltic that follow rules, worldwide. The experience from ship damages is reflected in the strength level used in the Finnish-Swedish Ice Class rules.

3. ICE ACTION ON SHIPS

Understanding how ice and cold temperature acts on a ship is the footing for the hull design. The ice type encountered and the way ship is operating in ice determines the ship-ice interaction. The most demanding ship-ice interaction scenarios do not apply to all operational profiles; ships might not require to encounter multi-year ice or might not require to go astern in ice. The design for the hull and propulsion machinery strength is based on evaluating the ship-ice interaction scenarios. Evaluating the different scenarios that the ship encounters in Arctic ice conditions is the basis of defining ice class under the International Association of Classification Societies ice rules.

The ship may operate independently i.e. without any escort of icebreakers and then she encounters all ice present in the operational area. Independent operation can be divided further into different operational scenarios; the ship may be on transit and then she can avoid the worst ice conditions. The encountered ice conditions are in this case less severe than the average conditions in the operational area. The maneuvering capability of ships transiting must be adequate in order to be able to avoid severe ice conditions. Ships can either navigate individually or be escorted by icebreakers. In both operational conditions, ships face the scenario of breaking ice floes.

Definitions related to ice loading

Before looking at the different ship-ice interaction scenarios, some of the definitions pertaining to ice action are in place. A ship operating in open pack ice with a total concentration of ice equal to one tenth (1/10) would prefer to sail at high speed, but will slow down in case of an ice collision. As the ice becomes more concentrated (e.g. 6/10) , the ship will face several different ice floes acting simultaneously and the designer must form, at least qualitatively, a model of the ice forces from these scenarios. Finally, when ice becomes solid or the ice channel is very narrow then, the ship should be able to act some of the scenarios below [13]:

- Ship breaking the level ice (ramming with the stem).
- Ship sailing in broken ice channel.
- Ship widening the ice channel.
- Ship ramming a ridge
- Ship making a turning circle in ice
- Ship going astern

In all these scenarios, two distinctions are of great importance, local and global ice loads.

Local ice loads are defined as the ice pressure that uniformly act on local patches and items, such as shell plates and stiffeners. Local loads refer to loading that is either a part of a single contact (the ice pressure on the considered area is important) or a total load on any single hull structural element (one frame, one plate panel). Thus, the local forces (usually stemming from one interaction case) are important from design of the smaller hull structural elements.

Global ice loads on ships are bending moments on hull girder and depend on ship operation (ship speed and power), ice conditions (ice concentration, thickness and floe size) and ship-ice interaction. Global load refer to the total contact load from any one single interaction scenario leading to bending failure of the ice sheet, or collision with a single ice floe. Global forces can also refer to the sum of all the ice loads acting simultaneously at the ship.

Ideally, the ship hull design could start from determining the local and global forces but this task is far beyond the present capability and knowledge. In some simplified cases the local force can be determined using semi-empirical methods i.e. making a simple theoretical model and determining the model parameters by fitting the calculated results to some measured results. This kind of load calculating methods exists for frame and plating loads for ships and the global loads pertaining to ship performance in ice.

The definition of ship performance in ice is not based on the worst encountered (or largest encountered) ice loads but rather on an adequate average performance in 'average' ice conditions. Thus, the ship is expected to get stopped in locally worst conditions. The description of the ice cover based on the equivalent ice thickness contains this idea of averaging. The basic case of all ice performance is sailing in level ice. Global ice loading is important in determining the ship performance in ice as the longitudinal component of global ice forces contributes to the global (or total) ice load. The maxima included in the time history of the ice load are not the important for performance as the ship inertia smoothens their effect.

As the ship performance depends on the ensemble of several contacts, the resistance forces are described in an average fashion by assessing the form of forces of various origins. This leads to a division of the resistance forces into components of similar origin. The most commonly accepted average forces are [46]:

- Forces from breaking the ice;
- Forces for submerging the broken ice;
- Forces from friction along the ship hull (both ice breaking and sliding along the hull);
- Hydrodynamic forces

The breaking forces are the largest of these accounted of about 50% of the resistance in lower speeds.

The concept of ice loads from individual impacts can be extended to other scenarios. For instance, when ice-breakers escort a single ship or one in a convoy, the case is similar to operating in an ice floe field. Closer to land where ice is steady, ships follow fixed fairways. While the ice break and refreeze, brash ice field is created. Brash ice is a rounded ice with a diameter of about 30 cm and acts as viscous fluid [13].

In contrast, the ice in pack ice is mostly broken and ridged. Ridges are broken ice floes forced up by pressure. Ships that penetrate ridges face greater ice load than in level ice. That’s the reason why some ships should overlap them in order to diminish the risk of damage. Hence the capability to go astern in case of beaching in ridges or to break the ridges by feeling the heeling tanks or using bow propellers are required for ships that operate independently.

Furthermore, ships that intend to operate independently should be able to withstand pressure on side area. Ship responds in six (6) degrees of freedom and ice fails more possibly on crushing rather than on flexural failure.

The analysis of ship-ice interaction scenarios aims to determine the contact force during the interaction, this includes the maximum force for strength design and the time averaged force for determining the performance. Forces can be from inertial (rigid body and hydrodynamic), bending or crushing origin. Each of these forces requires individual analysis methods. It is important to understand the basic mechanics of each of the main ship-ice interaction scenarios. A thorough analysis of what kind of scenarios a ship may encounter, contains more than 100 different cases.

<u>Level ice-ship impacts</u>

Understanding the ice-failure process is the most crusial factor for the estimation of the ice loads and thus the most crusial factor for the designing of ice capable ships. When a ship moves in ice infested seas, ice breaking is her way to move forward, either if there is a head on collision or an oblique collision on the side. The mechanism behind the breaking of ice (Figure VI-2) can be divided into:

- failure by crushing
- failure by shear fractures
- failure by flexural bending
- failure by splitting.

Every failure event is a part of a complete procedure leading to local load peak, as well as a step to the next event and another load peak. The maximum load peak occuring in the sequence of failure leads to the understanding of the local ice load during an ship-ice interaction. Global ice loads also can be determined from the interaction of the structure with large floes. Crushing is a hierarchy of cracking and extrusion processes, while crushing is interrupted by a flexural failure process.

The ice-failure mode is determined by the impact velocity, contact area, bow shape, buttock angle and ice thickness. Knowledge about the maximum local and global load as well as the frequency content of the load need to be known. Secondly, the ice movement around the structure must be clarifed, Figure VI-3 [13].

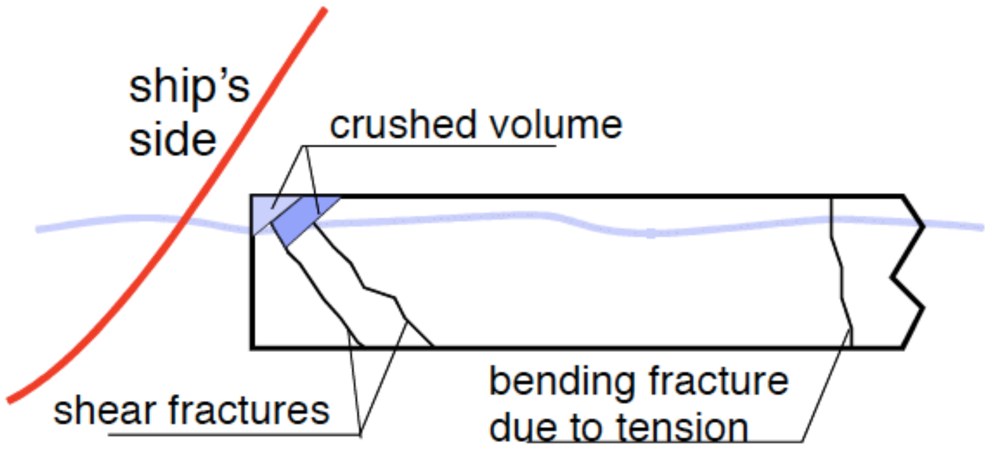


Figure VI-2: The procedure of the ice failure in the edge of the floe, during the interaction with the ship's side [13].

The general tendency is for the crushing force to drop towards the shoulder, while the flexural force tends to rise towards the shoulder. The specific shape of either curve depends, of course, on the hull form [12]. Figure VI-4 illustrates the nature of the two forces. The upward sloping curve is the flexural force, which increases as the flare angles become more vertical. The downward sloping line is the crushing forces, which reduces due the lower normal velocities. The two curves tend to cross, in which case the point of the crossover (can be anywhere on the bow) defines the maximum force value. The circle represent the peak force (the design force) and its location. This is normally the case on larger and lower ice class ships that the flexural forces influence greatly the maximum ice load. On small and higher class vessels, flexural failure may not matter and the peak force may be right at the stem. In this case, the force is essentially identical to that calculated using the ramming scenario in the longitudinal strength.

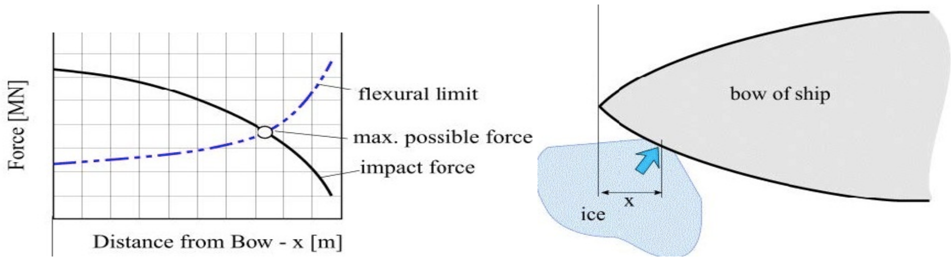


Figure VI-3: Combination of crushing and flexural forces over the bow of a ship [12].

Moreover, the ice mechanical property should be defined considering not only collision forces, but also penetration depth. If the contact area between an ice floe and the ship is *A* and the contact pressure is assumed to be p_c (this is not the case generally but for the present this simplification of constant pressure is enough), then the normal contact in direction of the ship hull outward normal is $F_n = p_c \cdot A$. Ice load varies widely according to the failure mode, temperature, salinity, impact velocity, contact area, size of the ice specimen, ship structure details. In other words, it is not easy task to provide a unified formulation that considers the above-mentioned parameters, sufficiently [46].

Local Ice Load

After the ship interaction with the impacted ice edge, it is assumed that the load acts on a load patch, a nominal rectangular area of non-zero pressure. Ice pressure is not measured directly. It is usually the total ice force *F*, acting to the side of the ship at the certain waterline that is measured on a certain area A_g and thus, the pressure is deduced as F/A_g. The gauge area used for the design of the scantlings of the ship is mentioned as *design load patch*. This load patch is simplified to a rectangular patch with the same aspect ratio for the structural response calculation of local shell structures such as plating, main frames, stringers and web frames. The design load patch is determined by a design pressure p_c, load height h_c and load length *L*. This idealization is sketched in Figure VI-4 [46].

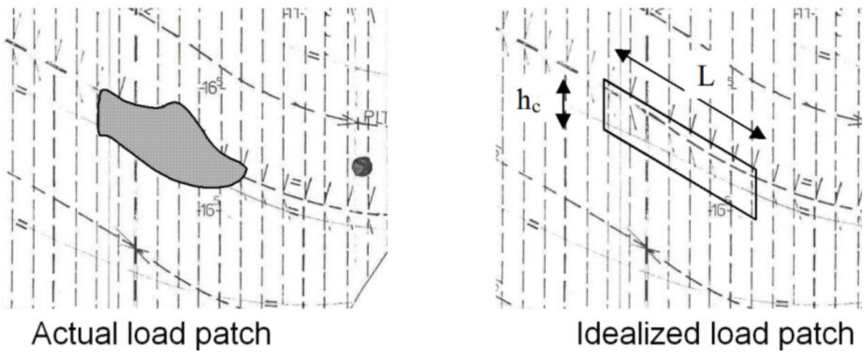


Figure VI-4: Actual load patch and its idealization for structural design [46].

The nature of load patch indicates structural idealizations that can be in simple response calculations; when designing any structural member, the load patch is placed at a location giving the largest response.

Total Ice Force

The total ice force F or its normal component F_n, used in the local ice load, derive from the analysis of the motion of the two colliding bodies. The ship is the impacting body, while the ice floe is the impacted one. The assessment of the total ice force leads to the determination of the design ice load. Two different methods of calculation can assess the total ice force.

The first one is based on the notion that a 3D impact between ice and ship's side can be represented as a 1D, normal collision between a single body and a rigid wall. The penetration depth in one side of the bow or bow shoulder of the ship, the pressure-area relationship of the impacted bodies and an energy based approach of the impact are the key factors for the estimation of the total ice load. This simplified approach assumed a resulting total ice force for collision of a ship in her side with the edge of a first-year ice floe [12]:

$F_n = C \cdot p_o^{0.36} \cdot V_{SHIP}^{1.26} \cdot \Delta^{0.64}$, where the constant C contains the dependency on ice strength.

Another case where the total ice force has been calculated is normal collision on multi-year ice floe. This case includes crushing of the ice edge followed by the ship sliding up onto the ice. For a collision where the ice mass is assumed large compared with the ship displacement, the force has been deduced as (Riska et al. 1996):

$$F_n = C \cdot \sin^{0.2}\phi \cdot \sqrt{\Delta \cdot A_{wp}} \cdot V_{SHIP},$$

where the constant C contains the dependency on ice strength and φ is the ice edge angle.

Design Point

A ship is designed, judging the requirements of the shipowner for a specific operational spectrum. As it is mentioned above, the load patch is used for the structural response calculation of local shell structures such as plating, main frames, stringers and web frames. The designer then, should determine the allowed structural response and how frequently it should be reached. The allowed structural response may be stressed up to yield point (Y), fully plastic stress (P) without permant deformation, as well as a Ultimate (U) stress point with small, but defined permanent deformation, reaching a specified value. The aim of the structural response formulation is the determination of a relationship between the limit structural response, the scantlings and the load.

Furthermore, the analysis of the structural response should be determined. The structural analysis gives the relationship between the maximum allowed response *(w)*, the load quantity (q) as well as the structural dimensions (scantlings, material properties and geometry).

This relationship, in case of side shell plating with plate thickness (t), can be stated as:

$w = f(q;t)$,where the function *f(·)* is determined by structural analysis using e.g. FEM. Using this relationship, the scantling resulting from certain structural limits and return period of load can be determined (Figure VI-5), [46].

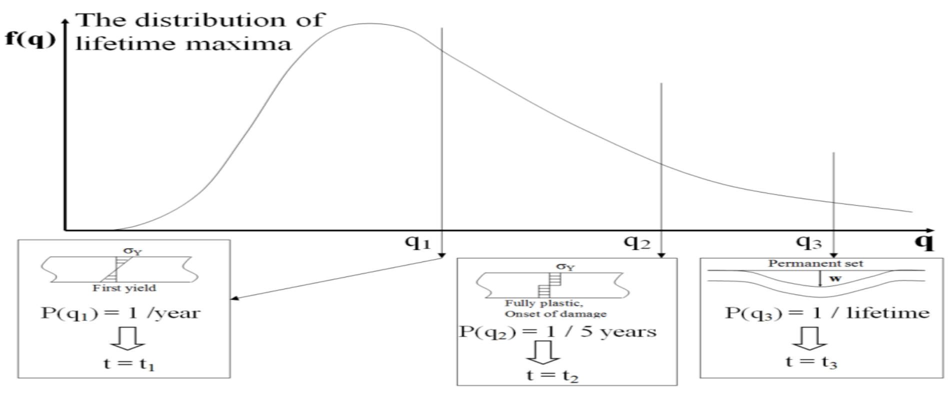


Figure VI-5: Process of determining the structural dimension (scantling), which in this example is a plate thickness, using different structural limits and at the same time different occurrence frequencies for the limits [46].

4. MATERIAL REQUIREMENTS

Material Grades and Classes

The material properties are very crusial for the proper design of an ice capable ship. Steel is preferred over other construction materials for arctic going ships because of its high strength, processability, availability and its relatively low price [29].

Steel grades A, B, D and E of normal strength; and AH, DH, EH and FH of higher strength are distinguished, based on their impact test requirements. According to established practice and IACS unified requirements (UR W11), the chemical composition of the marine steel grades are the one shown in Table VI-2 for normal strength steels and Table VI-3 for higher strength steels [57].

Grade	**A**	**B**	**C**	**D**
Chemical Composition %	***Carbon plus 1/6 of the manganese content is not to exceed 0.40%***			
C max.	0.21	0.21	0.21	0.18
Mn min.	2.5 x C	0.80	0.60	0.70
Si max.	0.50	0.35	0.35	0.35
P max.	0.035	0.035	0.035	0.035
S max.	0.035	0.035	0.035	0.035
Al (acid soluble min)	–	–	0.015	0.015

Table VI-2: Chemical composition for normal strength marine steels [57].

<table>
<tr><th>Grade</th><th>A32 / A36 / A40</th><th>D32 / D36 / D40</th><th>E32 / E36 / E40</th><th>F32 / F36 / F40</th></tr>
<tr><td>C max.</td><td colspan="3">0.18</td><td>0.16</td></tr>
<tr><td>Mn min.</td><td colspan="3">0.90 – 1.60</td><td>0.90 – 1.60</td></tr>
<tr><td>Si max.</td><td colspan="3">0.50</td><td>0.50</td></tr>
<tr><td>P max.</td><td colspan="3">0.035</td><td>0.025</td></tr>
<tr><td>S max.</td><td colspan="3">0.035</td><td>0.025</td></tr>
<tr><td>Al (acid soluble min)</td><td colspan="3">0.015</td><td>0.015 (3)</td></tr>
<tr><td>Nb</td><td colspan="3">0.02 – 0.05   {total:} {12} {max}</td><td>0.02 – 0.05</td></tr>
<tr><td>V</td><td colspan="3">0.05 – 0.10</td><td>0.05 – 0.10</td></tr>
<tr><td>Ti max.</td><td colspan="3">0.02</td><td>0.02</td></tr>
<tr><td>Cu max.</td><td colspan="3">0.35</td><td>0.35</td></tr>
<tr><td>Cr max.</td><td colspan="3">0.20</td><td>0.20</td></tr>
<tr><td>Ni max.</td><td colspan="3">0.40</td><td>0.80</td></tr>
<tr><td>Mo max.</td><td colspan="3">0.08</td><td>0.08</td></tr>
<tr><td>N max.</td><td colspan="3">–</td><td>0.009</td></tr>
</table>

Table VI-3: Chemical composition for higher strength marine steels [57].

Two examples of High Tensile Steels commonly used in the shipping industry are analysed. A High Stress, Low Alloy (HSLA) steel that is used massively in shipping industry is DH36 steel plate. Its chemical composition is given in Table VI-4. This steel is a hypoeutectoid alloy (0.14 wt % carbon) with ferritic and pearlite as the prime constituents and grain refining elements such as aluminum and vanadium. Using the lever rule, it can be shown that the volume fractions of pearlite and ferrite are 17.5% and 82.5%, respectively. The relative amount of pearlite makes this alloy more rust resistance compared to othen carbon steel alloys.

Ferritic or alpha iron (a-Fe) is a body centered cubic (BCC) crystal and has a lower strength and hardness but higher plasticity and toughness, relative to pearlite that has a two-phase lamellar strength, composed of alternating layers of a-Fe (88 wt %) and cementite or iron carbide (12 wt %) which account for the higher strength and hardness and lower plasticity and toughness [5].

Grade DH-36 steel / Chemical Composition											
C	Mn	Cu	Si	Cr	Mo	V	Ti	Al	Nb	P	S
0.14	1.37	0.14	0.22	0.08	0.03	0.001	0.003	0.017	0.03	0.007	0.001

Table VI-4: Major alloy content of Grade DH-36 steel (wt%) [5].

Another steel plate widely used in the shipbuilding industry both in hull construction and in the superstructure itself is EH36 Steel plate. This shipbuilding grade is used either in Icebreakers and Ice-Going Vessels or Offshore Structures and Pressure Equipments and its chemical composition is given in Table VI-5 [11].

Grade EH-36 steel / Chemical Composition										
C	Mn	Cu	Si	Cr	Mo	V	Ni	Cb	P	S
0.15	1.45	0.35	0.1 – 0.5	0.20	0.08	0.05 – 0.10	0.40	0.02 – 0.05	0.035	0.035

Table VI-5: Major alloy content of Grade EH-36 steel (wt%) [11].

Plate materials for hull structures are to be not less than those given in Rules and Regulations of the Classification Society under which, the vessels is constructed based on the as-built thickness of the material, the Polar Ice Class notation assigned to the vessel and the Material Class of structural members.

Steel grades for all weather exposed plating of hull structures and appendages situated below and above the level of 0.3 m below the lower ice waterline (LIWL) can be seen in Figure VI-6 [3].

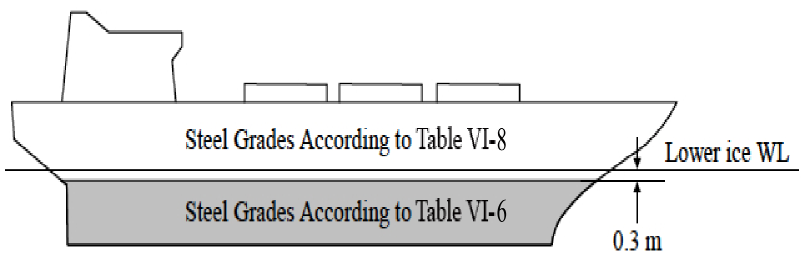


Figure VI-6: Steel Grade Requirements for Submerged and Weather Exposed Shell Plating [3].

Material classes specified in ABS Rules for Building and Classing Steel Vessels are applicable to Polar Class vessels. These material grades are mentioned in Table VI-6.

Structural members of polar class vessels should be built according to these material grades and the requirements for submerged exposed shell plating (Table VI-7).

Thickness t (mm)	*Material Class*		
	I	*II*	*III*
t≤15	A, AH	A, AH	A, AH
15≤t≤20	A, AH	A, AH	B, AH
20≤t≤25	A, AH	B, AH	D, DH
25≤t≤30	A, AH	D, DH	D[1], DH
30≤t≤35	B, AH	D, DH	E, EH
35≤t≤40	B, AH	D, DH	E, EH
40≤t≤45	D, DH	E, EH	E, EH

Table VI-6: Material Grades for Submerged Exposed Plating [4].

Structural Members	*Material Class*
Shell plating within the bow and the bow intermediate icebelt hull areas (B,BI_i)	II
All weather and sea exposed SECONDARY and PRIMARY structural members outside 0.4L amidships	I
Plating materials for stem and stern frames, rudder horn, rudder, propeller nozzle, shaft brackets, ice skeg, ice knife and other appendages subject to ice impact loads	II
All inboard framing members attached to the weather and sea-exposed plating including any contiguous inboard member within 600 mm of the shell plating	I
Weather-exposed plating and attached framing in cargo holds of vessels which by nature of their trade have their cargo hold hatches open during cold weather operations	I
All weather and sea exposed SPECIAL structural members within 0.2L from FP	II

Table VI-7: Material Classes for Structural Members of Polar Class Vessels [3].

Steel grades for weather exposed plating of hull structures and appendages situated above the level of 0.3 m below the lower ice waterline (LIWL), are to be not less than given in Table VI-8.

Thickness, t (mm)	*Material Grade I*				*Material Grade II*				*Material Grade III*					
	PC1-5		PC6 & 7		PC1-5		PC6 & 7		PC1-3		PC4 & 5		PC6 & 7	
	MS	HT	MS	HT	MS	HT	MS	HT	MS	HT	MS	HT	MS	HT
t ≤ 10	B	AH	B	AH	B	AH	B	AH	E	EH	E	EH	B	AH
10 ≤ t ≤ 15	B	AH	B	AH	D	DH	B	AH	E	EH	E	EH	D	DH
15 ≤ t ≤ 20	D	DH	B	AH	D	DH	B	AH	E	EH	E	EH	D	DH
20 ≤ t ≤ 25	D	DH	B	AH	D	DH	B	AH	E	EH	E	EH	D	DH
25 ≤ t ≤ 30	D	DH	B	AH	E	EH[2]	D	DH	E	EH	E	EH	E	EH
30 ≤ t ≤ 35	D	DH	B	AH	E	EH	D	DH	E	EH	E	EH	E	EH
35 ≤ t ≤ 40	D	DH	D	DH	E	EH	D	DH	F	FH	E	EH	E	EH
40 ≤ t ≤ 45	E	EH	D	DH	E	EH	D	DH	F	FH	E	EH	E	EH
45 ≤ t ≤ 50	E	EH	D	DH	E	EH	D	DH	F	FH	F	FH	E	EH

Table VI-8: Steel Grades for Weather Exposed Plating [3].

Notes:

1. Includes weather-exposed plating of hull structures and appendages, as well as their outboard framing members, situated above a level of 0.3 m below the lowest ice waterline.
2. Grades D, DH are allowed for a single strake of side shell plating not more than 1.8 m wide from 0.3 m below the lowest ice waterline.

Design Average Temperature (DAT -X ºC)

Ships operating in the polar regions are subjected to highly concentrated loading from ice features and air temperatures down to -50°C. A variety of factors should be taken into account in order to decide the proper steel grade [29]:

· Design minimum temperature

· Associated wind speed

· Likelihood of exposure of the structural member to impact loads at low temperatures

· Stress category of the member, and anticipated strain rate

· Steel thickness

· Stress relieving and post-welded heat treatment

· Amount of cold-forming (unless its effects have been nullified)

· Accessibility to structural components for welding inspection and periodic surveys

· Weld acceptance criteria

· Provision of artificial means of heating (Rapo 1983)

Ice rules regarding steel grades are set, in order to make easier the decision of the right steel grade due to material thickness and the location of the exposed plating. The notation DAT (-X ºC) indicate the Design Average Temperature applied as basic for approval. The requirements apply to materials in ships of any type intended to operate for longer periods in areas with a low air temperature. The DAT notation shows the design-ambient air temperature for structural material properties where temperature of -X ºC designates temperature in Celsius (ºC) [20].

In Figure VI-7 the required steel grade according to DAT (-X ºC) is presented. The figure shows that the requirement on material grade depends on three things:

- Design temperature.
- Structural category.
- Thickness of the structural member.

If the structural category is known, the material grade can be selected based on the design temperature and plate thickness. Thus, if a 30mm plate on a ship were to be applied for structural category III with a design temperature of -30ºC, grade E or EH would be acquired.

In general, transition from ductile to brittle behaviour is the main reason for having material requirements. Operating a ship in temperature below the material transition temperature will result in a structure with changed structural properties. A cooled structural member may become stronger because of decreased interatomic spacing, which increases attraction between the atoms. It may also become more brittle depending on the characteristics of the material.

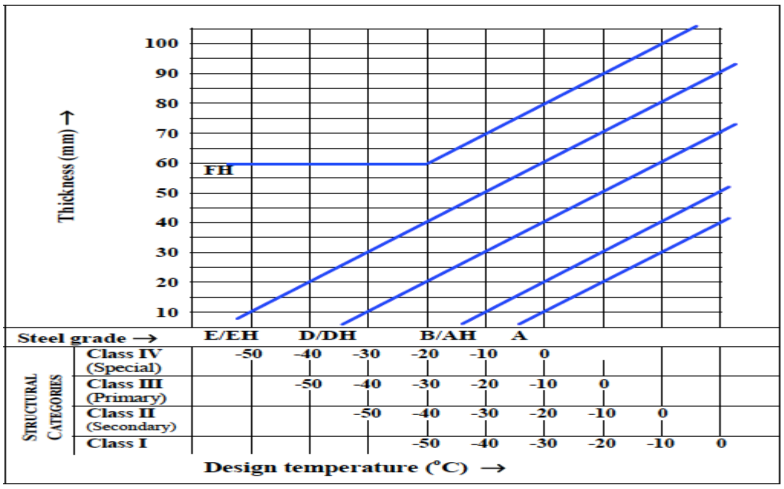


Figure VI-7: Required steel grades according to DAT (-X oC) [20]

The design temperature defines the minimum temperature of the ambient air in which the ship is supported to operate in. The structural member category depends on the location of the structural member and its load case. Material requirements depending on the thickness of structural member are influenced by the boundary conditions, where the distance between the plate surface leads to zero lateral stress throughout the plate thickness. Increasing the carbon content normally hardens steel. This treatment will results in higher yield strength and a less ductile behaviour of the material.

VII. ICE CLASS RULES – STRUCTURAL STANDARDS DEVELOPMENT

The determination of scantlings, as well as the design of ship structures, follow some rules and regulations. At present, there are three main sets of ice class rules: the Finnish-Swedish Ice Class Rules (FSICR), the Russian Maritime Register of Shipping (RMRS) ice rules and the unified Polar Class (PC) rules of the International Association of Classification Societies (IACS). The classification societies and some maritime authorities (Finnish and Swedish Maritime Administrations and Transport Canada) have developed rules for ice capable ships. These ice class rules cope with several different ice class ship categories, depending on the ability of the vessel to operate in various ice conditions. Ice class rules define the scantlings of the hull and shaftline structures and set some requirements for ship performance in ice and structural arrangement.

1. INTRODUCTION TO THE ICE CLASS RULES

The Finnish Transport Safety Agency (Trafi) and the Swedish Transport Agency (STA) have developed the Finnish-Swedish Ice Class Rules in co-operation with classification societies and researchers from the private sector [44].

The demand for navigation in Baltic seas set the development of the rules in the 1930's with its latest version to be published in 2010. Most of the members of the International Association of Classification Societies (IACS) have adopted the Finnish-Swedish Ice Class rules and incorporated them in their own regulations on the classification of ships. The Finnish-Swedish Ice Class Rules are primarily intended for the design of merchant ships trading in the Northern Baltic in winter. Special consideration should be given to ships designed for independent navigation in ice, or for ships designed for navigation in other sea areas than the Baltic Sea.

The FSICR contain requirements for hull, machinery and also performance of ship in ice. Four different ice classes are defined and also the open water ships have their own ice class notations (II and III). This is because the fairway dues are dependent on the ice class – higher ice class ships pay less fairway dues as these ships use less icebreaker support. The Finnish-Swedish ice classes are [46]:

1. ice class 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, maximum level ice thickness 1.0 m;
2. ice class 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, maximum level ice thickness 0.8 m;
3. ice class IB; the same as above for the ice class IA except the maximum level ice thickness 0.6 m;
4. ice class IC; the same as above for the ice class IA except the maximum level ice thickness 0.4 m;
5. ice class II; ships that have steel hull and they 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;
6. ice class III; corresponding to barges.

FSICR are established as the rules for ships navigating in the Baltic, following the design and operational requirements used there. The Finnish-Swedish ice class rules have been descrided as an 'industry standard' for the first year ice conditions and IACS polar class rules have equivelant notations in order to classify them. The classification societies follow their notations, but the basic rules are the same as FSICR. The corresponding class notations are stated in the Table VII-1.

Rule System	Corresponding classes, Notation			
Finnish-Swedish Ice Class Rules	IA Super	IA	IB	IC
American Bureau of Shipping	IAA	IA	IB	IC
Bureau Veritas	IA Super	IA	IB	IC
Det Norske Veritas-GL	ICE-1A*	ICE-1A	ICE-1B	ICE-1C
Lloyd's Register	1AS	1A	1B	1C
Nippon Kaiji Kyokai (Class NK)	IA Super	IA	IB	IC
Registro Italiano Navale	IAS	IA	IB	IC
Korean Register of Shipping	IA Super	IA	IB	IC
China Classification Societiy	B1*	B1	B2	B3

Table VII-1: Equivalent notations for the Finnish-Swedish ice classes [46].

The design scenario of FSICR regarding the hull is an impact with level ice of a certain thickness (h_o), as well as a collision with ridges, 80% thicker than the ice thickness (h_o) of the level ice. The highest machinery and hull loads and the performance requirements do not have a common design ship-ice interaction scenario as the largest response occurs in different kinds of scenario. The design scenarios for hull, machinery and performance are stated in Table VII-2 [40].

Hull	Impact with level ice of thickness h_0	The ship can encounter thick level ice in ridges where the consolidated layer can be 80% thicker than the ice thickness. Also channel edges can be very thick.
Propulsion machinery	Impact with large ice floes	Propeller encounter only broken ice and the design scenario is an impact with these floes. Large ice floes can be encounter among the level ice floes for example in old channels
Propulsion power	Ships must make at least 5 knots in the specified brash ice channel	Ships must be able to follow icebreakers at a reasonable speed and also to proceed in old brash ice channels independently at reasonable speeds.

Table VII-2: Design ship-ice interaction scenarios used in FSICR [40].

The design point in the FSICR is maximum stress up to yield point, elastic limit state ; and the estimation for the frequency that the yield point is reached is about once a week; the scantling equations have been modified satisfying this requirement. The yield point in plating is reached more often than in the frames – this suggests a correct structural hierarchy in FSICR .

Except of the requirements for scantlings, powering requirement is based on the other hand, on ensuring an efficient winter navigation system. The Finnish and Swedish winter navigation system consist of: a) icebreakers that escort the merchant fleet through the worst ice conditions, b) ice strenghtened merchant fleet, c) rules, regulations and fees assigned by maritime authorities. All ships fulfilling the requirements for an ice class set by Finnish or Swedish maritime authorities. If the capability of the ships is low in Finnish or Swedish ports that are icebound every winter, many icebreakers will be needed to escort them or a delay in the departures will cause heavy traffic, late delivery timetables and the winter navigation system would be very extensive to maintain. Thus the merchant ships are required to have some ice capability so that the escort distances in ice will be shorter and escort speed higher; thus, higher ice class ships pay lower fairway dues [46].

The Russian Maritime Register of Shipping (RMRS) ice rules consist of nine ice classes – three categories form the group of ships navigating in non-arctic ice seas (ice1, ice2, ice3) and six ice categories (Arc4 – Arc9) that form the group of arctic ships capable to Polar operations. The ship categories for non-arctic and arctic ships are shown in Table VII-3 and Table VII-4, respectively. The RMRS ice rules contain also three parts; hull, machinery and powering. The powering requirements for the Baltic are the same as the corresponding FSICR ice classes, while the structural limit in the design point is full plastic response for plating and frames. The design limit for stringers and web frames is the yield one [49]. The RMRS rules are mainly used for ships with the Russian flag or ships operating in Russian waters but their analysis is not part of this thesis concern.

Ship category	**Permitted thicknes of ice, m**		**Type of operation**
	Independent navigation in open pack ice at speed of 5 knots	Navigation in channel following an icebreaker in compact ice at a speed of 3 knots	
Ice1	0.40	0.35	Episodically
Ice2	0.55	0.50	Regularly
Ice3	0.70	0.65	Regularly

Table VII-3: Russian Maritime Register of Shipping non-arctic category ships [49].

Ship category	**Permitted speed in knots**	**Ice concentration and type**	**Ice thickness in m**		**Methods of Surmounting ice ridges**
			Winter spring navigation	Summer autumn navigation	
Arc4	6 - 8	Open floating first-year ice	0.6	0.8	Continuous motion
Arc5		Open floating first-year ice	0.8	1.0	
Arc6		Open floating first-year ice	1.1	1.3	
Arc7		Open floating first-year ice	1.4	1.7	Episode ramming
Arc8	10	Close floating second-year ice	2.1	3.0	Regular ramming
Arc9	12	Very close floating and compact second-year ice	3.5	4.0	Surmounting of ice ridges and episodic ramming of compact ice fields

Table VII-4: Russian Maritime Register of Shipping arctic category ships [49].

The third set of ice class rules were established by IACS. These rules have been under development since mid 90's and in 2008 the rules were finally accepted. At the moment all IACS members are adopting these rules into their rule structure and deleting their old versions for polar classes.

There are seven polar classes in IACS ice rules. These classes are described in Table VII-5 and the ice description follows the World Meteorological Organization's practice. It is noticable that the ice capability decriptions included are rather cursory. This was deliberate an IMO intend to make the definitions even more general, with an intention to remove any reference to 'summer/autumn' operation for the PC6 and PC7.

Hull design in PC classes is based on plastic structural limit and it has been stated that the return period of the loads causing response up to the limit is one year. The machinery rules for PC classes are based on the same theory of ice loads in the FSICR.

Polar Class	Ice Description
PC 1	Year-round operation in all Polar waters
PC 2	Year-round operation in moderate multi-year ice conditins
PC 3	Year-round operation in second-year ice with old ice inclusions
PC 4	Year-round operation in thick first-year ice with old ice inclusions
PC 5	Year-round operation in medium first-year ice with old ice inclusions
PC 6	Summer/Autumn operation in medium first-year ice with old ice inclusions
PC 7	Summer/Autumn operation in thin first-year ice with old ice inclusions

Table VII-5: Ice classes of the IACS unified ice rules [3].

The short survey of ice classes show that it is difficult to select an ice class based solely on the ice class description. The ice class that a ship should have is in principle set by the ice conditions and the required safety level –but in practice the required ice class is decided by the requirements of the maritime authorities. In Finland and Sweden the maritime authorities set the required ice class for each port in the Traffic Restrictions. These requirements develop when winter proceed. Russian and Estonian authorities follow roughly a similar procedure; only the requirements are slightly lower than to Finland and Sweden. The Canadian system is called the Arctic Ice Regime Shipping System (AIRSS 1996) – in this system an Ice Numeral is calculated based on the prevailed ice conditions and ship ice class, and if the numeral is negative, the ship cannot enter the area. The selection of a suitable ice class must take into account what the authorities require in different ice conditions.

The class equivalencies agreed for the ice classes used in the Baltic are not valid for Arctic ice classes. However, many ships having a Baltic ice class (IA and IA Super) have navigated in the Arctic successfully. The experience has prompted an action to parallel the lowest PC classes with the highest Baltic classes and treat the classes PC6, Arctic5 and IA Super as equivalent (and also PC7, Arctic4 and IA). This equivalency is recognised by the Baltic authorities and also by the Canadian authorities in the following form: 'As an interim measure for navigation purposes, Transport Canada consider that PC6 and PC7 vessels should be allowed to operate as Type A and B vessels (Baltic 1AS and 1A construction) respectively'.

2. FINNISH-SWEDISH ICE CLASS RULES (FSICR)

The Ice Class Rules & Regulations as they are set up in Trafi (Finnish Transport Safety Agency) together with the distinguished hull regions and hull structural design topics are examined and analysed [53].

As it is mentioned above, four ice classes are defined in the Finnish-Swedish Ice Class Rules, in order of strength from high to low: IA Super, IA, IB, and IC. The ice thickness for IA Super is higher than the maximum level of ice thickness observed in the Baltic outside the fast ice zone.

In this section, the basic Ice Class rules are presented, giving emphasis to the hull design rules, especially the calculations of the design ice load, the respective design load patch and the scantlings of side shell plating and framing.

Ice Class Draught

Upper and lower ice waterlines

The upper ice waterline (UIWL) shall be the envelope of the highest points of the waterlines at which the ship is intended to operate in ice. The line may be a broken line.

The lower ice waterline (LIWL) shall be the envelope of the lowest points of the waterlines at which the ship is intended to operate in ice. The line may be a broken line.

Maximum and minimum draught fore and aft

The maximum and minimum ice class draughts at fore and aft perpendiculars shall be determined in accordance with the upper and lower ice waterlines.

Restrictions on draughts when operating in ice shall be documented and kept on board readily available to the master. The maximum and minimum ice class draughts fore, amidships and aft shall be indicated in the class certificate. The draught and trim, limited by the UIWL, must not be exceeded when the ship is navigating in ice. The salinity of the sea water along the intended route shall be taken into account when loading the ship.

The ship shall always be loaded down at least to the LIWL when navigating in ice. Any ballast tank situated above the LIWL and needed to load down the ship to this water line, shall be equipped with devices to prevent the water from freezing. In determining the LIWL, regard shall be paid to the need for ensuring a reasonable degree of ice-going capability in ballast. The propeller shall be fully submerged, if possible entirely below the ice. The forward draught shall be at least:

$(2 + 0.00025 \cdot \Delta) \cdot h_o$ [m] but need not exceed $4h_o$,

where

Δ is displacement of th ship [t] on the maximum ice-class draught according to UIWL

h_o is the level ice thickness [m] according to Table VII-6.

Hull structural design

The method for determining the hull scantlings is based on certain assumptions concerning the nature of the ice load on the structure. These assumptions are from full scale observations made in the northern Baltic.

It has thus been observed that the local ice pressure on small areas can reach rather high values. This pressure may be well in excess of the normal uniaxial crushing strength of the sea ice. The explanation is that the stress field in fact is multiaxial.

Further, it has been observed that the ice pressure on the frame can be higher than on the shell plating at midspacing between frames. The explanation for this is the different flexural stiffness of the frames and shell plating. The load distribution is assumed as shown in Figure VII-1.

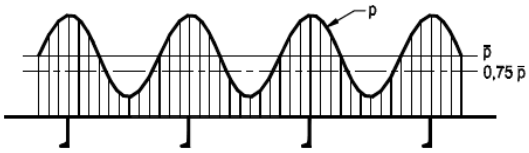


Figure VII-1: Ice load distribution on a ship's side [53].

Direct analyses are to be carried out using the load patch defined by p, h and l_α. The pressure to be used is the design ice pressure, while h is the load height and l_a is the load length.

The design scenario for each ice class ships in the worst ice conditions in Baltic Seas, is a collision with a level ice edge, a channel edge when the ship is escorted or with consolidated layer of an older, ice ridges.

As the consolidated layer of ridges is 1.8 times thicker than the level ice at the same location, and the maximum average level ice thickness in the middle of the sea basins is about 60 cm, this results in about 1.0 m equivalent ice thickness h_o (Table VII-7). It should be noted that this design scenario does not state ship speed – it is considered that no speed restrictions should exist, as this would handicap much of the navigation in ice. It is still somewhat unclear, however, which ship-ice interaction scenario causes the highest loads.

The load patch is to be applied at locations where the capacity of the structure under the combined effects of bending and shear are minimized. In particular, the structure is to be checked with load centred at the UIWL, $0.5h_o$ below the LIWL, and positioned several vertical locations in between. Several horizontal locations shall also be checked, especially the locations centred at the mid-span or –spacing. Further, if the load length l_α cannot be determined directly from the arrangement of the structure, several values of l_α are to be checked using corresponding values for c_α.

Acceptance criterion for designs is that the combined stresses from bending and shear, using the von Mises yield criterion, are lower than the yield point σ_y. When the direct calculation is using beam theory, the allowable shear stress is not to be larger than $0.9\cdot\tau_y$, where

$$\tau_y = \sigma_y / \sqrt{3}.$$

If scantling derived from these regulations are less than those required by the classification society for a not ice strengthened ship, the latter shall be used.

Hull regions

Bow area

The bow region is the region from the stem to a parallel line and $0{,}04\cdot L$ aft of the forward borderline of the part of the hull where the waterlines run parallel to the centerline.

The overlap over the borderline need not exceed:

- 6 m for the notations **ICE CLASS IA SUPER** & **ICE CLASS IA**
- 5 m for the notations **ICE CLASS IB, ICE CLASS IC** and **ICE CLASS II**

Midbody Region

The midbody region is the region from the aft boundary of the bow region to a line parallel to and 0,04·*L* aft of the aft borderline of the part of the hull where the waterlines run parallel to the centerline.

The overlap over the borderline need not exceed:

- 6 m for the notations **ICE CLASS IA SUPER & ICE CLASS IA**
- 5 m for the notations **ICE CLASS IB, ICE CLASS IC**

Stern Region

The stern region is the region from the aft boundary of the midbody region to the stem.

L shall be taken as the ship's rule length used by classification society.

In Figure VII-2 there is a description of hull regions in Ice Class vessels.

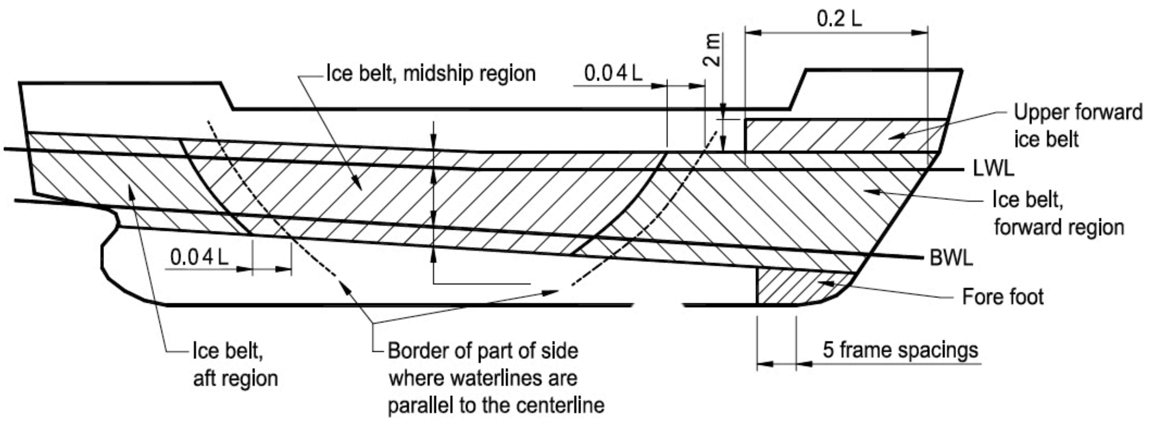


Figure VII-2: Longitudinal and Vertical hull parts in Ice Class vessels [53].

Vertical extension of ice strengthening for plating (ice belt)

The vertical extension of the ice belt is defined in Table VII-6.

		Vertical extension of ice strengthened area for:			
		plating		*ordinary stiffeners and primary supporting*	
Notation	**Hull region**	**Above UIWL**	**Below LIWL**	**Above UIWL**	**Below LIWL**
IA Super	Bow	0.60 m	1.2 m	1,2 m	Down to double bottom or below top of floors
	Midbody				2.00 m
	Stern		1.0 m		1.60 m
IA	Bow	0.50 m	0.90 m	1.00 m	1.60 m
	Midbody		0.75 m	1.00 m	1.30 m
	Stern			1.00 m	1.00 m
IB and IC	Bow	0.40 m	0.70 m	1.00 m	1.60 m
	Midbody		0.60 m	1.00 m	1.30 m
	Stern			1.00 m	1.00 m

Table VII-6: Vertical extension of the ice belt for plating, ordinary stiffeners and primary supporting members [53].

In addition, the following areas shall be strengthened:

- *Fore foot*: For ice class IA Super, the shell plating below the ice belt from the stem to a position five main frame spaces abaft the point where the bow profile departs from the keel line shall have at least the thickness required in the ice belt in the midbody region.
- *Upper bow ice belt*: For ice classes IA Super and IA on ships with an open water service speed equal to or exceeding 18 knots, the shell plate from the upper limit of the ice belt to 2 m above it and from the stem to a position at least 0.2 *L* abaft the forward perpendicular, shall have at least the ice thickness required in the ice belt in the midbody region. A similar strengthening of the bow region is advisable also for a ship with a lower service speed, when it is, e.g. on the basis of the model tests, evident that the ship will have a high bow wave.

Sidescuttles shall not be situated in the ice belt. If the weather deck in any part of the ship is situated below the upper limit of the ice belt (e.g. in way of the well of a raised quarter decker), the bulwark shall be given at the same strength as it is required for the shell in the ice belt. The strength of the construction of the freeing ports shall meet the same requirements.

Level ice thickness and design height

An ice-strengthened ship is assumed to operate in open sea conditions corresponding to a level ice thickness not exceeding h_o. The design height (h) of the area actually under ice pressure at any particular point of time is, however, assumed to be only a fraction of the ice thickness. The value for h_o and h are given in Table VII-7.

Ice Class	*h_o [m]*	*h [m]*
IA Super	1.0	0.35
IA	0.8	0.3
IB	0.6	0.25
IC	0.4	0.22

Table VII-7: Level ice thickness and design height of Finnish-Swedish Ice Classes [53].

Ice pressure

The design ice pressure [MPa] is determined by the formula:

$$p = c_d \cdot c_p \cdot c_a \cdot p_0 .$$

c_d is a factor which takes account of the influence of the size and engine output of the ship This factor is taken as maximum c_d=1. It is calculated by the formula:

$$c_d = \frac{a \cdot k + b}{1000}$$

where

$$k = \frac{\sqrt{\Delta \cdot P}}{1000}$$

Δ is the displacement of the ship at maximum ice class draught [t],
P is the actual continuous engine output of the ship [kW],
α and *b*, as given in Table VII-8.

p_0 is the nominal ice pressure; the magnitude of the nominal ice pressure is 5.6 Mpa, because the material properties of the Baltic ice do not change much through the winter in different Baltic Seas areas.

Factors	Region			
	Bow		Midbody & Stern	
	k≤12	k≥12	k≤12	k≥12
α	30	6	8	2
b	230	518	214	286

Table VII-8: Factors α and b for the calculation of the ice pressure [53].

The factor of c_p takes account of the probability that the design ice pressure occurs in a certain region of the hull for the ice class in question and its value is given in the Table VII-9.

Ice Class	Region		
	Bow	**Midbody**	**Stern**
IA Super	1.0	1.0	0.75
IA	1.0	0.85	0.65
IB	1.0	0.70	0.45
IC	1.0	0.50	0.25
IA	1.0	N/A	N/A

Table VII-9: Value of c_p, related to the longitudinal region of the ship [53].

The third factor used to define the ice pressure is a coefficient dependent on the load length, c_a. c_a is a factor which takes into account the probability that the full length of the area under consideration will be under pressure at the same time. Each structural member has an associated load length l_a – this is the length of the load that influences the response (stress) in the member. The load length coefficient is defined as:

$$0.35 \le c_a = \sqrt{\frac{l_0}{l_a}} \le 1.0$$

where the reference length is l_0=0.6 m.

In principle, each structural member should be designed by trying all load lengths and then selecting the design case to be the length that gives the maximum stress. There is no need to do this calculation, as the load lengths are given in the rules, as shown in Table VII-10.

Structural member	Type of framing	Design load length l_a [m]
Shell plating	Transverse	Frame spacing
	Longitudinal	1.7·frame spacing
Frames	Transverse	Frame spacing
	Longitudinal	Span of frame
Ice stringer		Span of stringer
Web frame		2·web frame spacing

Table VII-10: Load lengths, associated with different structural members [53].

In conclusion, the ice load in FSICR is, in principle, defined so that the ice pressure is constant for all classes (nominal ice pressure p_o) and the load height is the class factor (from 0.35 m for ice class IA Super to 0.22 m for ice class IC). The total ice load for each structural member depends on the line load:

$$q = p \cdot h$$

and the width (horizontal span or spacing) contributing to the design load length (l_a) of each structural member. For transverse frames the load is, for example, $F=q \cdot s$, where s is the frame spacing.

To obtain the ice pressure p, the nominal ice pressure is modified by these three coefficients (c_a, c_p, c_d), all of which are less than one. An analysis of the mechanics of collision between ice and a ship suggests that it is the ship displacement and speed that influence the contact force. Here it should be noted that the basic rule requirement is at least 5 knots speed in channels of a given thickness.

However, the total contact force in collision with ice is not an important factor for most of the structural members (they are sensitive to a load patch that is smaller than the total load patch size). This has led to the definition of the size quantity of

$$k = \sqrt{P \cdot \Delta}$$

and a size coefficient for ice pressure c_d, which is linearly dependent on k.

The ship hull is divided into three hull regions shown in Fig. VII-7: bow, midbody, and stern. Each of these has a design ice pressure defined by a hull region factor c_p. This factor is for the bow region and is scaled according to the ice class for other region so that the stern region has the lowest design ice pressure. Even if the design ice pressure at the bow region is the same for a ship in all ice classes, the design force is not, as the load height is a class factor [48].

Determination of the design point

The aim of the structural formulae in the FSICR is to derive a relationship between the limit state, the scantlings and the load. Different limit states are given in Table VII-11 [39]. Kaldasaun (2010) has mentioned also other limit states: Serviceability limit to state, fatique limit state and accidental limit state. Serviceability is used to define allowable failure limits under deterioration of normal conditions. This limit state refers to local failures that reduces to durability or efficiency of the structure or reduce aesthetic appearance of the structure but do not lead to collapse or ultimate failure of the structure. Serviceability limit state is relevant for this analysis. Fatique limit state presents the occurence of fatique cracks in structural details due to stress concentration and damage accumulation under repeated loads, but it is not a major concern in ice-strengthened ship hull structures if only ice loads are considered. Accidental limit state defines excessive structural damages as a result of accidents, such as grounding, collision, fire or explosion, but this analysis is only related to damages due to ice loading.

Limit state (label)	**Plating**	**Frames**
Elastic (Y)	Stress reaching the yield stress σ_y somewhere in the plate	Stress reaching the yield stress σ_y somewhere in the plate
Plastic (P)	Stress distribution reaching full plasticity somewhere in the plate; Permanent deformation still zero	2-hinge formation at the frame support
Ultimate (U)	Permanent deformation (w_p) reaching a specified value	3-hinge formation at the frame supports and the mid-span

Table VII-11: Definitions of the limit states for plating and frames (Riska & Kåmåråinen-2011) [39].

Scantlings

Once the ice load is specified and the limit state is defined, the scantlings can be calculated. The limit state used in the Finnish-Swedish Ice Class Rules is the yield limit – consequently, only the elastic response of the structure needs to be derived. The plate thickness equations are based on a similar equation used to car decks under tire loading. The frame equations are based on simple beam formulation. The effect of load height on plate response is taken into account with a constant dependent on *h/s* (the constant is denoted here as *f(h/s)).*

Thickness *t* of shell plating for transverse framing is given by equations of the form

$$t = 667 \cdot s \cdot \sqrt{\frac{f_1 \cdot p_{PL}}{\sigma_y}} + t_c[mm]$$

while for longitudinal framing the thickness of the shell plating shall be determined by the formula:

$$t = 667 \cdot s \cdot \sqrt{\frac{p_{PL}}{f_2 \cdot \sigma_y}} + t_c[mm]$$

where

p_{PL} is the equavelant plate pressure, at *0.75p*.

The origin of the constant 0.75 is in the pressure distribution across the plate and has to do with the effect of the pressure distribution on the response of transversely framed plating. σ_y is the yield strength of the material [N/mm^2], for which the following values shall be used:

- σ_y=235 N/mm^2 for normal-strength hull structural steel
- σ_y=315 N/mm^2 or higher for high-strength hull structural steel

s is the frame spacing [m]

The constant *f(h/s)* is different for transversely and longitudinally framed structures.

- Transversely framed structures:

$$f(h/s) = 1.3 - \frac{4.2}{(h/s + 1.8)^2} \leq 1.0$$

- Longitudinal framed structures:
  1. when $h/s \leq 1$

  $$f_2(h/s) = 0.6 + \frac{0.4}{(h/s)}$$

  2. when $1 \leq h/s < 1.8$

  $$f_2(h/s) = 1.4 - 0.4(h/s)$$

  3. when $1.8 \leq h/s \leq 3$

  $$f_3(h/s) = 0.35 + 0.183 \cdot (h/s)$$

  4. $h/s \geq 3$

  $f_4(h/s) = 0.9$

h is the design height as given in Table VII-7.

t_c is increment for abrasion and corrosion [mm]; normally t_c shall be 2 mm; If a special surface coating, by experience shown capable to withstand the abrasion of ice, is applied and maintained, lower values may be approved.

In general, the frame scantlings include the frame section modulus Z and shear area A. These are calculated for transverse frames with equations of the form

$$Z = \frac{q \cdot s \cdot l_a}{m \cdot \sigma_y}$$

$$A = \frac{1}{2} \cdot \frac{1.2 \cdot q \cdot l_a}{\tau_y}$$

where τ_y is the shear strength and the factor 1.2 stems from taking the shear stress distribution across the web into account. *m* is the factor dependent on the end connections of the frame (m=5...7). The equations for longitudinal frames are similar but contain a factor that is dependent on the load height and frame spacing.

Finally, the bottom plating in the forward region (below the lower forward ice belt) shall not be less than the thickness of:

$$t = 0.7 \cdot (s + 0.8)\sqrt{235 \cdot L / \sigma_F}\,(mm) \geq 12mm$$

Some Observations

The structure of the Finnish-Swedish Ice Class Rules is quite simple and the flow of the calculations is easy to follow and perform. Some observations can be made, however, concerning the structure of the rules and the main points of the rules rationale. The observations include [48]:

a) The ice load is independent of the hull shape. The simplicity of the formulation is the main reason for this, and not much knowledge exists on the effect of the hull shape. The load is constant along the whole bow and can be qualitatively justified by the fact that two physical effects influence the load: speed of indentation into the ice and frame angle. The indentation speed depends on the projection of the speed on the shell normal. This decreases when moving from the stem towards the bow shoulder area. The frame normal angle (frame inclination on the vertical plane including the frame normal) is usually greatest at the bow and decreases towards the shoulder area. The ice load increases with the indentation speed, whereas the load decreases with the frame normal angle – these effects have opposite trends along the bow waterline.
b) According to some other ice class rules, the longitudinal location of the structures influences the required scantlings. This is not the case in the FSICR and similar arguementation as that used above.
c) The ship size description includes both the ship propulsion power and displacement through the factor k. This factor could be called an ‘aggressive factor’ as it describes the ship inertia and instantaneous speed. The drawback is that there is no theoretical justification for the use of this factor. However, it can be mentioned that the factor *k* accounts for the possibility of colliding with the ice at high speed – thus the power to be used in calculations is the actual power delivered continuously to the ship propellers (or propulsion) – and the possibility of penetrating severe ice by using ship inertia. The latter scenario may occur in a channel in which there are thick side ridges, including a consolidated layer.
d) The design point includes the yield as the limit state. If the loading for plating and framing had similar return periods, this would induce an unsafe structural strength hierarchy. Plating and frames would be similar strength and, as frames have less

plastic reserve than plating, under ultimate loads the frames would collapse, first leading to greater damage than just plating failing. This is corrected in the present rules, however, with different safety factors for plating and frames.

3. IACS UNIFIED REQUIREMENTS FOR POLAR SHIPS

The IACS Unified Requirements for Polar Ships apply to ships constructed of steel and intended for navigation in ice-infested polar waters, except ice breakers [3]. A key element of the overall development was to agree on the upper and lower capability bounds for polar ships, and to decide on the number of polar classes that would be appropriate. The high end was a ship capable of operating safely anywhere in the Arctic or Antarctic oceans at any time of year, while the lower threshold was set at a capability level similar to Baltic IA.

It was expected (and desired) that a ship capable of operating safely in the Arctic or Antarctic oceans at any time of year (though safe operation would still require due caution) would comply largely with a PC 1 classification, and that some of the Baltic and 'Baltic plus' merchant vessels with successful Arctic service would meet PC6 and PC7 structural requirements.

The ice description based on the World Meteorological Organization (WMO) Sea Ice Nomenclature is given in Table VII-12 [19].

POLAR CLASS	Icebreaker assisted operations			Independent operations					
				In open ice (concentration < 6/10) (1)			In close ice (concentration ≥ 6/10) (1)		
	Operations	Ice description (2)	Max. ice thk (m)	Operations	Ice description (2)	Max. ice thk (m)	Operations	Ice description (2)	Max. ice thk (m)
1	year-round	all multi-year ice	3,5	year-round	all multi-year ice	3,5	year-round	second-year ice which may include multi-year ice inclusions	2,0
2	year-round	moderate multi-year ice	3,0	year-round	moderate multi-year ice	3,0	year-round	thick first-year ice which may include old ice inclusions	1,5
3	year-round	second-year ice which may include multi-year ice inclusions	2,5	year-round	second-year ice which may include multi-year ice inclusions	2,5	year-round	medium first-year ice which may include old ice inclusions	1,2
4	year-round	thick first-year ice which may include old ice inclusions	1,5	year-round	thick first-year ice which may include old ice inclusions	1,5	year-round	medium first-year ice which may include old ice inclusions	1,0
5	year-round	medium first-year ice which may include old ice inclusions	1,0	year-round	medium first-year ice which may include old ice inclusions	1,0	summer / autumn	medium first-year ice which may include old ice inclusions	0,8
6	summer/ autumn	medium first-year ice which may include old ice inclusions	0,8	summer / autumn	medium first-year ice which may include old ice inclusions	0,8	summer / autumn	thin first-year ice	0,6
7	summer/ autumn	thin first-year ice which may include old ice inclusions	0,6	summer / autumn	thin first-year ice which may include old ice inclusions	0,6	summer / autumn	thin first-year ice	0,4

(1) Portion of sea covered by the ice, expressed in tenths
(2) Based on World Meteorological Organization (WMO) Sea Ice Nomenclature

Table VII-12: Polar Class Description [19].

The basic structural requirements and regions based on the proper design scenario and the development of design loads and ice pressures, as well as hull structural scantlings are described in this section [3].

Upper and Lower Ice Waterlines

The upper and lower ice waterlines upon which the design of the vessel has been based are to be defined by the maximum and lower draughts fore, amidships and aft, respectively. The lower ice waterline is to be determined with due regard to the vessel's ice-going capability in the ballast loading conditions (e.g. propeller submergence).

Structural Requirements for Polar Class Ships & Hull Regions

The hull of all ships having an additional class notation **POLAR CLASS** is divided into areas reflecting the magnitude of the load that are expected to act upon them.

In the longitudinal direction, there are four regions:

- Bow (B)
- Bow intermediate (BI)
- Midbody (M)
- Stern (S)

The bow intermediate, midbody and stern regions are further divided into:

- bottom (b)
- lower (l)
- icebelt region (i)

The extent of this hull area is indicated in Figure VII-3, where h_i measured at aft end of the Bow region in m, is given in Table VII-13.

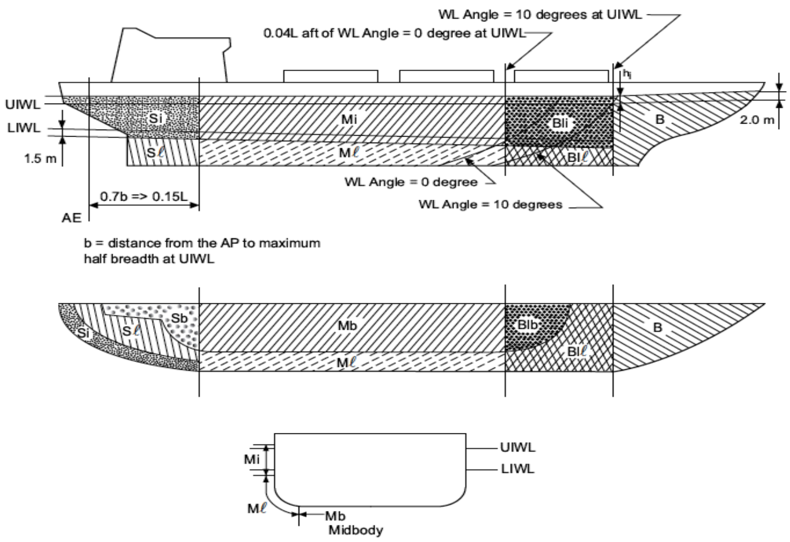


Figure VII-3: Longitudinal and Vertical hull parts in Polar Class vessels [3].

POLAR CLASS	hi, in m
1 to **4**	1.5
5 to **7**	1.0

Table VII-13: Value of hi for hull area extents [3].

The boundary between the Bow and the Bow Intermediate regions is to be located:

- aft of the intersection point of the line stem and the ship baseline, and
- forward of 0.45L of the forward perpendicular (FP).

The boundary between the bottom and lower regions is to be taken at the point where the shell is inclined 7º from the horizontal.

Moreover, the hull angles measured at the Upper Ice Waterline (UIWL) are very important for the calculation of design ice loads, due to the bow shape coefficient (*fa*). Thus, the Polar Class Ships should have a specific hull shape. The maximum, appropriate hull angles γ and α, given in Table VII-14. For the calculations of design ice load, the angles β and β′ (θ) should also be known.

POLAR CLASS	**1**	**2**	**3**	**4**	**5**	**6**	**7**
Stem angle at the bow γ in degree	25	25	30	30	45	60	70
Waterline angle at the bow α in degree	30	30	30	30	40	40	40

Table VII-14: Maximum value of angles γ and α for the bow [3].

The hull angles are defined in Figure VII-4.

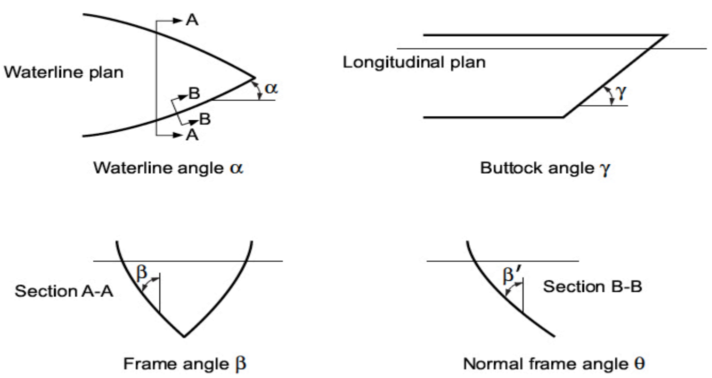


Figure VII-4: Definitions of hull angles α, β, γ and β' [3].

Note:

β = frame angle at upper ice waterline [deg]
β' = normal frame angle at upper ice waterline [deg], can be found also as (θ),
α = upper ice waterline angle [deg],
γ = buttock angle at upper ice waterline (angle of buttock line measured from horizontal) [deg]

$$\tan(\beta) = \frac{\tan(a)}{\tan(\gamma)}$$

$$\tan(\beta') = \tan(\beta) \cdot \cos(a)$$

Design Ice Load

The design scenario that forms the basic of the ice loads for plating and framing design is a glancing collision on the shoulder of the bow (see Figure VII-5) [18]. In this scenario, the ship is assumed to be moving forward at the design speed, striking an angular ice edge. During the collision, the ship penetrates the ice and rebounds away. The ship speed, ice thickness and ice strength are assumed to be class dependent. The maximum force can be found by equating the normal kinetic energy with the energy used to crush the ice. The ice crushing force cannot exceed the force required to fail the ice in bending. The combination of angles, ice strength and thickness determine the force limit due to bending.

The rule scenario is strictly valid only for the bow region, and for the stern of double-acting ships. In order to produce a balanced structural design, loads on the other hull areas are set as a proportion of the bow area by using empirical hull area factors (AF). The loads on the other hull areas are not strongly dependent on bow angles, and so bow loads are normalized using a 'standard' set of bow angles before being applied elsewhere.

The design loads are developed in several stages that are described in the following sections. Firstly, the total load is found as the minimum of the crushing and flexural limiting loads for the design ice. Secondly, the patch over which this load is applied is determined and idealized. Thirdly, the distribution of the load within the patch is modified to account for local loading peaks.

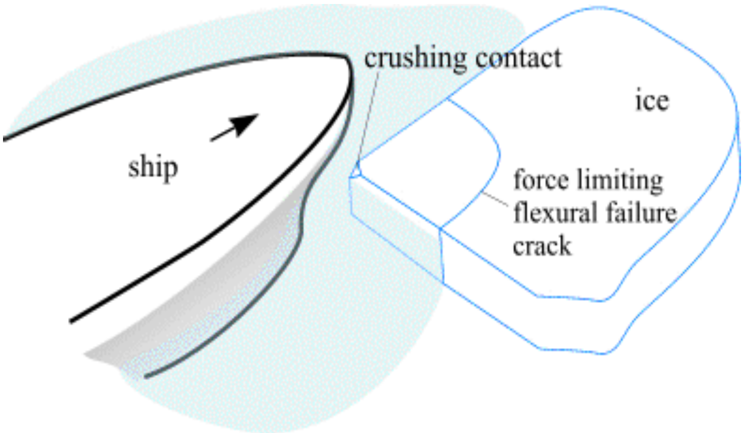


Figure VII-5: Design scenario- crushing and flexural failure during glancing collision [18].

In brief, the design ice load is characterized by average pressure (P_{avg}) uniformly distributed over a rectangular load patch of height (b) and width (w).

Within the Bow area of all polar classes, and within the Bow Intermediate Icebelt area of polar classes PC6 and PC7, the ice load parameters are functions of the actual bow shape. To determine the ice load parameters (P_{avg}, b and w), it is required to calculate the following ice load characterictics for sub-regions; shape coeffficient (f_{ai}), total glancing impact force (F_i), line load (Q_i) and pressure (P_i).

In other ice-strengthened areas, the ice load parameters (P_{avg}, b_{NonBow} and w_{NonBow}) are determined independently of the hull shape and based on a fixed load patch aspect ratio, AR=3.6.

Design ice forces calculated according to the method mentioned above, are only valid for vessels with icebreaking forms. Design ice forces for any other bow forms are to be specially considered by the member society, however until now, are calculated in a same way, due to lack of further knowledge.

Glancing Impact Load Characteristics

The design scenario is a glancing collision with an ice edge. The ice load is derived from the sollution of an energy method, based on collision model, where kinetic energy is equal to ice crushing energy. The derivation and development of all these equations, parameters and factors are described in Chapter VIII.

Design Ice Force in Bow Area (F_{BOW})

Design ice force calculated according to max(F_i), [MN] is shown in Figure VII-6, where

$$F_n = f_a \cdot CF_C \cdot \Delta_{ship}^{0.64}$$

f_a : the shape coefficient, in each region of the bow.

CF_c : Crushing failure class factor, defined in Table VII-15 for each Polar class.

Δ: Displacement in t, to be taken not less than 5000t and is valid only for ships with icebreaking forms (i.e. the normal frame angle θ shall be at least 10 degrees in the bow area). However, ships without icebreaking form, but with ice strengthened hull and proper hull shape can also included to the calculations.

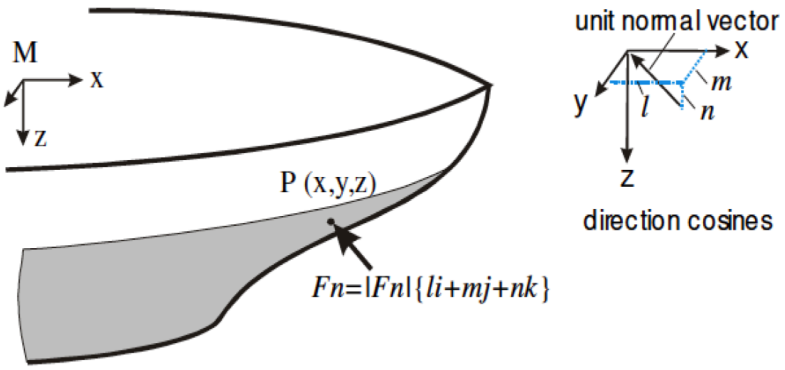


Figure VII-6: Design Ice Force and Collision Geometry [12].

All functions of the hull angles should be measured at the upper ice waterline (UIWL). The influence of the hull angles is captured through calculation of a bow shape coefficient (fa_i) The waterline length of the bow region is to be divided into four sub-regions «*i*» of equal length. Forces (F_i), line loads (q_i), pressure (p_i), bow shape coefficients (fa_i) and load patch aspect ratios (AR_i) are to be calculated with respect to the mid-length position x of each region.

POLAR CLASS	Cc (crushing failure)	CF_c (flexural failure)		C_D (load patch dimensions)	C_Δ (displacement)	C_L (longitudinal strength)
		Brackish water	Open sea			
1	17.69	76.92	68.60	2.01	250	7.46
2	9.89	54.45	46.80	1.75	210	5.46
3	6.06	25.64	21.17	1.53	180	4.17
4	4.50	17.05	13.48	1.42	130	3.15
5	3.10	11.94	9.00	1.31	70	2.50
6	2.40	8.70	5.49	1.17	40	2.37
7	1.80	6.69	4.06	1.11	22	1.81

Table VII-15: Glancing impact load characteristics-Class factors [3] .

Shape Coefficient (fa_i): The bow shape coefficient (fa_i), in each sub-region i of the bow area, is to be obtained from the following formula:

$fa_i = min(fa_1, fa_2, fa_3)$,

where

$$f_{a1} = [0.097 - 0.68 \cdot (\frac{x}{L} - 0.15)^2] \cdot \frac{a}{\sqrt{\theta}}$$

$$f_{a2} = 1.2 \cdot CF_F / [\sin(\theta) \cdot CF_C \cdot \Delta^{0.64}]$$

$$f_{a3} = 0.60$$

and

Δ: Displacement as mentioned above, not less than 5000t

θ: Normal frame angle, in degree, in sub-region i of the bow area.

Load patch aspect ratio, AR_i: The aspect ratio of the load patch describes the proportional relationship between its width and its height. The load patch aspect ratio AR_i, in each sub-region i of bow area, is to be obtained from the following formula,

$$AR_i = 7.46 \cdot sin\theta_i$$

be taken not less than 1.3.

θ_i = normal frame angle of sub-region *i* [deg]

Line load Q_{BOW}: The line load Q_{BOW}, in MN/m, is to be obtained from the following formula,

$$Q_{BOW} = max(Q_i)$$

where

$$Q_i = F_i^{0.61} \cdot CF_D / AR^{0.35}$$

Q_i : Line load in sub-region *i* of the bow area

F_i : Force of sub-region *i* [MN]

CF_D : Load Patch Dimension Class Factor from Table VII-15

AR_i : Load patch aspect ratio of sub-region *i*

Pressure P: The pressure $p_{BOW} = max\ (p_i)$

$$P_i = F_i^{0.22} \cdot CF_D^2 \cdot AR_i^{0.3}$$

where

P_i : Pressure in sub-region *i* of the bow area, [MPa]

F_i : Force of sub-region *i* [MN]

CF_D : Load Patch Dimension Class Factor from Table VII-15

AR_i : load patch aspect ratio of sub-region *i*

Design ice force in areas other than the bow

The force F_{NonBow}, in MN, is to be obtained from the following formula:

- when $\Delta \leq C_\Delta$:
  $$F_{NonBow} = 0.36 \cdot CF_C \cdot \Delta^{0.64}$$

- when $\Delta > C_\Delta$:
  $$F_{NonBow} = 0.36 \cdot CF_C \cdot (CF_{DIS}^{0.64} + 0.10 \cdot (\Delta - CF_{DIS}))$$
  where
  CF_C : Crushing Force Class Factor from Table VII-15
  Δ : Displacement, in [kt], to be taken not less than 10 kt
  C_Δ : Displacement Class Factor from Table VII-15

Line load Q_{NonBow}: The line load Q_{NonBow}, in MN/m, is to be obtained from the following formula,

$$Q_{NonBow} = 0.639 \cdot F_{NonBow}^{0.61} \cdot CF_D$$

where

CF_D : Load Patch Dimensions Class Factor from Table VII-15.

Design load patch:

(i) In the Bow area and the Bow Intermediate Icebelt area for ships with class notation PC6 and PC7, the design load patch has dimensions of width, w_{Bow} and height b_{Bow}, defined as follows:

$$w_{Bow} = F_{Bow} / Q_{Bow}$$
$$b_{Bow} = Q_{Bow} / P_{Bow}$$

where

F_{Bow} = maximum force F_i in the Bow area [MN]
Q_{Bow} = maximum line load Q_i in the Bow area [MN/m]
P_{Bow} = maximum pressure P_i in the Bow area [MPa]

(ii) In hull area othen than Bow and Bow Intermediate for PC6 and PC7, covered above, the design load patch has dimensions of width, w_{NonBow}, and height b_{NonBow}, defined as follows:

$$w_{NonBow} = F_{NonBow} / Q_{NonBow}$$
$$b_{NonBow} = w_{NonBow} / 3.6$$

where,

F_{NonBow} = force F_i in the area other than the bow [MN]

Q_{NonBow} = line load Q_i in the area other than the bow [MN/m].

Pressure within the design load patch:

1. The average pressure P_{avg}, with a design load patch is determined as follows:

$$P_{avg} = \frac{F}{(b \cdot w)} [MPa]$$

where,

$F = F_{Bow}$ or F_{NonBow} as appropriate for the hull area under consideration [MN],

$b = b_{Bow}$ or b_{NonBow} as appropriate for the hull area under consideration [m],

$w = w_{Bow}$ or w_{NonBow} as appropriate for the hull area under consideration [m].

2. Areas of higher, concentrated pressure exist within the load patch. In general, smaller areas have higher local pressures. Accordingly, the peak pressure factors listed in Table VII-16 are used to account for the pressure concentration on localized structural members.

Structural Member		**Peak Pressure Factor (PPF)**
Plating	Transversely-Framed	$PPF_p = (1.8 - s) \geq 1.2$
	Longitudinally-Framed	$PPF_p = (2.2 - 1.2 \cdot s) \geq 1.5$
Frames in Transverse Framing Systems	With Load Distributing Stringers	$PPF_t = (1.6 - s) \geq 1.0$
	With No Load Distributing Stringers	$PPF_t = (1.6 - s) \geq 1.2$
Load Carrying Stringers Side and Bottom Longitudinals Web Frames		$PPF_t = 1$, if $S_w \geq 0.5 \cdot w$ $PPF_t = 2.0 - 2.0 \cdot S_w/w$, if $S_w < (0.5 \cdot w)$
s : frame or longitudinal spacing [m] S_w : web frame spacing [m] w : ice load patch width [m]		

Table VII-16: Peak Pressure Factors [3].

Hull Area Factors

Associated with each hull area is an Area Factor that reflects the relative magnitude of the load expected in that area. The Area Factor (AF) for each hull area is listed in Table VII-17.

In the event that a structural member spans across the boundary of a hull area, the largest hull area factor is to be used in the scantling determination of the member.

Due to their increased manoeuvrability, ships having propulsion arrangements with azimuthing thruster(s) or 'podded' propellers shall have specially considered: Stern Icebelt (S_i) and Stern Lower (S_l) hull area factors.

Hull Area		**Area**	**Polar Class**						
			PC1	**PC2**	**PC3**	**PC4**	**PC5**	**PC6**	**PC7**
Bow (B)	All	B	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Bow Intermediate (BI)	Icebelt	BI_i	0.90	0.85	0.85	0.80	0.80	1.00*	1.00*
	Lower	BI_l	0.70	0.65	0.65	0.60	0.55	0.55	0.50
	Bottom	BI_b	0.55	0.50	0.45	0.40	0.35	0.30	0.25
Midbody (M)	Icebelt	M_i	0.70	0.65	0.55	0.55	0.50	0.45	0.45
	Lower	M_l	0.50	0.45	0.40	0.35	0.30	0.25	0.25
	Bottom	M_b	0.30	0.30	0.25	**	**	**	**
Stern (S)	Icebelt	S_i	0.75	0.70	0.65	0.60	0.50	0.40	0.35
	Lower	S_l	0.45	0.40	0.35	0.30	0.25	0.25	0.25
	Bottom	S_b	0.35	0.30	0.30	0.25	0.15	**	**
*Bow Intermediate for PC6 & PC7, the ice load parameters are functions of the actual bow shape, measured at the upper ice waterline. ** Indicates that strengthening for ice loads are not necessary.									

Table VII-17: Hull Area Factors (AF) [3].

Scantlings

Shell plating Requirements

The required minimum shell plate thickness, t, is given by:

$$t = t_{net} + t_s [mm]$$

where

t_{net} = plate thickness required to resist ice loads, according to the below equations [mm]

t_s = corrosion and abrasion allowance [mm]

The thickness of the shell plating required to resist the design ice load t_{net}, depends on the orientation of the framing.

In the case of transversely-framed plating (Ω ≥ 70 deg), including all bottom plating, i.e. plating in hull areas BI_b, M_b, S_b, the net thickness is given by:

$$t_{net} = 500 \cdot s \cdot ((AF \cdot PPF_p \cdot P_{avg}) / \sigma_y)^{0.5} / (1 + s / (2 \cdot b))[mm]$$

In the case of longitudinally-framed plating (Ω ≤ 20 deg), when b < s, the net thickness is given by:

$$t_{net} = 500 \cdot s \cdot ((AF \cdot PPF_P \cdot P_{avg}) / \sigma_y)^{0.5} \cdot (2 \cdot b / s - (b / s)^2)^{0.5} / (1 + s / (2 \cdot l))[mm]$$

or when b ≥ s:

$$t_{net} = 500 \cdot s \cdot ((AF \cdot PPF_P \cdot P_{avg}) / \sigma_y)^{0.5} / (1 + s / (2 \cdot l))[mm].$$

In the case of obliquely-framed plating (20 deg < Ω < 70 deg), linear interpolation is to be used, where

Ω = smallest angle between the chord of the waterline and the line of the first level framing as illustrated in Figure VII-7 [deg].

s = transverse frame spacing in transversely-framed ships or longitudinal frame spacing in longitudinal-framed ships [m]

AF = Hull Area Factor from Table VII-17

PPF_p = Peak Pressure Factor from Table VII-16

P_{avg} = average patch pressure, according to above mentioned equation

σ_y = minimum upper yield stress of the material [N/mm^2]

b = height of design load patch [m], where $b \leq (l-s/4)$ in the case of the equation for transversely-framed plating

l = distance between frame supports, i.e. equal to the frame span, but not reduced for any fitted end brackets [m].

The values of corrosion/abrasion additions, t_s, to be used in determining the shell plate thickness for each Polar Class are listed in Table VII-18.

Effective protection against corrosion and ice-induced abrasion is recommended for all external surfaces of the shell plating for all Polar ships.

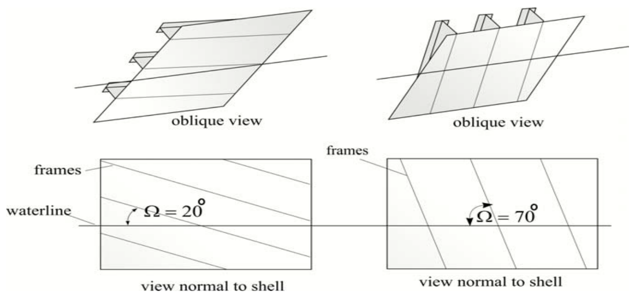


Figure VII-7: Shell Framing Angle Ω [3].

Polar ships are to have a minimum corrosion/abrasion addition of t_s = 1.0 mm applied to all internal structures within the ice-strengthened hull angles, including plated members adjacent to the shell, as well as stiffener webs and flanges.

Hull Area	**t_s [mm]**					
	With Effective Protection			**Without Effective Protection**		
	PC1 - PC3	**PC4 & PC5**	**PC6 & PC7**	**PC1 - PC3**	**PC4 & PC5**	**PC6 & PC7**
Bow; Bow Intermediate Icebelt	3.5	2.5	2.0	7.0	5.0	4.0
Bow Intermediate Lower; Midbody & Stern Icebelt	2.5	2.0	2.0	5.0	4.0	3.0
Midbody & Stern Lower; Bottom	2.0	2.0	2.0	4.0	3.0	2.5

Table VII-18: Corrosion-Abrasion Additions for Shell Plating [3].

Framing requirements

Framing members of Polar class ships are to be designed to withstand the design ice load [2].

The design span of framing member is to be determined on the basis of its mould length. If brackets are fitted, the design span may be reduced in accordance with the usual practice of each member society. Brackets are to be configured to ensure stability in the elastic and post-yield response regions.

When calculating the section modulus and shear area of a framing member, net thickness of the web, flange (if fitted) and attached shell plating are to be used. The shear area of a framing member may include the material contained over the full depth of the member, i.e. web area including portion of flange, if fitted, but excluding shell plating. The actual net effective shear area, A_w, of the framing member is given by:

$$A_w = h \cdot t_{wn} \cdot \sin\varphi_w / 100 [cm^2]$$

h = height of stiffener [mm], see Figure VII-8

t_{wn} = net web thickness [mm] = $t_w - t_c$

t_w = as built web thickness [mm], see Figure VII-8

t_c = corrosion deduction [mm] to be subtracted from the web and flange thickness (as specified by each member society, but not less than t_s = 1.0 mm, as required from the rules for corrosion thickness.

φ_w = smallest angle between shell plate and stiffener web, measured at the midspan of the stiffener, see Figure VII-8. The angle φ_w may be taken as 90 degrees provided the smallest angle is not less than 75 degrees.

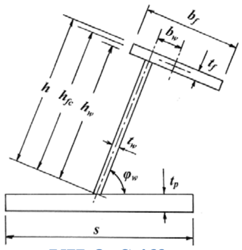


Figure VII-8: Stiffener geometry [3].

When the cross-sectional area of the attached plate flange exceeds the cross-sectional area of the local frame, the actual net effective plastic section modulus Z_p is given by:

$$Z_p = A_{pn} \cdot t_{pn} / 20 + \frac{h_w^2 \cdot t_{wn} \cdot \sin\varphi_w}{2000} + A_{fn} \cdot (h_{fc} \cdot \sin\varphi_w - b_w \cdot cos\varphi_w) / 10 [cm^3]$$

h, t_{wn}, t_c, and φ_w, as given above

A_{pn} = net cross-sectioned area of the local frame [cm^2]

t_{pn} = fitted net shell plate thickness [mm] (shall comply with t_{net})

A_{fn} = net cross-sectional area local frame flange [cm^2]

h_{fc} = height of local frame measured to centre of the flange area [mm], see Figure VII-8.

b_w = distance from mid thickness plane of local frame web to the centre of the flange area [mm], see Figure VII-8.

Transversely-Framed Side Structures and Bottom Structures

The local frames in transversely-framed side structures and in bottom structures (i.e. hull areas BI_b, M_b and S_b) are to be determined so that the combined effects of shear and bending do not exceed the plastic strength of the member. The plastic strength is defined by the magnitude of midspan load that causes the development of a plastic collapse mechanism [2]. The actual net effective shear area, A_w is to comply with the following condition: $A_w \geq A_t$, where:

$$A_t = 100^2 \cdot 0.5 \cdot LL \cdot s \cdot (AF \cdot PPF_t \cdot P_{avg}) / (0.577 \cdot \sigma_y) [cm^2]$$

where

LL = length of loaded portion of span = lesser of a and b [m]

a = frame span determined on the basis of its moulded length

b = height of design ice load patch [m]

s = transverse frame spacing [m]

AF = Hull Area Factor from Table VII-17

PPF_t = Peak Pressure Factor from Table VII-16

P_{avg} = average pressure within load patch [MPa]

σ_y = minimum upper yield stress of the material [N/mm^2]

The actual net effective plastic section modulus of the plate/stiffener combination, Z_p, is to comply with the following condition: $Z_p \geq Z_{pt}$ where Z_{pt} is to be the greater calculated on the basic of the two load conditions:

a) Ice load acting at the midspan of the transverse frame, and
b) The ice load acting near a support.

The A_1 parameter reflects the two conditions:

$$Z_{pt} = 100^3 \cdot LL \cdot Y \cdot s \cdot (AF \cdot PPF_t \cdot P_{avg}) \cdot a \cdot A_1 / (4 \cdot \sigma_y)[cm^3]$$

where

$$Y = 1 - 0.5 \cdot (LL / a)$$

A_1 = maximum of

$$A_{1A} = 1/[1 + j/2 + k_w \cdot j/2 \cdot ((1 - a_1^2)^{0.5} - 1)]$$

$$A_{1B} = 1 - 1/(2 \cdot a \cdot Y))/(0.275 + 1.44 \cdot k_z^{0.7})$$

j=1 for framing with one simple support outside the ice-strengthened areas

=2 for framing without any support

$a_1 = A_t/A_w$

A_t = minimum shear area of transverse frame [cm^2]

A_w = effective net shear area of transverse frame [cm^2]

$$k_w = 1/(1 + 2 \cdot A_{fn} / A_w)$$

A_{fn} = net cross-sectional area local frame flange [cm^2]

$k_z = z_p/Z_p$ in general

= 0.0 when the frame is arranged with end bracket

z_p = sum of individual plastic section moduli of flange and shell plate as fitted [cm^3]

$$z_p = (b_f \cdot t_{fn}^2 / 4 + b_{eff} \cdot t_{pn}^2 / 4)/1000$$

b_f = flange breadth [mm], see Figure VII-8

$t_{fn} = t_f - t_c$ net flange thickness [mm]

t_f = as built flange thickness [mm], see Figure VII-8

t_{pn} = the fitted net shell plate thickness [mm] (not to be less than t_{net})

b_{eff} = effective width of shell plate flange [mm], $b_{eff} = 500 \cdot s$

Z_p = net effective plastic section modulus of transverse frame [cm^3]

Side Longitudinals (Longitudinally-Framed Ships)

Side longitudinals are to be dimensioned so that the combined effects of shear and bending do not exceed the plastic strength of the member. The plastic strength is defined by the magnitude of midspan load that causes the development of a plastic collapse mechanism [2].

The actual net effective shear area of the frame, A_w is to comply with the following condition: $A_w \geq A_L$, where:

$$A_L = 100^2 \cdot (AF \cdot PPF_s \cdot P_{avg}) \cdot 0.5 \cdot b_1 \cdot a / (0.577 \cdot \sigma_y)[cm^2]$$

where

AF = Hull Area Factor from Table VII-17

PPF_s = Peak Pressure Factor from Table VII-16

P_{avg} = average pressure within load patch [MPa]

$b_1 = k_o \cdot b_2$ [m]

$k_o = 1 - 0.3/b'$

$b' = b/s$

b = height of design ice load patch

s = spacing of longitudinal frames [m]

$b_2 = b \cdot (1 - 0.25 \cdot b)$ [m], if $b' < 2$

b_2 = s [m], if $b' > 2$

a = longitudinal design span

σ_y = minimum upper yield stress of the material [N/mm^2]

The actual net effective plastic section modulus of the plate/stiffener conbination, is to comply with the following condition: $Z_p \geq Z_{pL}$,

where:

$$Z_{pL} = 100^3 \cdot (AF \cdot PPF_s \cdot P_{avg}) \cdot b_1 \cdot a^2 \cdot A_4 / (8 \cdot \sigma_y)[cm^2]$$

AF, PPF_s , P_{avg}, b_1, a, σ_y are given above
and

$$A_4 = 1/[2 + k_{wl} \cdot ((1 - a_4^2)^{0.5} - 1)]$$

$\alpha_4 = A_L / A_w$

A_L = minimum shear area for longitudinal.

A_w = net effective shear area of longitudinal [cm^2]

$k_{wl} = 1/(1 + 2 \cdot A_{fn} / A_w)$

with

A_{fn} : net cross-sectional area local frame flange [cm^2].

4. COMPARISON OF THE ICE CLASS RULES

Differences between the FSICR and IACS Polar Class rules

The FSICR and the IACS Polar rules have been developed to satisfy the design, construction and operation of ice capable ships in Baltic and Polar regions, respectively. However, the transition from Ice Class to Polar Class categories is done so that the two highest Finnish – Swedish ice classes are considered equivalent to the two lowest of IACS polar class rules, regarding first-year ice conditions.

Note that for ice class IA in higher than thin first-year ice conditions, contact speed with ice should be decreased to below 1 knot, when operating independently, if collision with ice thicker than medium first-year ice cannot be avoid. In case of assistance by icebreakers, the beam of the assisted ship should not exceed the width of the icebreaker, otherwise two or more icebreakers may be used to meet the requirements.

Additionally, a ice class ship sailing in Polar Waters should take into account the following issues:

1. Ice compression in the sea area
2. In Baltic Seas there is not swell like in the Arctic and Antarctic. As a consequence, the vertical extension of the ice belt in the bow area may not be adequate if the vessel is operated in high swell and floating ice
3. The bottom of the ship may have to be strengthened if the ship is to be used in use conditions in shallow waters, such as river delta areas [39].

These differences result to different approach in the construction for the two ice class rules. In order to clarify the differences in the rules, the main differences in the structural requirements of the ships are listed [52]:

1. The ice belt regions for the two rules differ. The FSICR divide the ship into three longitudinal regions: bow, midbody, aft. The midbody and aft regions have the same vertical area, extenting from above the Upper Ice Waterline to below the Lower Ice Waterline. The bow region, however, is further reinforced in the vertical direction, divided into three different areas: upper forward ice belt, ice belt and fore foot. The extent of reinforcement for the side shell plating is lower than the extent for framing. The longitudinal regions of the midbody ice belt extent between the parallel body of the ship's hull.

   In contrast, the Polar Class requirements divide the hull into four longitudinal regions: bow, bow intermediate, midbody and stern and three vertical: bottom, lower and ice belt region. The differences in longitudinal and vertical extent of an IA ice class and a Polar Class 7 (PC7) vessel, are demostrated in Figure VII-9.

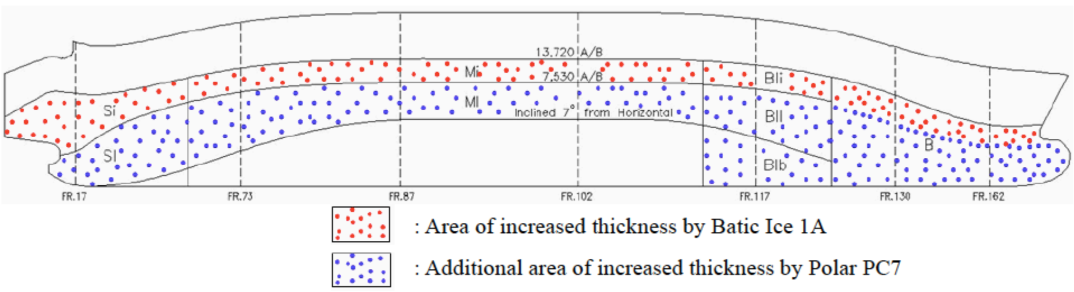


Figure VII-9: Strengthened zone by Baltic 1A and Polar PC7 in membrane type LNG carrier [33]

2. For the determination of ice load in the Polar Class requirements, a glancing impact of level ice with the ship's bow is the scenario for the assessment of the design ice load, while in the FSICR, the ship encounters thick level ice in ridges, leading to a thicker ice.
3. Furthermore, for the estimation of ice load in Polar Class requirements, the hull shape of the vessel should be known. The hull angles (flare, waterline, buttock angle) have a direct influence in the estimation of the design ice load. In contrast, the FSICR load do not depend on the the hull angles, directly.

4. Additionally, the propulsion power is a class dependent for FSICR requirements, while in Polar requirements the vessel's speed take part in the estimation of the design ice load.
5. The average pressure of the design ice load is assumed to act uniformly inside the load patch, while in the Polar Class, peak pressure factors (PPF) are used to account for the pressure concentration that occurs within the load patch on structural members.
6. In FSICR, the maximum corrosion/abrasion margin is 2 mm and if special coating is applied and maintained to structures, then lower values may be approved. On the other hand, Polar Rules treat corrsosion/abrasion margin as ice class notation and coating dependent.
7. Regarding the design point, the FSICR limit state for plating and framing is the first yield stress, while the Unified Rules for Polar Class plating and framing are based on the formation of elasto-plastic response mechanisms [26]. The FSICR frames require brackets at the connection of a side longitudinal to a web frame.
8. Polar Class requirements are very sufficient regarding the material class selection, as a conbination of the location, the structural member and the polar class, while FSICR does not require notations for the material selection.

The differences above define the different approach regarding the requirements in the FSICR and Polar Ice Class Unified Rules. However, the equivalencies that are established by the Administrations are valid and determine the equivalent safety level and performance in the same ice conditions.

5. COMPARISON OF EQUIVALENT ICE CLASSES

Two ice classes are in principles equivalent, if they meet the same requirements for safety and vessel performance in the same ice conditions. The latter is usually given by requirements for vessel propulsion power, while the safety level is not given explicity in any ice class rules. The safety level refer to a certain sea area and icebreaking assistance and the decision about the equivalency is on the maritime authorities of the port state concern. Apart from the hull requirements, the ship should satisfy the requirements of the authorities, regarding the machinery, propulsion and winterization of the exposed equipments, but these are out of the scope of this section [44].

The scantlings of a certain ice class are the main criteria for the determination of the equivalencies with another ice class. However, the scantling of FSICR and Polar Class Unified Rules rarely match and undersized plating is not strengthened by thick frames.

Comparison of scantlings for FSICR and IACS Polar Class equivalent categories

Ice class IA Super

The plate thickness in PC6 class is thinner than that of FSICR IA Super, especially in the bow intermediate area and the difference gets larger with increasing ship displacement. Vertical frames in PC6 are stronger than those of IA Super but the longitudinal frames are weaker in PC6 for other areas than the bow. Here it should be remembered that in calculating the PC-classes, no brackets were assumed on frames. As the FSICR require brackets especially on the longitudinal frames, the difference between FSICR and IACS rules diminishes.

Ice class IA

The comparison between FSICR IA and PC7 is exactly similar to the previous comparison. The plate thickness in the bow intermediate area in PC7 is somewhat smaller than that of ice class IA, especially for larger ships and horizontal framing. The horizontal frames of smaller ships in PC7 are weak, especially as it should remembered that the section modulus is the plastic one.

In Tables VII-19 and VII-20, the plate thickness and frame section modulus between FSICR and IACS PC comparison are stated, while in Table VII-21, the rule formulation comparison between FSICR and IACS. The ship is divided to regions in order to extract the appropriate results [44].

	Transverse framing	**Longitudinal framing**
Bow intermediate	PC from 10% (small ships) to 20% (large ships) thinner	PC from 5% (small ships) to 20% (large ships) thinner
Midship	PC about 15% (small ships) to 25% (large ships) thinner	PC about 10% thinner
Stern	PC from 10% (small ships) to 20% (large ships) thinner	Comparable

Table VII-19: The plate thickness comparison between FSICR and IACS Polar Class Rules [44].

	Transverse framing	**Longitudinal framing**
Bow intermediate	PC much (up to 300%) stronger	PC about 20% smaller (small ships) to 20% larger (large ships)
Midship	PC much (up to 300%) stronger	PC about 40% smaller (small ships) to 30% smaller (large ships)
Stern	PC much (up to 300%) stronger	PC about 50% smaller (small ships) to 20% smaller (large ships)

Table VII-20: The frame section modulus comparison between FSICR and IACS Polar Class Rules. (Note that the IACS requirement is a plastic section modulus.) [44].

	Finnish-Swedish rules	**International Association of Classification Societies rules**
Minimum bow draught (Ballast condition)	$T = (2 + 0.00025 \cdot \Delta) \cdot h_0$	NA
Ice belt extent	0.4 to 0.6 m above LWL	1.2 to 2.0 m above LWL
Midship area	Extends aft from flat side at both forward and aft shoulders	Extends aft from flat side at forward shoulders. Stern area length fixed (0.15·L)
Influence of P and Δ	Through a factor $k = \sqrt{P \cdot \Delta}$	Power is not included, displacement through shape factors
Plate thickness Bow transverse framing	$t = 667 \cdot s \cdot \sqrt{\dfrac{f_1 \cdot p_{PL}}{\sigma_y}} + t_c [mm]$	$t_{net} = 500 \cdot s \cdot ((AF \cdot PPF_p \cdot P_{avg}) / \sigma_y)^{0.5} / (1 + s / (2 \cdot b)) [mm]$
Plate thickness Bow longitudinal framing	$t = 667 \cdot s \cdot \sqrt{\dfrac{p_{PL}}{f_2 \cdot \sigma_y}} + t_c [mm]$	$t_{net} = 500 \cdot s \cdot ((AF \cdot PPF_P \cdot P_{avg}) / \sigma_y)^{0.5} / (1 + s / (2 \cdot l)) [mm]$
Frame section modulus Bow-transverse	$Z = \dfrac{p_{ice} \cdot s \cdot l \cdot h}{f(h/l) \cdot \sigma_y}$	$Z = \dfrac{(1 - \frac{h}{2 \cdot l}) \cdot p_{ice} \cdot s \cdot l \cdot h}{\sigma_y}$
Bow- longitudinal	$Z = \dfrac{f(h/s) \cdot p_{ice} \cdot s \cdot l^2}{\sigma_y}$	$Z = C \cdot \dfrac{(1 - 0.3 \cdot \frac{s}{h}) \cdot (1 - \frac{s}{4 \cdot h}) \cdot p_{ice} \cdot l^2}{\sigma_y}$

Table VII-21: The rule formulation comparison between FSICR and IACS Polar Class rules [44].

VIII. ENERGY BASED ICE COLLISION FORCES – BACKGROUND NOTES TO DESIGN ICE LOADS

Ice forces on ships and structures are typically the result of collisions. The magnitude of the force is determined by some form of limits. In some cases the ice strength is the determining factor, while in others the force may be limited by available kinetic energy. In such cases the available kinetic energy is expended in crushing (irrecoverable) and potential (recoverable) energy. Energy methods provide a simple way of determine forces.

IACS design loads derive from an energy based approach of different ship-ice interaction scenarios. Higher polar class ships face a head on (ramming) impact on the stem, while the scenario for lower polar class ships is a *glancing impact* on the bow or bow shoulder. The task that should be fulfilled is to develop load models for these certain scenarios. A standard methodology of analysis of impact events is the key behind the sollution of design ice load [12].

1. GENERAL APPROACH

The problem under discussion is one of impact between two objects. Most of the scenarios, except ramming, occur quickly and thus, can be assumed as single point collision. This method was proposed by Popov (1967) and developed by C. Daley (2000) with a different approach of ice crushing model [12].

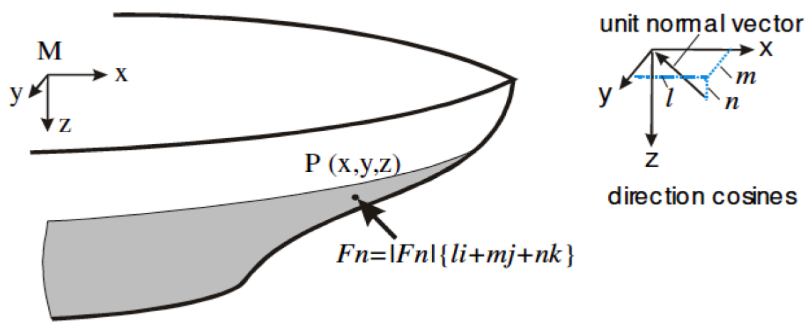


Figure VIII-1: Collision point geometry [12].

In general, it is assumed that one body is initially moving (the impacting body) and the other is at rest (the impacted body). This concept applies to a ship striking an ice edge. The energy approach is based on equating the available kinetic energy with the energy expended in crushing and potential energy:

$$KE_e = IE + PE \, .$$

The available kinetic energy is the difference between the initial kinetic energy of the impacting body and the total kinetic energy of the both bodies at the point of maximum force (Figure VIII-1). Only in the case of a direct (normal) collision involving one infinite (or very large) mass will the effective kinetic energy be the same as the total kinetic energy. In such a case all motion will cease at the time of maximum force.

The Popov's model follows the below assumptions:

1. Ship is considered as a rigid body
2. Average pressure follows a power area-ice pressure relationship

3. Added water mass coefficient is considered
4. No sliding and ice force action point found in the collision point
5. No friction between ice and ship's side happens

The indentation energy is the integral of the indentantion force F_n on the crushing indentation displacement δ:

$$IE = \int_0^{\delta_m} F_n(\delta) \cdot d\delta$$

The potential energy is the energy that has been expended in recoverable process, which can be either rigid body motions (pitch/heave) or elastic deformation (of either bodies). The potential energy is the intergral of the indentation force F_n on the recoverable displacement δ_e:

$$PE = \int_0^{\delta} F_n(\delta) \cdot d\delta_e$$

These equations are the basis of the solutions.

2. ICE INDENTATION

Ice crushing force derivation

In order to pose and solve the general energy equations it is necessary to formulate an equation relating force to indentation. By using the pressure-area relationship to describe the ice pressures, it is easy to derive a force-indentation relationship. Force is related only to indentation and the maximum force occurs at the time of maximum penetration in ice, as a sequence of crushing, extrusion and flexural failure. The mechanics are based on the Popov collision but amended to include a wedge shaped ice edge and a pressure/area ice indentation model.

The average pressure (P) is found from a Sanderson-type pressure-area relationship (Sanderson, 1988):

$$P_{av} = P_0 \cdot A^{ex}$$

where P_0 is the pressure at 1 m^2, and *ex* is a class-dependant constant.

The ice force is related to the nominal contact area:

$$F_i = P_{av} \cdot A = P_0 \cdot A^{1+ex}$$

In the case of a glancing collision scenario of a ship with an infinite ice mass, the ice edge of a channel, is regarded as the reference force. The available energy may be the 'normal' or 'effective' kinetic energy. In this case, the ice floe is assumed to stay immobilized after the moment of the impact, thus the ice sliding velocity is supposed to be zero and no collision energy is assumed to be dissipated by the friction force [17].

The force is found by equating the normal kinetic energy with the ice crushing energy [12]:

$$KE_n = IE$$

The normal kinetic energy combines the normal velocity with the effective mass at the collision point is

$$KE_n = \frac{1}{2} M_e \cdot V_n^2,$$

combining the terms of indentation energy and the normal kinetic energy gives:

$$\frac{1}{2} M_e \cdot V_n^2 = \int_0^{\delta_m} F_n(\delta) \cdot d\delta$$

where

δ = normal ice penetration

F_n = normal force

M_e = effective mass = M_{ship}/C_o

V_n = normal velocity of the ship before the moment of the collision= $V_{ship} \cdot l$

l = direction cosine.

In order to find the force, ice penetration geometry and the pressure-area relationship should be calculated. The nominal area is found for a penetration δ (Figure VIII-2).

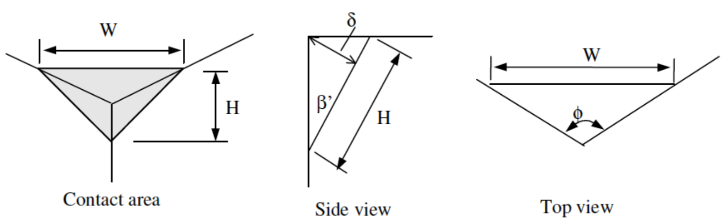


Figure VIII-2: Nominal contact geometry during oblique collision with an ice edge [12].

The nominal contact area is

$$A = W/2 \times H$$

The width (W) and height (H) of the nominal contact area can be determined by the normal penetration depth (δ) along with the normal frame angle (β') and the ice edge angle (φ),

$$W = 2 \cdot \delta \cdot \tan(\varphi/2)/\cos(\beta')$$

$$H = \delta/(\cos(\beta') \cdot \sin(\beta'))$$

Hence the area is

$$A = \delta^2 \cdot \tan(\varphi/2)/(\cos^2(\beta') \cdot \sin(\beta'))$$

The average pressure can be found from the equation

$$P_{av} = P_0 \cdot A^{ex}$$

and the normal force

$$F_i = P_{av} \cdot A = P_0 \cdot A^{1+ex}.$$

Substituting the above mentioned equations of area and pressure to the force equation:

$$F_n(\delta) = P_o \cdot (\delta^2 \tan(\varphi/2)/(\cos^2(\beta')\sin(\beta')))^{1+ex} =$$
$$= P_o \cdot k_a^{1+ex} \cdot \delta^{2+2ex}$$

where the angle factor is defined as

$$k_a = \tan(\varphi/2)/(\cos^2(\beta') \cdot \sin(\beta')).$$

Solving the energy balance equation, we can find the maximum penetration

$$\frac{1}{2} \cdot M_e \cdot V_n^2 = P_0 \cdot k_a^{1+ex} \int_0^{\delta_m} \delta^{2+2\cdot ex} \cdot d\delta .$$

We can extract the maximum penetration:

$$\delta_m = (1/2 \cdot M_e \cdot V_n^2 \cdot (3+2ex)/(P_o \cdot k_a^{1+ex}))^{1/(3+2ex)}$$

Substituting this into the expression for force, gives

$$F_n = P_o \cdot k_a^{1+ex} \cdot (1/2 \cdot M_e \cdot V_n^2 \cdot (3+2ex)/(P_o \cdot k_a^{1+ex}))^{(2+2ex)/(3+2ex)}$$

After simplifying the factors and collecting all shape related terms (comprising k_a and the terms with C_o and l) into a single term f_a,

$$f_a = (3+2\cdot ex)^{\frac{2+2ex}{3+2ex}} \cdot \left(\frac{\tan(\varphi/2)}{\sin(\beta') \cdot \cos^2(\beta')}\right)^{\frac{2+2ex}{3+2ex}} \cdot \left(\frac{1}{2 \cdot C_o} \cdot l^2\right)^{\frac{2+2ex}{3+2ex}}$$

With f_a, we can write the force equation as

$$F_n = f_a \cdot P_o^{(\frac{1}{3+2ex})} \cdot V_{ship}^{(\frac{4+4ex}{3+2ex})} \cdot M_{ship}^{(\frac{2+2ex}{3+2ex})}$$

Which for *ex=-0.1, φ=150 deg,* the equation becomes

$$F_n = f_a \cdot P_o^{0.36} \cdot V_{ship}^{1.28} \cdot M_{ship}^{0.64}$$

where

$$f_a = 1.94 \cdot \left(\frac{\tan(\varphi/2)}{\sin(\beta') \cdot \cos^2(\beta')}\right)^{0.32} \cdot \left(\frac{1}{2 \cdot C_o} \cdot l^2\right)^{0.64}$$

This equation is quite complex for a rule equation, that's why the following equation is proposed instead,

$$f_a = (0.097 - 0.68 \cdot (\frac{x}{L} - 0.15)^2) \cdot \frac{a}{\sqrt{\beta'}} .$$

The normal ice load (F_n) is further simplified by converting the above-mentioned value $P_o^{0.36} V_{ship}^{1.28}$ into class factor CF_C (Crushing Class Factor), so finally the equation applied to the IACS polar rules is:

$$F_n = f_a \cdot CF_c \cdot \Delta_{ship}^{0.64} .$$

So, the crushing force is extracted with a single factor of crushing (f_a) to include all form related terms and constants. However, the flexural force should also be included in the process of ship-ice impact, in order to identify the thorough design force.

Ice flexural failure

In larger ships, flexural failure is also important in ice failure and the ice force is a limitation of ice crushing force by the flexural failure force and vice versa.

The maximum force depends on normal (true) frame angle. Furthermore, it is impossible to express all the angle influences in one precise equation.

The normal force is limited to

$$F_{n,\lim} = \frac{1}{\sin(\beta')} \cdot 1.2 \cdot \sigma_f \cdot h_{ice}^2$$

where

h_{ice}= ice thickness [m] <class dependent>

$\beta' = \theta$ = normal (true) frame angle,

σ_f = ice flexural strength [Mpa] <class dependent>

There are various ice flexural strength equations. However, an equation that was extracted from the compilation of results of over 900 measurements shows a dependence of flexural strength on the brine volume of sea ice [9]:

$$\sigma_f = 1.76 \cdot e^{-5.88\sqrt{v_b}}$$

where

σ_f : flexural strength of sea ice, in MPa,

v_b : brine volume fraction, in ‰.

Design load patch

To continue with the design, the load patch (Figure VIII-3) can be found from normal force F_n [12].

The force can be calculated anywhere on the bow. In order to create a single design load patch for the whole bow, the largest F_i, Q_i, and p_i of at least four points around the bow area along the upper design ice waterline (UIWL) shall be taken. This maximum values, labeled F_{max}, Q_{max}, and p_{max} are combined to create a conservative load patch.

The shape of the nominal contact area between the ship and ice is simplified to an equivalent rectangular patch. The aspect ratio of this patch is retained, but its area is reduced to account for edge spalling effect observed in ice interaction. This reduction result to a rise in the design pressure, while the force remains unchanged. With the force and new patch dimensions, we can find the line load (Q) and the patch pressure (p).

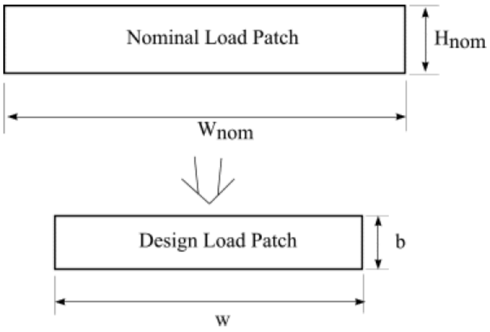


Figure VIII-3: Nominal and design rectangular load patches [12].

The pressure area relationship for ice, relating force and nominal contact area shall be solved for the normal contact area:

$$F_n = A^{1+ex} \cdot P_o \rightarrow A = \left(\frac{F_n}{P_o}\right)^{\frac{1}{1+ex}}.$$

The aspect ratio (AR) remains the same and equal to:

$$AR = 2 \cdot \tan(\varphi / 2)\sin(\beta')$$

and assuming φ = 150 deg,

$$AR = 7.46 \cdot \sin(\beta').$$

Therefore,

$$A = H_{nom} \cdot H_{nom} \cdot AR$$

and using the above mentioned equation for the area A, derives that the nominal height:

$$H_{nom} = \left(\frac{F_n}{P_o \cdot AR^{1+ex}}\right)^{\frac{1}{2+2ex}}$$

and the nominal width:

$$W_{nom} = \left(\frac{F_n}{P_o \cdot AR^{1+ex}}\right)^{\frac{1}{2+2ex}} \cdot AR.$$

The rule (design) patch length (w):

$$w = W_{nom}^{wex} = F_n^{wex/(2+2ex)} \cdot P_o^{-wex/(2+2ex)} AR^{wex/2},$$

where, with wex = 0.7 and ex = *-0.1,*

$$w = F_n^{0.389} \cdot P_o^{-0.389} AR^{0.35}.$$

The design load height is:

$$h = \frac{w}{AR} = F_n^{0.389} \cdot P_o^{-0.389} AR^{-0.65}$$

Assuming that the line load and ice pressure of the load patch is respectively:

$$Q = F_n / w$$

and

$$p = Q / b,$$

the resulting equations are:

$$Q = F_n^{0.611} \cdot P_O^{0.389} \cdot AR^{-0.35}$$

and

$$p = F_n^{0.222} \cdot P_O^{0.778} \cdot AR^{0.3}.$$

It is more convenient to express w and b in terms of F_n, Q and p, as follows,

$$w = F_n / Q$$

$$b = Q / p.$$

The design patch length for the bow (Figure VIII-4) is set as:

$$w_{bow} = F_{max} / Q_{max},$$

$$b_{bow} = Q_{max} / P_{max}.$$

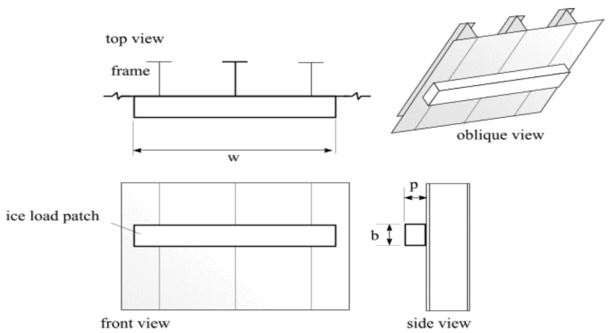


Figure VIII-4: Ice load patch configuration [12].

In non-bow areas, only a single set of values is calculated, with the normalized values for f_a and AR.

Ice loads are quite peaked within the load patch. To account for this, a set of peak pressure factors (PPF) is used when using the pressure in design formulae. Figure VIII-5 illustrates how the pressure in the design formula is magnified. The effect of this factor is that smaller structural elements experience larger design pressures. This is another form of pressure-area effect.

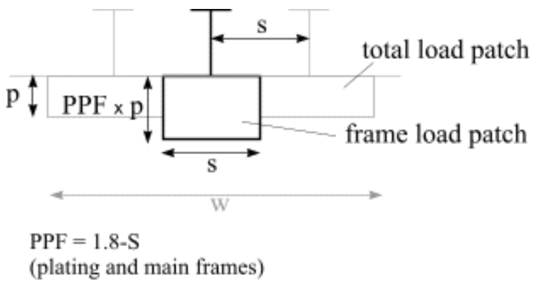


Figure VIII-5: Peak Pressure Factor used to design individual elements [12].

Rule formulae and method

The section above show how the design ice load is calculated. The class factors that are to be found in the Unified Requirements can be found in Table VIII-1, deriving from the above mentioned equations for crushing force, flexural force and line load .

Crushing class factor	$CF_c = P_o^{0.36} \cdot V_{ship}^{1.28}$
Flexural class factor	$CF_F = \sigma_f \cdot h_{ice}^2$
Patch class factor	$CF_D = P_o^{0.389}$

Table VIII-1: Class factors found in IACS Unified Rules for Polar Class Ships [12].

The rule formulae simplify the equations by using these class factors in place of class-dependent physical parameters, shown in Table VIII-2.

Physical Values						Class Factors			
Class	V_{ship} *m/s*	P_o *MPa*	h_{ice} *m*	σ_f *MPa*	***D_lim*** *KT*	CF_c	CF_F	CF_D	CF_{DIS}
PC1	5.70	6.00	7.0	1.40	250	17.7	68.6	2.011	250
PC2	4.40	4.20	6.0	1.30	210	11.2	46.8	1.750	210
PC3	3.50	3.20	5.0	1.20	180	7.6	30.0	1.574	180
PC4	2.75	2.45	4.0	1.10	130	5.0	17.6	1.418	130
PC5	2.25	2.00	3.0	1.00	70	3.6	9.0	1.310	70
PC6	2.25	1.40	2.8	0.70	40	3.2	5.5	1.140	40
PC7	1.75	1.25	2.5	0.65	20	2.2	4.1	1.091	22

Table VIII-2: Class parameters and factors. [12]

[*] Note: *D_lim* and CF_{DIS} are used in the midbody in lieu of the flexural limit applied in the bow. There is limited theoretical justification for the approach. It is similar to that used in current rules systems and is applied conservatively to larger ships of higher classes. When operating experience with larger ships becomes available this factor should be revisited.

With these class factors, the bow force and force to the other regions are calculated by the equations, mentioned in the IACS rules:

$$F_n = f_a \cdot CF_c \cdot \Delta_{ship}^{0.64}$$

and

$$F_n = f_a \cdot CF_c \cdot DF$$

respectively,

where

$$fa_i = min(fa_1, fa_2, fa_3)$$

$$f_{a1} = [0.097 - 0.68 \cdot (\frac{x}{L} - 0.15)^2] \cdot \frac{a}{\sqrt{\theta}}$$

$$f_{a2} = 1.2 \cdot CF_F / [\sin(\theta) \cdot CF_C \cdot \Delta^{0.64}] \text{ \{bow region\}}$$

$f_{a3} = 0.6$ (limiting case of the crushing equation) and

$$f_a = 0.36 \text{ \{other hull regions\}}$$

Regarding the factor *DF*,

$$DF = M_{ship}^{0.64}, \quad M_{ship} < CF_{DIS}$$

$$DF = CF_{DIS}^{0.64} + 0.1 \cdot (M_{ship} - CF_{DIS}), \quad M_{ship} > CF_{DIS}$$

3. DESCRIPTION OF THE MASS REDUCTION COEFFICIENT C_o

An impact taking place in a single point 'P' (Figure VIII-1), will result in a normal force F_n. The ship's side is considered to have sloping side in bow and bow shoulder. Point 'P' will accelarate and a component on the accelaration will be along the normal vector, with the magnitude a_n [12].

The collision can be modeled as if point P was a single mass (a 1 degree of freedom system) with an equivalent mass M_e:

$$M_e = F_n / a_n$$

The equivalent mass is linearly proportional to the mass (displacement) of the ship and depends on the inertial properties of the ship (mass, radius of gyration, hull angles and moment arms of the ship), and can be expressed as

$$M_e = M_{ship} / C_o$$

where C_o is the mass reduction coefficient (Popov, 1972).

The inertial properties of the vessel are as follows,

Hull angles at point P:

a = waterline at point P
β = frame angle
$\beta' = \theta$ = normal frame angle,
γ = sheer angle

The various angles are related as follows,

$$tan(\beta) = tan(a) \cdot tan(\gamma)$$

$$tan(\beta') = tan(\beta) \cdot tan(a)$$

Based on these angles, the direction cosines, *l,m,n* are

$$l = sin(a) \cdot cos(\beta')$$

$$m = cos(a) \cdot cos(\beta')$$

$$n = cos(\beta')$$

and the moment arms are

$$\lambda l = ny - mz \text{ (roll moment arm)}$$

$$\mu l = lz - nx \text{ (pitch moment arm)}$$

$$nl = mx - ly \text{ (yaw moment arm)}$$

The added mass terms are as follows (from Popov):

$$AM_x = \text{added mass factor in surge} = 0$$

$$AM_y = \text{added mass factor in sway} = 2T/B$$

$$AM_z = \text{added mass factor in heave} = 2/3\cdot(B\cdot C_{wp}/2)/(T\cdot(C_b\cdot(1+C_{wp})))$$

$$AM_{rol} = \text{added mass factor in roll} = 0.25$$

$$AM_{pit} = \text{added mass factor in pitch} = B/((T\cdot(3-2\cdot C_{wp})\cdot(3-C_{wp}))$$

$$AM_{yaw} = \text{added mass factor in yaw} = 0.3+0.05\cdot L/B$$

The mass radii of gyration (squared) are:

$$rx^2 = C_{wp}\cdot B^2/(11.4\cdot C_m)+H^2/12 \text{ (roll)}$$

$$ry^2 = 0.07\cdot C_{wp}\cdot L^2 \text{ (pitch)}$$

$$rz^2 = L^2/16 \text{ (yaw)}$$

With the above quantities defined, the mass reduction coefficient is:

$$C_o = l^2/(1+AM_x)+m^2/(1+AM_y)+n^2/(1+AM_z)+$$
$$+\lambda l^2/(rx^2(1+AM_{rol}))+\mu l^2/(ry^2(1+AM_{pit}))+nl^2/(rz^2(1+AM_{yaw}))$$

4. PRINCIPLES BEHIND THE ASSESSMENT OF THE DESIGN ICE LOAD

After the description of the basic topics in FSICR, Polar Class Rules and 'Popov Oblique Impact' Energy Method regarding hull design ice load and scantlings, it is high time to analyze the principles behind the determination of the design ice load that consist of an average pressure p_{avg}, the design load height (h or b) and a design load width (l_a or w).

The ice load in the FSICR is, in principle, defined so that the ice pressure is constant for all classes (nominal ice pressure p_o) and the load height h is the class factor (from 0.35 m for ice class IA Super to 0.22 m for ice class IC). The magnitude of the nominal ice pressure is 5.6 MPa.

The design ice load for each structural member of a specific ice class vessel is determined by this constant load height h (class factor), an average pressure that depends on the displacement of the ship in the maximum ice class draught and the actual continuous engine output and the load length l_a that is associated with the structural member that is under consideration [53].

In contrary to this procedure, the determination of the design ice load in IACS polar rules is based on the assessment of the total nominal force (F_n) and the load patch dimensions, width (w) and height (b). The total nominal force (F_n), line load (Q_{BOW}) and average pressure (p_{avg}) derive from hull shape coefficients in the upper ice waterline and class factors that include parameters such as crushing and flexural failure, displacement, longitudinal strength, for each class [3]. After the estimation of these values, the load patch dimensions result as the fractions of:

$$w_{bow} = F_{max}/Q_{max},$$

$$b_{bow} = Q_{max}/P_{max}.$$

Finally, the 'Popov oblique impact' method, regarding the formulas of design ice load from which the equations of the IACS Polar Class rules derive, is based on the assessment of the maximum, design ice force and the tranformation of the actual, triangular ice penetration area of the ship's side during the impact to the ice floe, to a nominal rectangular load patch and finally to a design load patch. The normal force depends on the geometry of the ice edge, the hull shape in the upper ice waterline, the velocity of the ship V_{ship}, which is class dependent, ice pressure P_o which is also, class dependent and factors that determine the mass reduction coefficient, according to the Popov approach (1972).

The estimation of the design load patch is based on the assumption that the normal, rectangular load patch can be reduced in size to the desired load patch with the same total ice force acting on it and same aspect ratio (AR). The reduction is conservative and is done to account for the typical concentration of force that takes place as ice edges spall off [12].

After the determination of the total normal force and the design load patch, the line load Q and the design ice pressure p can be assessed, using selected exponents (*wex*, *ex)*. The formulas that are presented in this Chapter, regarding the total normal force, the lone load and the design pressure are:

$$F_n = f_a \cdot P_o^{(\frac{1}{3+2ex})} \cdot V_{ship}^{(\frac{4+4ex}{3+2ex})} \cdot M_{ship}^{(\frac{2+2ex}{3+2ex})},$$

$$w = W_{nom}^{wex} = F_n^{wex/(2+2ex)} \cdot P_o^{-wex/(2+2ex)} AR^{wex/2}$$

and

$$w = F_n^{0.389} \cdot P_o^{-0.389} AR^{0.35}.$$

These class related parameters are then transformed into class factors that can be found in the IACS Polar Class Unified Rules (Tables VII-15 & VIII-2).

IX. ESTIMATION OF DESIGN ICE LOAD IN A LNG CARRIER

In order to testify the validity of the theory presented in the previous chapters and clarify the theory for the ice strengthened and polar ships, a present vessel, LNG Carrier 'Lena River' that operates in the Baltic seas and the Arctic oceans is being used to estimate the potential ice loads that occur in harsh conditions. The IACS and FSICR rules are being followed, regarding the ice classification and methods of ice load calculations, as well as the Administration's requirements for sailing the specific seas in the particular period of the year.

The calculations of the ice loads are based on the glancing (or oblique) collision scenario of an ice floe with the bow, bow shoulder and midship area of the vessel using either the IACS rules or the FSICR. Furthermore, an energy based approach of the ice loads from which the Unified IACS Rules (URs) derive is being used and the results are compared.

The general particulars of the LNG Carrier 'Lena River' are presented, paying attention to special features such as cargo containment system (CCS) and propulsion system. The appropriate draft, hull angles and ship's coefficients are reckoned and the design of the vessel is examined, following the FSICR, as well as the equivalent IACS Polar Class rules.

1. INTRODUCTION

In December 2012, the 'Ob River', a LNG Carrier owned by Dynagas, operating for Gazprom Marketing & Trading (GM&T), became famous for becoming the first LNG Carrier completing her LNG supply via Northen Sea Route. 'Lena River', sister vessel of 'Ob River', is the subject vessel that will be used in order to extract the appropriate conclusions, regarding the ice loads in a harsh environment such as Northen Sea Route.

The following technical issues in relation to LNG Carrier 'Lena River', are discussed in the present chapter:

- Main Particulars Class notations & Basic Design
- Cargo Containment System (CCS)
- Propulsion System
- Calculation of the hydrostatic particulars and the actual displacement in the Upper Ice Waterline (UIWL)
- Calculation of Design Ice Load, based on Finnish Maritime Administration (FMA), IACS polar rules and 'Popov' terms energy-based method.
- Confirmation of the final scantlings in proper areas.
- Conclusions derived from the calculations.

The target trade route, Northen Sea Route, is characterized by requirements from environment conditions, harsh sea conditions and hazards. For this reason, certificates and documents issued by institutes and approved by the Russian authorities, such as Ice Certificate and Certificate of Engine Power, should certify that the ship is capable of sailing in those ice seas. Safe speeds for the vessel in different thicknesses of ice, safe distances from the escort icebreakers, suitability of the main engine power of the vessel and proper propeller and propeller tip immersion should be assessed. All the related informations and drawings are available, in order to develop clear and reliable results.

2. GENERAL PARTICULARS, CLASS NOTATIONS AND BASIC DESIGN

Lena River is a liquified natural gas (LNG) carrier with 155K m^3 capacity, GazTransport & Technigaz (GTT) Mark III membrane type, developed to operate in ice infested seas with Ice Class 1A. In Table IX-1, the general particulars of the target vessel are given and the most crucial items are described thoroughly.

KIND OF VESSEL	155,000 CBM Class LNG Carrier
SHIP'S NAME / CALL SIGN	Lena River / V7AU9
FLAG / HOME PORT	MARSHALL ISLANDS / MAJURO
DATE OF BUILD	10/2013
OFFICIAL NUMBER	5073
IMO NUMBER – M.M.S.I. NUMBER	9629598 – 538005073
CLASS (*)	BV
LENGTH OVER ALL	288.10 m
LENGTH BETWEEN PERPENTICULARS	275.00 m
BREADTH MOULDED	44.20 m
DEPTH MOULDED	26.00 m
DEPTH to Trunk deck MOULDED	33.09 m
DRAFT MOULDED (Design, S.G. 0.46)	11.50 m
DRAFT MOULDED (Summer, Scant.)	12.50 m
LIGHTSHIP	31971 t
DEADWEIGHT / DISPLACEMENT (Summer load draft)	84585 t / 116556 t
GROSS TONNAGE / NET TONNAGE	100236 / 33759
SERVICE SPEED	19.58 knots (at design draft, MPP with 21% S.M.)
MAIN DIESEL GENERATOR ENGINE	Two (2) 12V50DF, MCR 11700 kW at 514 rpm, Two (2) 6L50DF, MCR 5850 kW at 514 rpm (Wartsilla-Hyundai)
PROPELLING MACHINERY TYPE	Dual Fuel Diesel Electric Driven (DFDE)
MAXIMUM PROPULSION POWER	24900 kW x 83 rpm

Table IX-1: Ship's General Particulars.

(*) The class notations of the target vessel: I, +HULL, +MACH, Luqufied gas carrier / LNG Unrestricted navigation, +VeriSTAR-HULL, +AUT-IMS, +AUT-UMS, +SYS-IBS, +SYS-NEQ-1,BWE, CPS(WBT), INWATERSURVEY, CLEANSHIP (C), ERS-S, MON-SHAFT, GREEN PASSPORT, ICE CLASS 1A, COLD (H-10, E-30), Spectral fatigue (worldwide navigation with 10% North Atlantic), DFL40, LI-HG-S3

The class notations that are relevant to navigation in Northen Atlantic is COLD (H-10, E-30) and ICE CLASS 1A.

COLD (H-10, E-30) is a class notation that covers the hull, stability and material approval for the cold environment. H-10 defines the lowest mean daily average air temperature (ºC) in the area of operation, to be considered for the hull exposed to low air temperature, while E-30 is the lowest design external air temperature (ºC) in the area of operation to be considered for the equipments exposed to low air temperature, both provided by the ship designer. The latter temperature can be set to 20 ºC below the lowest mean daily average air temperature. Furthermore, class requirement is the sea water temperature not to be below -2 ºC and wind speed not exceed 30 knots.

In Figure IX-1, the general arrangement of the vessel as well as the tanks arrangement are shown.

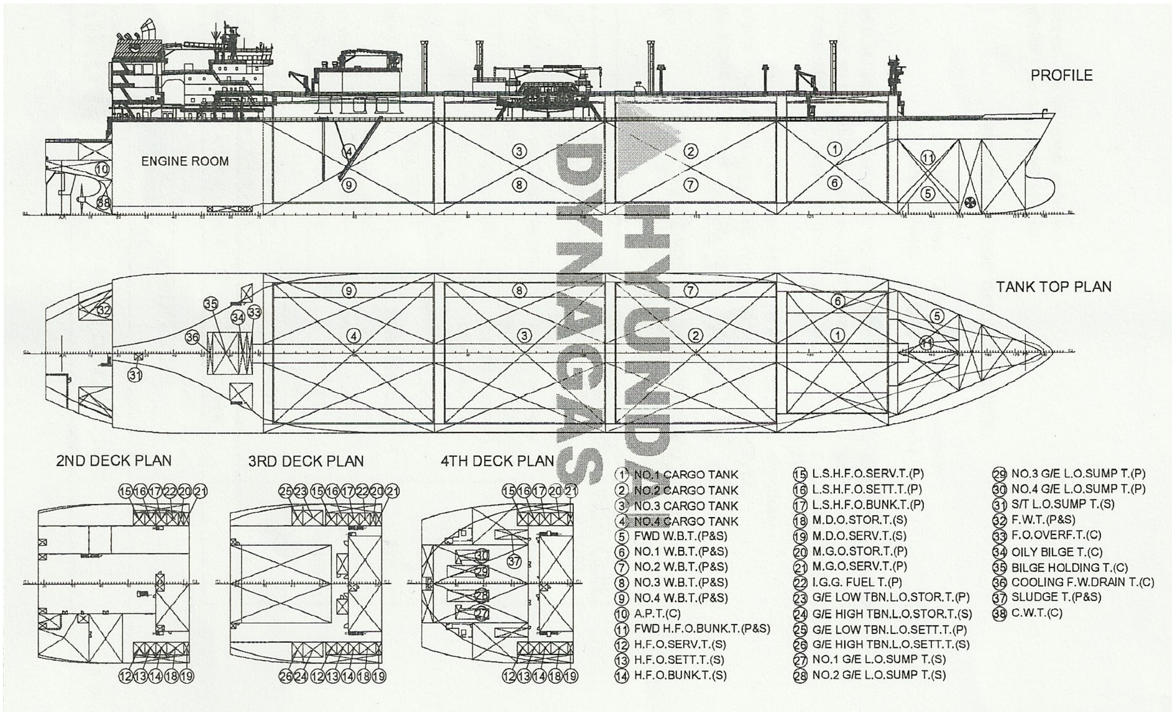


Figure IX-1: General arrangement of LNGC 'Lena River'.

The design was comformed with the ice class level of ICE-1A, following the Finnish-Swedish Ice Class Rules in compliance with the Finnish Maritime Administration (FMA). External shell in the ice belt area is reinforced with thicker plates and high tensile steel grade DH and EH while the forebody ice belt zone outside the tangential line is further reinforced with additional longitudinal stiffeners and increased section modulus compared to the midship area.

The thicknesses of the plates in the ice strengthened region derive from the regulations, analysed thoroughly in Chapter VII 'Ice Class Rules – Structural Standards Development'.

According to the Finnish-Swedish Ice Class Rules, the maximum frame spacing of longitudinal frames is 0.35 m for ice classes IA Super and IA. It is as well, stipulated that longitudinal frames shall be attached to all the supporting web frames and bulkheads by brackets to ensure stability in the elastic and post-yield response region. However, the structure consists of a combination of transverse and longitudinal stiffening and more shophisticated methods can be used for the determination of hull scantlings. As a result, at the midship region the frame spacing for the longitudinal stiffeners exceed 0.35 m, reaching 0.805 m.

In Figure IX-2, the ice belt region is presented, divided into aft, midship and fore part. while the vertical extension of the ice strenghtening for both plates and frames are given in Table 2.

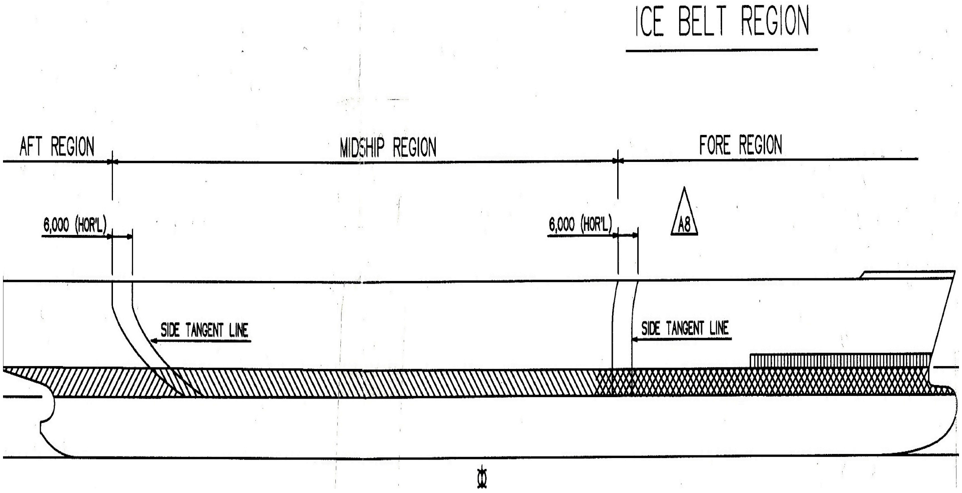


Figure IX-2: Ice belt region

AFT REGION	MIDSHIP REGION	FORE REGION	POSITION	
LOAD WATERLINE (L.W.L) + 500			**PLATE**	**U.I.W.L.**
LOAD WATERLINE (L.W.L) + 1,000			**FRAME**	
BALLAST WATERLINE (B.W.L) - 600			**PLATE**	**L.I.W.L.**
B.W.L – 1,000	*B.W.L. – 1,300*	*B.W.L. – 1,600*	**FRAME**	

Table IX-2: Vertical extension of the ice strengthening.

It is obvious that the hull structural design of 'Lena River' follows the rules of Finnish Maritime Administration. The vertical extension of the ice strengthening for ordinary stiffeners and primary supporting members follow the rules presented in FSICR. However, there is a difference with the present rules, regarding the extension of the strengthened plating in the ice belt, due to an amendment in the Ice Class Regulations of 2010, changing the rule for ICE-1A from 0.6 m below LIWL to 0.9, 0.75, 0.75 below LIWL for Fore, Midship and Aft Region, respectively. However, the forefoot extension is exactly from the stem to a position five ordinary stiffeners spaces aft of the point where the bow profile departs from the keel line, as the requirements define. Furthermore, the extent of the upper fore ice belt is $0.2 \cdot L$, following the requirements. Finally, the overlap over the borderlines between the bow and aft regions with the midship region follow the rule of not exceeding 6 m for the notation ICE CLASS IA.

3. CARGO CONTAINMENT SYSTEM (CCS)

The structural safety should be guaranteed to a significant extent considering LNG cargo, so that an environmental disaster in case of leakage to be prevented. The study of structural risk analysis involves safety criteria of cargo containment system. The target vessel is designed using GTT Mark III containment system for LNG cargo [23].

The Mark III membrane system is a cryogenic liner directly supported by the ship's inner hull. This liner is composed of a primary metallic membrane positioned on a prefabricated insulation panel including a complete secondary membrane (Figure IX-3).

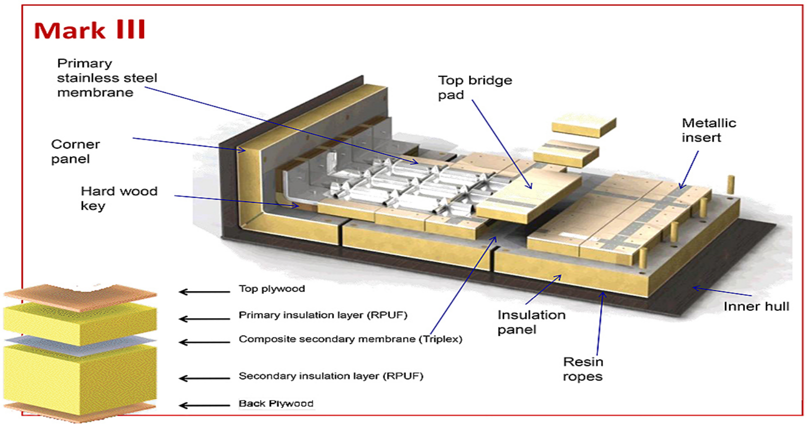


Figure IX-3: GTT Mark III membrane system [43].

The primary membrane is made of corrugated stainless steel 304 L, 1.2 mm thick. It contains the LNG cargo and is directly supported by and fixed to the insulation system. Standard size of the corrugated sheets is 3 m x 1m.

The secondary triplex membrane is made of a composite laminated material: a thin sheet of aluminium between two layers of glass cloth and resin. It is positioned inside the prefabricated insulation panels between the two insulation layers.

The insulation consists of a load-bearing system made of prefabricated panels in reinforced polyurethane foam including both primary and secondary insulation layers and the secondary membrane. The standard size of the panels is 3 m x 1 m. The panels are bonded to the inner hull by means of resin ropes which serve a double purpose: anchoring the insulation and spreading evenly the loads. The thickness of the insulation is adjustable from 250 mm to 350 mm to fulfill any Boil-Off Rate (B.O.R.) requirement. Mark III Standard I.P, used in 'Lena River', is 270 mm and lead to a Boil-Off Rate (BOR) of 0.14%. The thickness of the primary and secondary panel is 100 mm and 170 mm, respectively (Figure IX-4) [26].

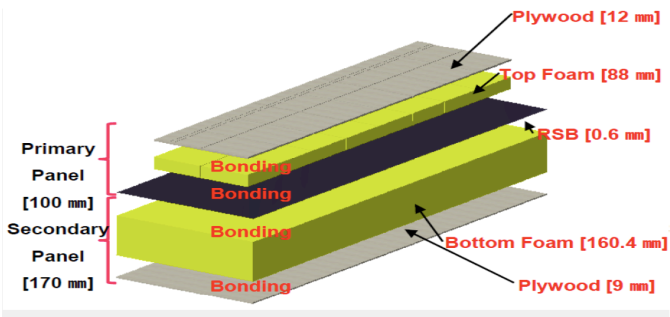


Figure IX-4: Primary and Secondary Insulation Panels in Mark III Standard [26].

The investigation of the elongation of the membrane itself and its welding connection prove that the membrane system is flexible enough to accomodate a significantly large elongation caused by accidental ice loads. Therefore, the safety of the hull as tank boundary is adopted as alternative criterion to define a survival condition of the membrane LNG carriers with GTT Mark III containment system.

Tank No.1 is the basic target area in the present thesis, since the fore area is estimated to have the greater probability of interactions with ice floes or ice channel's edge, while the vessel sails with the escort of icebreakers through ice channels.

4. DFDE (DUAL FUEL DIESEL ELECTRIC) PROPULSION SYSTEM

The LNG carrier sailing in the Northern Sea Route is obliged to follow two leading icebreakers in a proper distance. In order to succeed at this and acquire the Certificate of Engine Power, a LNG carrier shall be driven by a propulsion plant operating for long hours at low speeds. Moreover, the extremely low temperatures of the cooling seawater as well as the combustion air consumed by the main engine plant are issues of major concern.

The Certificate of Engine Power is a document issued by an institute approved by the Russian authorities that certifies the suitability of the main engine power of the vessel. Each certificate confirms that the main engine can produce a vessel speed of 4 knots or more in ice 60 cm thick following in the lead created by icebreakers.

'Lena River' is driven by two high speed propulsion motors (GE Energy / 12,580 kWx652 rpm) and a reduction gear (Renk / Gear Ratio: 650/83). The propulsion plant is fed by 4 Wärtsilä Dual Fuel, medium speed generators and the engines can work with Boil Off Gas (BOG), Heavy Fuel Oil (HFO) and Medium Diesel Oil (MDO) and is shown in Figure IX-5.

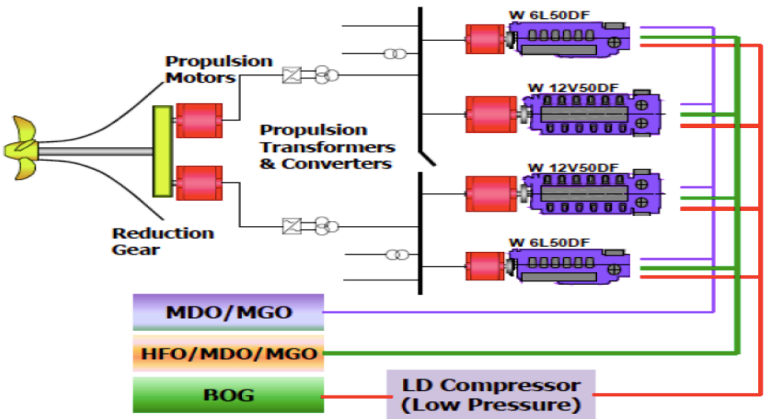


Figure IX-5: DFDE (Dual Fuel Diesel Engine) propulsion system [26].

With the introduction of Dual Fuel (DF) engines, electric propulsion became highly attractive for LNG carriers, especially since the total propulsion efficiency increased with about 43% compared to the steam turbine system. The emissions will also be lower due to the increased efficiency, and the possibility to operate 100% on gas. With the Stricter Emission Limits applied to the vessels with the IMO Tier III, 0.1% Sulphur contents in ECA and EEDI, DFDE propulsion systems have become a solution to merchant vessels. Another advantage for the electrical system is the considerably less total installed power onboard, since the electric power plant will serve both the propulsion system and cargo handling system.

5. CALCULATION OF ACTUAL DISPLACEMENT FOR UPPER ICE WATERLINE

In order to proceed with the glancing impact load scenario and calculate the load patch, force (*F*), line load (*Q*), pressure (*P*) and load aspect ratio (*AR*), the actual displacement and the basic coefficients of form should be assessed at the level of the Upper Ice Waterline (UIWL).

The observed draft at the draft marks to be used is given in Table IX-3.

Draft \ Region	AFT (m)	MIDSHIP (m)	FORE (m)
UIWL	13.2	12.9	12.9

Table IX-3: Observed draft at Aft, Midship and Fore Region.

Based on the method given in the 'Final trim & stability booklet' for LNG carrier 'Lena River', a calculation of the actual displacement and hydrostatic particulars can be made, using the following format and trimmed hydrostatic data (Table IX-4).

	Calculation items	Derived from	Results of calculation		
1	Observed draft at draft marks		FORE	MIDSHIP	AFT
		PORT	12.9	12.9	13.2
		STARBOARD	12.9	12.9	13.2
2	Arithmatical mean draft	(PORT+STBD)/2	12.9	12.9	13.2
3	Draft correction to f.p., m/s and a.p.	DRAFT CORRECTION TABLE	0	0	0
4	Draft at (f.p.) , (m/s) , (a.p.)	(2) + (3)	(A) 12.9	(B) 12.9	(C) 13.2
5	Factor		1	6	1
6	Deflection correction	(4) x (5)	12.9	77.4	13.2
7	Main draft correction for deflection	1/8 x Σ(6)	12.9375		
8	Actual trim	(A) – (C)	-0.3		
9	Displacement at draft (7) and trim (8)	hydro. Table	121,083 (t)		
10	Measured S.G. of sea water		1.026		
11	Actual displacement	(9) x (10) / 1.025	121,201 (t)		
12	L.C.B.≈L.C.G. at draft (7) and trim (8)	hydro. Table	-1.205 m from Midship (M/S)		
13	MOULD VOLUME		117262.85 m^3		
14	K.B. (m)		6.785 m		
15	WP Area		10360.575 m^2		
16	Wetted Surface		15821.025 m^2		

Table IX-4: Calculation of main hydrostatic particulars for draft in Upper Ice WaterLine (UIWL).

For the same mean draft, the coefficient of hull form can be assessed, following the data of 'Trimmed Hydrostatic Particulars' in 'Final Trim & Stability Booklet' (Table IX-5).

COEFFICIENT OF FORM		
BLOCK COEFFICIENT	(C_B)	0.749
MIDSHIP SECTION COEFFICIENT	(C_M)	0.995
WATERLINE COEFFICIENT	(C_W)	0.851
PRISMATIC COEFFICIENT	(C_P)	0.753

Table IX-5: Coefficients fo Hull Form.

6. CALCULATION OF DESIGN ICE LOADS

As it is previously mentioned, in order to determine the scantlings, a specific design scenario is assumed. This scenario does not extremely differ at vessels operating in Arctic with those operating in Baltic seas.

The design scenario for Polar Class vessels is a glancing impact on the bow and bow shoulder with channel edge or ice floe, while for Ice Class ships is a collision with a channel edge or with a consolidated layer of older ridges. In both Ice Class and lower Polar Class (PC6 & PC7) vessels, there is a limitation in the impact conditions, regarding ramming. Moreover, the design ice load in both cases, is characterized by an average pressure (P_{avg}), uniformly distributed over a rectangular load patch of height *(d)* and width *(w)*.

In this chapter, the ice load parameters for the target vessel 'Lena River' are presented. These parameters derive from the Finnish-Swedish Ice Rules, IACS Polar Rules and an energy based method, assuming a 'Popov type' collision.

Design Ice Load determined by the Finnish-Swedish Ice Class Rules

The design ice pressure [MPa] with the method of FSICR is determined by the formula:

$$p = c_d \cdot c_p \cdot c_a \cdot p ,$$

where:

c_d : Coefficient taking account of the influence of the size and engine output of the ship
c_p : Coefficient taking account of the propability of the design ice pressure occuring in a particular region of the hull for the additional class notation
c_a : Coefficient taking account of the probability that the full length of the area under consideration will be under pressure at the same time
p_o : Nominal ice pressure, in MPa, to be taken equal to 5,6.

All the appropriate equations and values for the calculation of the design ice pressure has been analysed thoroughly in Chapter VIII.

The ice load parameters (P_{avg}, h, l_a) for the bow, bow shoulder and midship region are presented in Table IX-6. It is easily understood that going aft from the bow to the midship region, the pressure declines, while the load patch size at the midship region increases (P_{avg}, h, l_a : *1.632, 0.3, 0.8*), mostly because of the great decline in the coefficient c_d, thus the influence of size and engine output of the ship. The design ice pressure reduction can be certified by the decline of the plate thickness in the midship region.

Design Ice Load Calculation				
Region	***Fr.170-184***	***Fr.151-166***	***Fr.140-151***	***Midship***
c_d	0.848	0.848	0.848	0.396
c_p	1.000	1.000	1.000	0.85
c_a	1.000	0.898	0.811	0.662
p_o (MPa)	5.600	5.600	5.600	5.600
$k = \sqrt{\Delta \cdot P} / 1000$	54.935	54.935	54.935	54.935
l_a	0.533	0.7446	0.9112	0.8
Height of load area (Ice Class IA)	0.3	0.3	0.3	0.3
p (MPa)	4.747	4.261	3.852	1.632
Original Plate thickness (mm)	37	37	35	28.5

Table IX-6: Ice load parameters and main design load particulars.

Design Ice Load determined by IACS Polar Class Rules

The ice load parameters determined by IACS Polar Class Rules are functions of the actual bow shape measured at the Upper Ice Waterline (UIWL) and the calculation of the ice load characterictics for sub-regions of the bow area is needed. In other ice-strengthened areas than the bow, the ice load parameters are assessed independently of the hull shape based on a fixed load aspect ratio *(AR = 3.6)*.

The ice load characterictics are: shape coefficient (fa_i), total glancing impact force (F_i), line load (Q_i) and pressure (P_i). The equations for the calculation of ice load parameters and characteristics are presented analytically in Chapter V-II, 'Ice Class Rules -Structural Standards Development/ IACS Requirements for Polar Class Ships'.

The final results for the determination of ice-strengthened area for bow, bow intermediate and midship region are given in Table IX-7.

Glancing impact load in Bow Area						**Glancing impact load in other than Bow Area**	
Frame:		***Fr.164***	***Fr.151***	***Fr.145***	***Fr. 140***	***Midship Area***	
Shape	**c_1 (nd)**	0.312	0.577	0.546	0.529	***CF_D***	1.110
	c_2 (nd)	0.442	0.424	0.368	0.338	**CF_C**	1.800
	c_3 (nd)	0.600	0.600	0.600	0.600	**CF_{DIS}**	22.000
	$min(c_i)$ (nd)	**0.312**	**0.424**	**0.368**	**0.338**	**DF**	17.150
C_{ARi}		2.233	2.206	2.547	2.772		
F_{BOW} (MN)		**12.098**	**16.459**	**14.272**	**13.112**	***F_{NONBOW} (MN)***	**11.114**
q_i (MN/m)		**3.835**	**4.646**	**4.050**	**3.734**	***Q_{NONBOW} (MN/m)***	3.082
p_{avg} (MPa)		**2.713**	**2.893**	**2.927**	**2.947**	***p_{NONBOW} (MPa)***	**3.076**
w_{bow} (m)		**3.543**				***w_{NONBOW} (m)***	3.606
b_{bow} (m)		**1.577**				***b_{NONBOW} (m)***	1.002

Table IX-7: Calculation of ice parameters and characteristics, based on IACS Polar Class Requirements.

The F_{BOW} is obtained as the maximum F of the sub-regions of bow and bow intermediate areas. In other words, $F_{BOW} = max\ (F_i)$ and from the Table IX-7, it is distinguished that maximum force found at Frame 151, equal to

$\boxed{F_{BOW} = 16.459\ \text{MN}}$.

In the same way, the average pressure (p_{BOW}) and line load (Q_{BOW}) can be found as the maximum values from the Table IX-7, exert at Frame 140 and 151, respectively.

$\boxed{p_{BOW} = 2.947\ \text{MPa}}$ and

$\boxed{Q_{BOW} = 4.646\ \text{MN/m}}$.

Finally, a conclusion that can be notified from the shape coefficients involving to the calculation of the force in sub-regions, is that while crushing failure is the cause for breaking the ice in Frame 164, the flexural failure occurs at the ice floe when going aft from the bow area to the frames of bow shoulder. As it is mentioned in Section VI-3 'Level ice-ship impacts', the general tendency is ice to crush in the bow area and fail in flexural forces, while moving aft.

Energy-based Ice Collision Forces

This method has been described in Chapter VIII, 'Energy-based Ice Collision Forces-Background notes to design ice loads' and the appropriate equations as well as the theory behind the 'Popov glancing collision' are thoroughly covered.

In this scenario, the target ship, 'Lena River' is assumed to be moving forward at the design speed, striking the angular ice edge of the channel. The impact force between the ship and ice is strongly influenced by the masses of the vessel and the ice. The impact forces depend on the ice mass in an ascending way. The bigger the ice floe mass is, the bigger the impact with the ship's side is. When ice mass gets very large, the force reaches an upper limit, depending on ship's mass and not on floe's mass that is considered infinite.

The ship speed, ice thickness and ice strength are class dependant. The combination of hull angles, ice strength and thickness determines the limitation of the force due to bending. The rule scenario is strictly valid only for the bow region, and for the stern of double-acting ships.

The 'Popov' type collision assumes that the ice indentation can be descrided by a pressure-area relationship. The force increase to a maximum point and either crushing or flexural failure may occur. The crushing limiting force is found by equating normal kinetic energy with the energy needed to crush the ice. This crushing force should not exceed flexural limiting load. Then, the load patch calculation follows the method used in IACS polar class rules. 'Lena River' is an Ice Class 1A ship and can be equated to Polar Class 7 (PC7) when operating in Arctic seas. The class dependant factors for 'Lena River' can be found at Table IX-8. The values are taken by Table VIII-2 in Section VIII-2 for PC7 vessels.

Ship's Class	Physical Values					Class Factors			
	V_{ship}	P_o	h_{ice}	σ_f	D_lim	CF_c	CF_F	CF_D	CF_{DIS}
PC7	1.75	1.25	2.5	0.65	22	2.2	4.1	1.091	22

Table IX-8: Class-dependant factors and parameters [12].

The assessment of forces for bow and bow shoulder areas are presented in Table IX-9. The same frames have been selected with the ones in IACS Polar rules' method, in order to compare finally the upcoming results. Useful conclusions regarding the mechanism of the collision in bow and bow intermediate area can be extracted.

Ship Main Parameters			Fr. 164	Fr. 151	Fr.145	Fr.140	units
1)	Ship Name	SN					
2)	Length	L_{WL}	279.2	279.2	279.2	279.2	m
3)	Beam	B	44.2	44.2	44.2	44.2	m
4)	Draft	T	12.9375	12.9375	12.9375	12.9375	m
5)	Height	H	26.0	26.0	26.0	26.0	m
6)	Block Coef.	CB	0.75	0.75	0.75	0.75	nd
7)	Waterplane Coef	Cwp	0.85	0.85	0.85	0.85	nd
8)	Midship Coefficient	Cm	0.995	0.995	0.995	0.995	nd
9)	Mass	M	121201	121201	121201	121201	tonnes
10)	Ship Speed	Vs	1.75	1.75	1.75	1.75	m/s
Hull Angles and coordinates							
11)	*Alpha*	*a*	15	26	26	26	deg
12)	*Beta*	*b*	18.00	19.00	22.00	24.00	deg
13)	*Beta prime*	*b'*	17.42	17.20	19.96	21.81	deg
14)	*gamma*	*g*	37.89	55.95	51.60	47.60	deg
15)	Symmetrical		no	no	no	no	text
16)	x coordinate	x	131.06	120.66	115.86	111.86	m
17)	y coordinate	y	1.5	5.8	8.1	10.4	m
18)	z coordinate	z	0	0	0	0	m
Ice Crushing Terms							
19)	Ice strength term	Po	1.25	1.25	1.25	1.25	Mpa
20)	Ice exponent (process PA)	ex	-0.1	-0.1	-0.1	-0.1	nd
21)	Wedge angle	f	150	150	150	150	deg
22)	Wedge angle	f	2.62	2.62	2.62	2.62	rad
23)	form factor 1	fx	2.80	2.80	2.80	2.80	nd
24)	form factor 2	fa	10.54	10.64	9.62	9.12	nd
Popov Terms							
25)	x dirn cosine	l	0.2952	0.4188	0.4120	0.4070	nd
26)	y dirn cosine	m	0.9087	0.8586	0.8448	0.8345	nd
27)	z dirn cosine	n	0.2952	0.2956	0.3413	0.3715	nd
28)	roll moment arm	λl	0.4492	1.7147	2.7648	3.8639	m
29)	pitch moment arm	μl	-39.2440	-35.6711	-39.5445	-41.5570	m
30)	yaw moment arm	ηl	120.4102	101.1674	94.5386	89.1059	m
31)	Surge Added Mass	Amx	0.0000	0.0000	0.0000	0.0000	nd
32)	Sway Added Mass	Amy	0.5854	0.5854	0.5854	0.5854	nd
33)	Heave Added Mass	Amz	1.1905	1.1905	1.1905	1.1905	nd
34)	Roll Added Mass	Amrol	0.2500	0.2500	0.2500	0.2500	nd
35)	Pitch Added Mass	Ampit	1.2258	1.2258	1.2258	1.2258	nd
36)	Yaw Added Mass	Amyaw	0.6158	0.6158	0.6158	0.6158	nd
37)	roll gyrad(squared)	rx2	202.9327	202.9327	202.9327	202.9327	m2
38)	pitch gyrad(squared)	ry2	4645.96	4645.96	4645.96	4645.96	m2
39)	yaw gyrad(squared)	rz2	4872.04	4872.04	4872.04	4872.04	m2
40)	Mass Reduction Coef.	Co	2.6291	2.1150	1.9898	1.9023	nd
41)	Effective mass	Me	46100373	57305299	60911244	63713211	kg
42)	Normal Speed	Ve	0.432	0.733	0.721	0.712	m/s
43)	Kinetic Energy	KEe	4304697	15388716	15835497	16160356	kgm2/s2
44)	Impulse	Ie	19922257	41996546	43921745	45379030	kg-m/s
	Results						
45)	pen(n)	ζn	0.969	1.262	1.593	1.636	m
46)	Normal Force	Fn	12.44	20.2	27.83	27.65	MN
47)	Flexural strength	σ_f	0.65	0.65	0.65	0.65	Mpa
48)	Maximum Force Flexural Strength	Fn,lim	16.512	16.489	14.282	13.12	MN
49)	**Design Force**	$\mathbf{F_{min}}$	**12.44**	**16.489**	**14.282**	**13.12**	MN
50)	Average Pressure	P_{avg}	2.65	2.81	2.83	2.85	MPa
51)	Design Width	w	3.11	3.60	3.58	3.57	m
52)	Design Height	b	1.45	1.61	1.40	1.29	m

Table IX-9: Assessment of main parameters for bow and bow shoulder area with 'Popov glancing collision'.

7. SCANTLINGS ASSESSMENT AND CONFIRMATION

As it is mentioned in Chapter VII, for both Ice and Polar Class rules, shell plating scantlings depend on the average pressure derived by the design ice load.

The original thicknesses and grades of the steel plates at the ice belt region can be seen in the «Shell Expansion» drawing. At the stem, the thickness of the plates is fourty four (44) mm and the grade of the high tensile steel is E, marked EH. At the upper forward ice belt, the thickness is twenty eight (28) mm and the grade of the high tensile steel is D, marked DH. At the forefoot where the bulbous bow area is, the thickness is fourty four (44) mm and the grade of the high tensile steel is E, marked EH. The forward region of the ice belt, is constructed using high tensile EH steel of thirty seven (37) mm, turning to high tensile, grade DH steel of thirty five (35) mm, while going aft. At the midship region, there is a decline in the thickness of the steel plates (28.5 mm), while the grade remains DH. Finally, at the aft region, the thickness of the plates increase slightly to twenty nine (29) mm and the grade remains D, high tensile. In conclusion, the design of an ice strengthened ship is basically focused on the stem and bow area, remains enhanced at the forward region and there is a slight drop at the midship and aft region.

In FSICR, the equations that give the thicknesses of the shell plates for transverse framing are (see also Section VII-2/ Scantlings) :

$$t = 667 \cdot s \cdot \sqrt{\frac{f_1 \cdot p_{PL}}{\sigma_y}} + t_c [mm]$$

where the constant $f_1(h/s)$:

$$f_1(h/s) = 1.3 - 4.2/(h/s + 1.8)^2$$

and for longitudinal framing:

$$t = 667 \cdot s \cdot \sqrt{\frac{p_{PL}}{f_2 \cdot \sigma_y}} + t_c [mm] ,$$

where the constant $f_2(h/s)$, when $h/s \leq 1$ is:

$$f_2(h/s) = 0.6 + \frac{0.4}{(h/s)}$$

and when $1 \leq h/s < 1.8$, is:

$$f_2(h/s) = 1.4 - 0.4(h/s) .$$

h is the design height as given in Table VII-7.

Regarding the IACS polar rules, the required minimum shell plate thickness, t, is given by:

$t = t_{net} + t_s\ [mm]$

where t_{net} is the plate thickness required to resist ice loads.

As it was thoroughly mentioned in Chapter VII, Section ‘IACS Scantlings’, in case of transversely-framed plating ($\Omega \geq 70$ deg), net thickness is given by:

$$t_{net} = 500 \cdot s \cdot ((AF \cdot PPF_p \cdot P_{avg}) / \sigma_y)^{0.5} / (1 + s/(2 \cdot b))[mm]$$

In case of longitudinally-framed plating (Ω ≤ 20 deg), when b < s, the net thickness is given by:

$$t_{net} = 500 \cdot s \cdot ((AF \cdot PPF_P \cdot P_{avg}) / \sigma_y)^{0.5} \cdot (2 \cdot b / s - (b / s)^2)^{0.5} / (1 + s / (2 \cdot l))[mm]$$

or when b ≥ s:

$$t_{net} = 500 \cdot s \cdot ((AF \cdot PPF_P \cdot P_{avg}) / \sigma_y)^{0.5} / (1 + s / (2 \cdot l))[mm]$$

Corrosion and abrasion allowance is presented by the magnitude t_s.

However, it should be clarified that for combined framed structures, the above mentioned equations are not valid or combined and more shophisticated methods should be used for the determination of hull scantlings.

In order to calculate the scantlings determined by the rules' equations, we should find areas that merely transverse or longituginal frames support the plating. The areas investigated are in bow region, aft and fore of the forward perpendiculars (F.P.). The estimation of the scantlings in both methods (FSICR and IACS Polar Class Rules), the same regions are investigated. Either transversely or longitudinally framed side shell regions are examined in different draft heights. In particular, the areas examined are:

- Frames 170-184, between No. 32-1 and No. 35 Side Shell Longitudinals, where the shell plates are primarily supported by transverse frames and the original thickness is 37 mm, grade EH.
- Frames 151-166, between No. 32-1 and No. 35 Side Shell Longitudinals, where the side shell plates are primarily supported by longitudinal frames and the original thickness is 37 mm, grade EH.
- Frames 140-148, between No. 32-1 and No. 38 Side Shell Longitudinals, where the side shell plates are primarily supported by longitudinal frames and the original thickness is 35 mm, grade DH.
- Finally, midship region is going to be calculated in order to confirm that the original thickness of the side shell plates used (28.5 mm, grade DH), are properly reckoned.

The calculation of the scantlings with both methods of FSICR and IACS Polar Class rules are presented in Tables IX-10 and IX-11, respectively.

Parameters	**FSICR**			
Framing	**Transversely (Fr. 170-184)**	**Longitudinally (Fr. 151-166)**	**Longitudinally (Fr. 140-148)**	**Transversely (Midship)**
Yield stress σ_y [N/mm^2]	$\sigma_y = 315$	$\sigma_y = 315$	$\sigma_y = 315$	$\sigma_y = 315$
Design Height [mm]	h=0.3	h=0.3	h=0.3	h=0.3
Span or spacing [mm]	s = 0.533	s = 0.438	s =0.536	s =0.8
$p_{PL} = 0.75 \cdot p_{avg}$ [MPa]	$p_{PL} = 3.56$	$p_{PL} = 3.196$	$p_{PL} = 2.889$	$p_{PL} = 1.224$
t_c = increment for abrasion and corrosion	t_c = 2 mm	t_c = 2 mm	t_c = 2 mm	t_c = 2 mm
$f_1(h/s) = 1.3 - 4.2/(h/s + 1.8)^2$	*f(h/s) = 0.55*			*f(h/s) = 0.41*
$f_2(h/s) = 0.6 + 0.4 \cdot s/h$		$f_2(h/s) = 1.184$	$f_2(h/s) = 1.32$	
$t = 667 \cdot s \cdot \sqrt{\frac{f_1 \cdot p_{PL}}{\sigma_y}} + t_c[mm]$	***t=30 mm***	—		***t=23.5 mm***
$t = 667 \cdot s \cdot \sqrt{\frac{p_{PL}}{f_2 \cdot \sigma_y}} + t_c[mm]$	—	***t=29 mm***	***t=32 mm***	

Table IX-10: Shell plating thickness in the ice belt, according to FSICR.

It should be notified that if a special surface coating is capable to withstand the abrasion of ice, FSICR approve even lower values, regarding increment for abrasion and corrosion.

Parameters	**IACS**							
Framing:	**Transverse (Fr. 170-184)**		**Longitudinal (Fr. 151-166)**		**Longitudinal (Fr. 140-148)**		**Transverse (Midship)**	
Yield stress σ_y [N/mm^2]	$\sigma_y = 315$		$\sigma_y = 315$		$\sigma_y = 315$		$\sigma_y = 315$	
b or l [mm]	$b = 1.61$		$l = 2.85$		$l = 3.2$		$b = 1.002$	
Span or spacing [mm]	s = 0.533		s = 0.438		s = 0.536		s = 0.8	
p_{avg} [MPa]	$p_{avg} = 2.947$		$p_{avg} = 2.947$		$p_{avg} = 2.947$		$p_{avg} = 3.076$	
PPF_P	(1.8-s)= 1.267 ≥1.2		(2.2-1.2·s)= 1.674 ≥1.5		(2.2-1.2·s)= 1.56 ≥1.5		1.2	
	Effective Protection							
	with	**without**	**with**	**without**	**with**	**without**	**with**	**without**
t_s = increment for abrasion and corrosion [mm]	$t_s = 2$	$t_s = 4$	$t_s = 2$	$t_s = 4$	$t_s = 2$	$t_s = 4$	$t_s = 2$	$t_s = 4$
$t = t_{net} + t_s$ [mm]	***t=27 mm***	***t=29 mm***	—	—	—	—	***t=24 mm***	***t=26 mm***
$t = t_{net} + t_s$ [mm]			***t=27.5 mm***	***t=29.5 mm***	***t=31 mm***	***t=33 mm***	—	—

Table IX-11: Shell plating thickness in the ice belt, according to IACS Polar Class Rules.

Judging by the results presented in the above Tables IX-10 & IX-11, it can be easily understood that the final approved thicknesses of the side shell plates are enhanced in order to overcome ever greater ice loads, since the calculated scantlings for the examined regions are slightly thinner, leading however to heavier ship's construction.

The comparison of the scantlings between the two approved methods show that FSICR give greater attention to the calculated thicknesses than the IACS Polar Class rules in the bow and bow intermediate regions, although the added abrasion and corrosion thickness added is lower in the former than in the latter method. In contract, the IACS Polar Class Rules seems to pay more attention to the side shell thicknesses in the midship region, even though the difference is not worth-mentioned.

8. CONCLUSIONS

In this section, the data summarization is displayed (Table IX-10) and the conclusions derived from the assessment of the design ice load and the scantlings with the above mentioned methods are presented.

First of all, it should be mentioned that the target vessel LNG-Carrier 'Lena River' is a ICE Class IA vessel, constructed following all the requirements issued by Finnish Maritime Administration, regarding the structure and the regions of the vessel. In other words, the forefoot extent, the upper fore ice belt, the vertical extent of the ice strengthening of the frames and the overlap over the boarderlines between the bow and midship region and midship and aft region have been constructed in a proper way. However, a contemporary amendment -regarding the vertical extent of the ice belt for the side shell plating below LIWL in bow, midship and aft region- is not followed, but this is just a notation to be stated.

Parameter \ Method based to:	FSICR	IACS		'Popov Glancing' Collision	units
Average Pressure	4.194	2.947		2.846	MPa
Design Force	-	16.567		16.512	MN
Design Load Width (w)	0.7684	3.543		3.60	m
Design Load Height (h)	0.3	1.61		1.61	m
Scantlings		Protection			
		with	without		
Fr. 170-184 (Transverse framing)	30	27	29	—	mm
Fr. 151-166 (Longitudinal framing)	29	27.5	29.5	—	mm
Fr. 140-148 (Longitudinal framing)	32	31	33	—	mm
Midship (Transverse framing)	23.5	24	26	—	mm

Table IX-12: Presentation of the results, calculated with the design methods of FSICR, IACS Polar Class & 'Popov Glancing Collision'.

The calculations of the design ice load in FSICR show that the design ice pressure depends on certain factors, such as the displacement, the engine output, the region where the impact occurs and the probability that the full length of the area under consideration will be under pressure at the same time. For a specific vessel, such as 'Lena River', assuming that the coefficients c_d and c_p remain constant, the coefficient that influences the magnitude of the design ice pressure is c_a. The structural construction of the vessel and the width of the load patch are the parameters behind this coefficient.

The design ice pressure exerting in the bow region, is considered to be greater in a transversely than in a longitudinally framed ice strengthened ship, due to greater value of coefficient c_a.

The design ice pressure in the midship region for a specific vessel declines, due to the decrease of all the coefficients c_d, c_a and c_p. In other words, the FSICR consider that the greater ice loads will happen in bow and bow shoulder of a ship and that is the reason why the bow is strengthened more, compared to midship and aft regions.

The calculations of the design ice load in IACS Polar Class rules result to larger load patches and total normal forces compared to the one found in FSICR. However, lower design ice pressures are also found.

The total normal force that occur during the impact of the bow of the ship in the Upper Ice Waterline with the ice edge lead to ice flexural failure and this conclusion can derive either from IACS Polar Class rules, or from 'Popov glancing collision' energy method. In general, it seems that while moving from the stem of the ship to the parallel body, crushing forces increase but the ice fails in flexural failure, due to the shape of the hull.

The force assessed in the midship section is calculated in reference to the bow region and is found lower than that in bow region. However, as the aspect ratio (AR) is constant, regarding the load patch, force is concentrated in smaller areas and as a result, the ice pressure is greater than the one found in bow region.

Comparison between IACS Polar Class rules and 'Popov glancing collision' energy method show that the two methods are equivalent and lead to same results, confirming that the IACS Polar Class rules derive from the former method.

Moreover, regarding the scantlings, FSICR and IACS Polar Class rules give similar results. Scantlings of side shell plates for the ice belt region in FSICR are slightly larger than in IACS Polar Class rules. However, FSICR are more concerned to the assessed scantlings, while the IACS Polar Class rules consider the corrosion and abrasion increment more, especially if there is not an effective protection.

Finally, the assessments prove that the scantling in the midship region decrease in FSICR and IACS Polar Class rules, as a result of lower design ice pressures compared to the design ice pressures found in bow region.

All the calculations and the relevant equations for the determination of design ice loads and scantlings can be found also in Appendix I (Chapter XIII).

X. CHALLENGES FOR FUTURE ARCTIC SHIPPING

The risk in Arctic is higher than in other oceans due to the unique characteristics, the inadequate, scientific background and the poor infrastructures. The probability of an unfortune incident can results to significant consequences and high risks in Arctic. Therefore, the arctic ships should be capable enough to face hazards.

A considerable increase in the size of ice capable merchant ships, encourage large ship operations in arctic ice. Oil and natural gas exploration, production and development in the region of Russian Arctic, as well as mining of minerals, increased the needs for larger, higher class ships. As the design load increases, heavier ship constructions are needed in order to minimize the possibility of damages from the collision with ice. Logicably, this increase in design load, result to an increase in hull lightship and thus less efficient ships able to operate in open waters and more expensive to build.

Furthermore, a basic principle for arctic ships is to retain the appropriate amount of power required to break ice or collide with ice and be able to navigate efficiently in open waters. The efficient ice capable ships require proper bow form and hull lines. In other words, the arctic ship should satisfy safety balance needs for ice infested seas, as well as commercial feasibility. Both requirements for enhanced engine power and hull strength needed for ice navigation are obstacles for cost efficient navigation in open waters.

In this chapter, the future challenges are present. The challenges can be focused on the ice loading rehabilitation and the unification of the existing rules for the design ice loads, the structural development and the minimizing of possible environmental effects.

1. CHALLENGES IN ICE LOADS

The Unified Rules (URs) represent the status requirements in ice-capable design. All the classification societies and maritime Administrations take part in the determination and the approval of the URs, making the basic step for the development of a thorough analysis in the field of ice-capable ships' construction. Unified Rules combine a modern understanding of ice loads with an approach of structural analysis that provide efficient and robust solutions. However, this analysis is far beyond the prefection, due to semi-empirical methods for the determination of design ice loads.

Classification societies publish rules which prescribe the strength of ships for navigating in different ice operation conditions, depending primarily on the thickness (and type) of ice. The IACS Polar Class Rules represent the latest scientific and engineering thinking of dimensioning ship structures in ice. Class factors and hull area factors are used in order the design ice load to be determined. However, the operating experience in very short and as a result the database for the calibration of the class and hull area factors is very limited.

Deeper analysis of ice mechanics and collection of data for all aspects of large, high class ships service experiences pose the demand for updated URs models. Equally importantly, enhanced and updated methods of design ice load assessment and a better calibration of class factors and hull areas factors need to be developed.

Moreover, the IACS Polar Class Rules consider the effect of ice load in bow and bow shoulder areas. As a result, steel thicknesses are usually greater in the bow and the calculation for the other regions is defined by hull area factors. This uncertainty can be considered a significant technlogical hurdle, as steel weight, cost and deadweight penalties are incurred in other ice-strengthening areas. There is a need to develop a better approach to the design of non-bow areas than relying on class area factors.

Additionally, URs approach structural design development using the formation of elasto-plastic response mechanisms as a design point, rather than the first yield point. The URs for plating and framing consider as the design point this elasto-plastic limit state. The load at this point is almost double that at yield point, while the deflection is still very small. There are even higher peak points with significantly small deflection and normal fabrication tolerance [15].

However, new requirements, such as the Common Structural Rules, are still based on the elastic section properties and are still encouraging design in a wrong direction. In contrast, plastic reserve is at least for new construction with proper steel, quite significant and comes with little cost. A method, based on full plastic capacity, would encourage better proportions and more effective steels [14].

Finally, factors that cause reduction in plate capacity should be included to the analysis. These are:

- the aging effects (fatigue, corrosion)
- poor hull maintenance and random flaws
- non-uniform load patterns.

2. EFFICIENT SHIP STRUCTURES FOR ARCTIC SHIPS

Arctic ships design seems to be unchanged since the mid-1980s. However, an increase in steel weight happens with the increase in ship's ice-going capability. The nature of ice load is fundamentally different to that of wave loading and structural design of large Arctic ships rely on enhanced steel thicknesses and restrictions, regarding stiffeners. A big challenge for the future is an increase of structural strength with a simultanious reduction in steel weight.

Improvements in structural design are considered to encompass not only new configurations but also use of advanced materials. Current Arctic ship designs are utilising high strength steels up to the limit of what may be considered standard steel types in the shipbuilding industry. In order to address the need to develop more efficient and lighter structures to resist ice loads for larger ships new materials should be considered.

The Sandwich Plate System (SPS) is a good solution to the problem as it is intended to replace steel plates and adjacent stiffeners in ship structures [29]. The SPS is composed of two thin steel plates boned to a polyurethane elastomer without stiffeners [Figure X-1a) and X-1b)].

SPS has approvals from the major Classification Societies for its use in newbuilding projects and the rehabilitation of ships. The mechanism behind SPS is that in flexure, the plates act as flanges and the core as the web. The SPS plate is suggested to be taken in to the plastic regime without local face plate buckling or bond delamination between sandwich cores.

The benefits of SPS construction over conventional steel structures are enlisted in brief, [29]:

- Simplified structure
- Reduced weight
- Increased fatigue resistance
- Reduced susceptibility to corrosion

- A60 fire rating
- Enhanced puncture, impact, blast and ballistic resistance
- Inherent structural damping reducing vibration and noise transmission

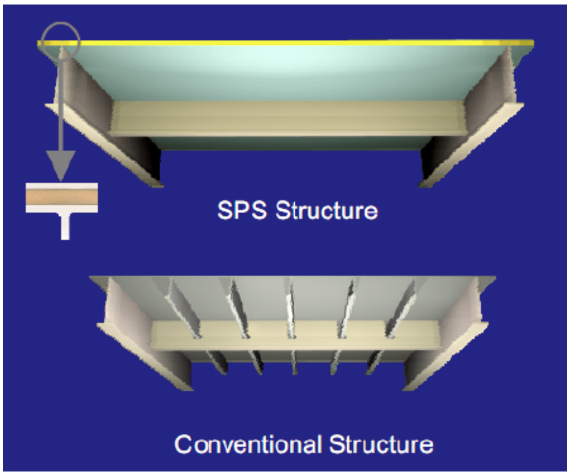


Figure X-1: a) Sandwich Plate System, b) Sandwich Plate System & Conventional Structure [29]

This innovative material for shipping industry can be combined with innovative design in ice capable ships. Bow propellers are used mainly in icebreakers and the technology can be expanded to commercial ships. Bow propeller removes the water from underneath the ice and ice does not collide with the ships stem.

However, the design that is assumed to be the most reliable in ice breaking ships is the one of azimuth thrusters. The development of azimuth thrusters result to rudders removal and protection of the hull in ice through the possibility of dispersing and flushing ice ridges and floes. The azimuth thrusters led to the concept of "Double Acting ships – (DAS)" or "dual mode ships", (Figure X-2). This ship has fully rotating thrusters at the stern and in heavier ice goes astern, penetrating in ice ridges.

Figure X-2: Fortum Shipping's two new 105,000 dwt DAS crude carriers [2].

In other cases, there is a cross-over ice thickness that a ship is advantageous to go astern in thick ice, while in thin ice go ahead. The location of the cross-over thickness depends on the bow and stern design [47]. This Double-Acting ship design can improve ship's performance in open water by giving more open water characteristics to the bow, without focusing on ice going features. Moreover, new ice breaking stern design for Double Acting ships can result in less ice resistance and higher propulsion efficiency. In conclusion, Double Acting ships can solve the problem of ships combining open water and ice condition operation, leading for both cases to less fuel consumption.

3. CHALLENGES IN DEVELOPING GREEN ICE CAPABLE SHIPS

New rules such as:

- Energy Efficiency Design Index (EEDI),
- Polar Code and
- EU Sulphur emissions directive

will regulate shipbuilding in the future. Obstacles and improper use of rules should be solved and Unified Rules for open water and ice operations should be in use [1].

Energy Efficiency Design Index (EEDI) is an approach to the reduction of the green house gases, taken by IMO, a efficiency ratio how much green house gases are released per one unit of productive work. Thus, EEDI acts as maximum allowed power limit or speed limit, while for ships in ice class rules, there is a requirement for minimum propulsion power so as to have a better ice performance. Consequently, the trends in EEDI and in ice performance seem to work in different directions [47].

EEDI formation at IMO has a three-time, descending trend in the future and all the ice class ships who intend to operate in open waters will be penalized and forbidden in the future. A solution should be given so that the clash between required minimum allowed power and maximum power that EEDI allows, finally extinguish.

The Polar Code is intended to supplement SOLAS and MARPOL, covering additional aspects of ship design and construction for international ships operating in the Polar Regions in order to ensure safety [1].

Polar Code divides ships into the following categories:

Category A ship is a ship designed for operation in polar waters in at least medium first-year ice, which may include old ice inclusions (IACS ice classes PC1 – PC5)

Category B ship is a ship not included in category A, designed for operation in polar waters in at least thin first-year ice, which may include old ice inclusions (IACS PC6 – PC7)

Category C ship is a ship designed to operate in open water or in ice conditions less severe than those included in categories A and B (other ice classes than the PC classes of IACS and ships without an ice class) [39].

It is the intention of the Polar Code to provide an international standard of shipping in Polar regions.

Last but not least, the purpose of this EU directive on sulphur emissions is to reduce the emissions of sulphur dioxide resulting from the combustion of certain types of liquid fuels and thereby to reduce the harmful effects of such emissions on man and the environment. From 2015 onwards, sulphur emissions should be dropped below 0.1%, ten times below the current level. In order to synchronize with the directive, ships are forced to use more expensive, low sulphur fuel with simultaneous modification of their engines, or install scrubbers to clean the emissions from sulphur. A third option is to use other fuels like liquefied natural gas or biofuels [39].

In spite of the problems, ice capable ships should apply the rules, in accordance with the International Rules for the protection of the environment.

4. DEFICIENCIES & SOLUTIONS FOR THE EXPANSION OF THE NSR

In Table X-1, the basic problems and possible solutions are mentioned in order to develop a more efficient and secure Northern Sea Route [24].

Problem/Deficiency	Solution/Remedy/Initiative
• Lack of search & rescue (SAR) capacity (sea area monitoring & aerial/vessel response)	• Greater airborne area surveillance and developmet of fleet of high-performance (ice-breaking, endurance & speed) salvage/rescue tugs • Expanded high definition coastal radar coverage
• Gaps in satellite communications. NSR is only partially covered by two INMARSAT geostationary satellites; gaps in coverage occur in the Laptev Sea & north of Severnaya Zemlya. [INMARSAT is used to transmit digital ice data & forecasts to vessels] • 2 satellite communication systems can support NSR operations: INMARSAT & Russia's OCEAN system • Few INMARSAT receivers compatible with OCEAN system & critical communication gaps remain along NSR with these systems	• Launch additional INMARSAT geostationary satellites • Develop compatibility hardware/software upgrades to enable greater interoperability of INMARSAT & OCEAN systems
• Insufficient numbers of icebreakers to accompany increasing number of transiting vessels	• Expansion of internationally-flagged, operated and owned/funded modern icebreakers (these vessels could also double as SAR vessels)
• Comparative lack of reliable charts	• Incentivise new polar hydrographic survey campaigns-oceanographic knowledge acquisition & UN funding
• Insufficient aids to navigation	• Internationally funded expansion of installed aids to navigation-charting, radar, buoyage, Arctic region notice to mariners service
• Lack of officers qualified to operate vessels in ice-covered waters	• Modifications to/expansion of STCW and deck officer training to cover icebreaking and polar navigation/seamanship
• Insufficient sea ice oil spill response technology and resources	• Extensive scientifically-driven and oil company funded R&D to develop any and all necessary safeguards and response requirements for oil spills in ice covered waters
• Lack of sufficient satellite-based synthetic aperture radar (SAR) [used in detection and monitoring of sea ice and pack ice] • Currently coverage by high definition SAR is not sufficient and there are particular gaps in the Laptev Sea	• In order to provide endemic coverage, European Space Agency (ESA) is proposing to build new SAR receiving station in the Russian Arctic to cover gap • Launch of additional SAR satellites to monitor ice coverage patterns to enable short, medium and long-term forecasting
• Lack of suitably equipped merchant vessels configured for operating in extreme polar conditions (deck machinery, sea water induction, hull strength, propulsion & manoeuvre)	• This will only be addressed and driven by economic and trading imperatives. When and if the NSR is viewed as a mainstream viable trading route, then owners will order suitably configured vessels
• Lack of holistic, internationally sanctioned regulations and best practises for polar shipping	• IMO is currently developing a draft international code of safety for ships operating in polar waters, - The Polar Code • Code will cover design, construction, equipment, operational, training, SAR & environmental protection matters relevant to ships operating in high latitudes

Table X-1: Problems and Solutions for the expansion of the Northern Sea Routes [24]

XI. CONCLUSIONS

The new routes in the Northern Atlantic Seas that have been formed due to climate changes, boost the discussions about navigation in ice conditions and the development of an ice shipping industry of ice capable ships, offshore structures and infrastructures for marine services. It is true that sea ice extent, especially in the Northern Russian Seas decline continuously in the last twenty years, revealing routes that are known as Northern Sea Route (NSR). Northern Sea Route gave a new prospect in marine transportations. Shorter voyages, less fuel consumptions and gas emissions, as well as lower risk of conflicts and attacks by pirates in high risk areas are most of the advantages.

However, sea ice conditions in the Arctic Seas, as well as wind currents show that the operational environment is not ship-friendly and ships that are about to operate in these harsh conditions should be reinforced with proper hull, engine and propulsion systems.

Mechanical and physical properties of different types of sea ice can change the operational scenario of an ice capable ship. Sea ice differs from ice in rivers and lakes, resulting to different types of formation. Thickness, geometry and age of sea ice are the key parameters to determine the strength of ice. These key parameters are being used by classification societies and maritime administrations in order to classify ships in proper and certain classes. Each class of a vessel type give to the ship some general characterictics, regarding the ability to operate in harsh ice conditions, independently or escorted by icebreakers, in certain speed.

In brief, ships were categorized to year-round or summer/autumn, able to operate independently or escorted in first-year (FY), second year or multi-year (MY) ice. The design of ice capable vessels consist of three main parts:

- Reinforced hull and winterized outfittings
- Propulsion machinery
- Propulsion power

Finnish-Swedish Ice Class Rules (FSICR) and IACS Polar Class rules included all the previous experience in order to result to safe and effective ice capable ships for Baltic and Arctic/Antarctic use, respectively. IACS Polar Class rules include more categories, but there are some equivalent categories, in order ships for Baltic use to be able to operate in Arctic conditions. Semi-empirical methods and operational scenarios for determining the design ice loads and scantlings for each ship category lead to the final construction.

Regarding the hull requirements, both Ice Class rules pay attention to the bow reinforcement, while the midship and aft regions are determined by Area Factors (AF) and the operational scenario for each is an ice-ship impact at the bow of the ship. However, FSICR reinforcement is localized in side area, while IACS polar ships need to be strengthened further in bilge and bottom areas of bow and aft regions.

The determination of the design ice loads is the most crusial factor for the further development of the ship. The design ice load lead to a design load patch, where ice pressure is assumed to act on a rectangular patch. Displacement and actual engine output are ship's factors that are taken into account in FSICR, while IACS polar class rules include hull shape, -through hull angles- displacement and safe, ship's speed. Both rules include class-dependent factors. Scantlings for shell plates and frames derive from the design ice load. Frame space or span -according to the orientation of the stiffeners (longitudinally or transversely)-, material properties, dimensions of the design load patch and average patch pressure are included in the assessments of both class rules.

Nevertheless, IACS Polar Class rules pay attention to the ice failure due to flexural or crushing failure, in order to determine the design ice load. Moreover, FSICR assume that the design point of the ship should be the first yield point, while the IACS polar class rules use a elasto-plastic design point and give emphasis to the materials' decision for the submerged and weather exposed shell plating, requiring from the certain material, proper temperature resistance, steel grade and thickness of the structural member. On the other hand, FSICR include in the operational scenario, collision of the ship with ice ridge, 1.8 times bigger than the ice floe thickness and have a stricter philosophy regarding the scantlings of the structural members, resulting to a heavier construction.

IACS approach to design ice load derive from an energy-based scenario, where the ship interact with an ice floe. In higher polar classes, the scenario is a head on (ramming) impact on the stem, while in the lower polar classes, a glancing impact on the bow or bow shoulder is used. When the ship collide with an infinite ice floe, such as an ice edge in an ice channel, the entire normal kinetic energy turns to indentation energy. This method can be used to determine the design ice load and penetration of ship in ice and in practise, result to almost the same outcomes with the IACS design ice load assessment.

Moreover, the principles followed for the determination of the design ice load in Baltic or Arctic/Antarctic vessels differ. The FSICR (Baltic) rules imply that the design ice pressure is acting in a load patch with dimensions that are determined by the class rules (design height h) and structural member that is under calculation (load length l_a). In contrast, IACS arctic rules estimate the total normal force (F_n), as well as the line load (Q) and the ice pressure (P), using class factors and hull shape coefficients and then the load patch dimensions are defined. However, behind these class factors and hull shape coefficients, there are assumptions that are taken by the classification societies and maritime administrations, in order to make the equations simplified. The equations from which the rule formulas of IACS Polar Class Rules derive, can be found in the 'Popov oblique collision' method. This energy-based method prove that the usage of the class factors hide parameters such as constant ice pressure for the period considered and ship's velocity allowed for safe operation, as well as assumptions regarding the features of the ice edge. The load patch dimensions result from the total design force (F_n) and the geometrical features of the ice penetration of the ship side, while the line load (Q) and ice pressure (P) depend also on the above mentioned parameters (displacement, velocity allowed and class dependent ice pressure).

Finally, it should be clarified that the theory behind the construction of an ice capable ship is the design of a less unsafe ship that can operate in harsh, ice conditions without increased potentials of disaster and without causing any problem to the crew and the operational spectrum. However, this comes to contrast with the operation of ships in open waters, where the ship should be lighter, cost-effective and environmental-friendly.

So, the challenge for the future is a vessel of lower lightship, with adequate, safety features to be able to operate, due to her operational spectrum in open water or ice-infested seas. Innovations in materials, new structures and propulsion systems should be made and the unification of the rules should adjust also these certain kind of vessels.

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XIII. APPENDIX

1. ICE STRENGTHENING CALCULATIONS (BASIC EQUATIONS & TABLES)

FSICR

Design Ice Load Calculation				
Region	***Bow (1)***	***Bow (2)***	***Bow Shoulder (3)***	***Midship (4)***
c_d	0.848	0.848	0.848	0.396
c_p	1.000	1.000	1.000	0.85
c_a	1.000	0.898	0.811	0.662
p_o ***(MPa)***	5.600	5.600	5.600	5.600
$k = \sqrt{\Delta \cdot P}\,/1000$	54.935	54.935	54.935	54.935
l_a	0.533	0.7446	0.9112	0.805
Height of load area (Ice Class IA)	0.3	0.3	0.3	0.3
p (MPa)	4.747	4.264	3.852	1.632
Design Plate thickness (mm)	30	33	32	23.4

Region (1): Fr. 170-184, *s=0.533 m (transversely-framed)*

Region (2): Fr. 151-166, *s=0.438 m (longitudinally-framed)*

Region (3): Fr. 140-148, *s=0.536 m (longitudinally-framed)*

Region (4): Midship Section, *s=0.8 m (transversely-framed)*

- Determination of design ice pressure

$$p = c_d \cdot c_p \cdot c_a \cdot p_0 .$$

$$c_d = \frac{a \cdot k + b}{1000}$$

$$k = \frac{\sqrt{\Delta \cdot P}}{1000}$$

Δ=121201 tonnes,

P=24900 kWatt

α=6, b=518 when *k>12* (*Table VII-8*)

$$0.35 \le c_a = \sqrt{\frac{l_0}{l_a}} \le 1.0$$

$l_o = 0,6$ *m,*

l_a *in Table VII-10,*

$c_p=1.0$ (*Table VII-9*).

- <u>Determination of scantlings</u>

Transverse-framing:

$$t = 667 \cdot s \cdot \sqrt{\frac{f_1 \cdot p_{PL}}{\sigma_y}} + t_c [mm]$$

$p_{PL}=0.75 \cdot p$,

p: design ice pressure

$$f_1(h/s) = 1.3 - 4.2/(h/s + 1.8)^2$$

t_c: corrosion and abrasion allowance

h: design height (*Table VII-7*)

Longitudinal-framing:

$$t = 667 \cdot s \cdot \sqrt{\frac{p_{PL}}{f_2 \cdot \sigma_y}} + t_c [mm]$$

$p_{PL}=0.75 \cdot p$,

when $h/s \leq 1$

$$f_2(h/s) = 0.6 + \frac{0.4}{(h/s)}$$

when $1 \leq h/s < 1.8$

$$f_2(h/s) = 1.4 - 0.4(h/s)$$

IACS Polar Class Rules

Values	**Fr.164**	**Fr.151**	**Fr.145**	**Fr.140**	Units	Values	**Midship**	Units
Cc (crushing failure)	1.80	1.80	1.80	1.80	nd			
C_F (flexural failure)	4.06	4.06	4.06	4.06	nd			
C_D (load patch)	1.11	1.11	1.11	1.11	nd			
C_Δ (displacement)	22	22	22	22	nd			
C_L (longitudinal strength)	1.81	1.81	1.81	1.81	nd			
Hull Angles and coordinates								
Alpha (a)	15	26	26	26	degrees			
Beta (β)	18.00	19.00	22.00	24.00	degrees			
Beta prime (β′)	17.42	17.20	19.96	21.81	degrees			
Gamma (γ)	37.89	55.95	51.60	47.60	degrees			
Distance from Bow	7.65	18.05	22.85	26.85	m			
Shape Coefficient						*Design Ice force*		
f_{a1}	0.312	0.577	0.546	0.529	nd	CF_D	1.110	nd
f_{a2}	0.442	0.424	0.368	0.338	nd	CF_C	1.800	nd
f_{a3}	0.600	0.600	0.600	0.600	nd	CF_{DIS}	22.000	nd
$min(f_{ai})$	**0.312**	**0.424**	**0.368**	**0.338**	nd	D_F	17.150	nd
Load Patch Aspect Ratio								
C_{ARi}	2.233	2.206	2.547	2.772	nd			
Design Ice Load								
F_{BOW}	**12.1**	**16.5**	**14.3**	**13.1**	MN	F_{NonBow}	11.114	MN
q_i	**3.835**	**4.646**	**4.050**	**3.734**	(MN/m)	Q_{NonBow}	3.082	MN/m
p_{bow} (MPa)	**2.713**	**2.893**	**2.927**	**2.947**	kPa			
w_{bow} (m)	**3.543**				m	w_{NonBow}	**3.606**	*(m)*
b_{bow} (m)	**1.577**				m	b_{NonBow}	**1.002**	*(m)*
p_{avg}	**2.947**				MPa		**3.076**	Mpa

- Determination of design ice load patch *(p_{avg}, w, b)* for Bow Region

$$F_n = f_a \cdot CF_C \cdot \Delta_{ship}^{0.64}$$

$$Q_i = F_i^{0.61} \cdot CF_D / AR^{0.35}$$

$$P_i = F_i^{0.22} \cdot CF_D^2 \cdot AR_i^{0.3}$$

$$w_{Bow} = F_{Bow} / Q_{Bow}$$

$$b_{Bow} = Q_{Bow} / P_{Bow}$$

where

$f_{ai}=min(f_{a1}, f_{a2}, f_{a3})$,

$$AR_i = 7.46 \cdot sin\theta_i$$

$$f_{a1} = [0.097 - 0.68 \cdot (\frac{x}{L} - 0.15)^2] \cdot \frac{a}{\sqrt{\theta}}$$

$$f_{a2} = 1.2 \cdot CF_F / [\sin(\theta) \cdot CF_C \cdot \Delta^{0.64}]$$

$$f_{a3} = 0.60$$

- Determination of design ice load patch *(p_{avg}, w, b)* for Non-Bow Region

when $\Delta \leq C_\Delta$:

$$F_{NonBow} = 0.36 \cdot CF_C \cdot \Delta^{0.64}$$

when $\Delta > C_\Delta$:

$$F_{NonBow} = 0.36 \cdot CF_C \cdot (CF_{DIS}^{0.64} + 0.10 \cdot (\Delta - CF_{DIS}))$$

$$Q_{NonBow} = 0.639 \cdot F_{NonBow}^{0.61} \cdot CF_D,$$

$$w_{NonBow} = F_{NonBow} / Q_{NonBow}$$

$$b_{NonBow} = w_{NonBow} / 3.6$$

$$P_{avg} = \frac{F}{(b \cdot w)} [MPa]$$

- Determination of scantlings

Region (1): Fr. 170-184, *s=0.533 m (transversely-framed)*

Region (2): Fr. 151-166, *s=0.438 m (longitudinally-framed)*

Region (3): Fr. 140-148, *s=0.536 m (longitudinally-framed)*

Region (4): Midship Section, *s=0.8 m (transversely-framed)*

$t = t_{net} + t_s$ *[mm]*

t_s: corrosion and abrasion allowance *(Table VII-18)*

Transversely-framed plating ($\Omega \geq 70$ deg):

$$t_{net} = 500 \cdot s \cdot ((AF \cdot PPF_p \cdot P_{avg}) / \sigma_y)^{0.5} / (1 + s / (2 \cdot b))[mm]$$

Longitudinally-framed plating ($\Omega \leq 20$ deg):

when $b < s$:

$$t_{net} = 500 \cdot s \cdot ((AF \cdot PPF_P \cdot P_{avg}) / \sigma_y)^{0.5} \cdot (2 \cdot b / s - (b / s)^2)^{0.5} / (1 + s / (2 \cdot l))[mm]$$

when b ≥ s:

$$t_{net} = 500 \cdot s \cdot ((AF \cdot PPF_P \cdot P_{avg}) / \sigma_y)^{0.5} / (1 + s / (2 \cdot l))[mm].$$

AF = Hull Area Factor *(Table VII-17)*

PPF_p = Peak Pressure Factor *(Table VII-16)*

σ_y = minimum upper yield stress of the material [N/mm^2]

Parameters	**IACS**							
Framing:	**Transverse (Fr. 170-184)**		**Longitudinal (Fr. 151-166)**		**Longitudinal (Fr. 140-148)**		**Transverse (Midship)**	
Yield stress σ_y [N/mm^2]	$\sigma_y = 315$		$\sigma_y = 315$		$\sigma_y = 315$		$\sigma_y = 315$	
b or l [mm]	$b = 1.61$		$l = 2.85$		$l = 3.2$		$b = 1.002$	
Span or spacing [mm]	s = 0.533		s = 0.438		s = 0.536		s = 0.8	
p_{avg} [MPa]	$p_{avg} = 2.947$		$p_{avg} = 2.947$		$p_{avg} = 2.947$		$p_{avg} = 3.076$	
PPF_P	(1.8-s)= 1.267 ≥1.2		(2.2-1.2·s)= 1.674 ≥1.5		(2.2-1.2·s)= 1.56 ≥1.5		1.2	
	Effective Protection							
	with	**without**	**with**	**without**	**with**	**without**	**with**	**without**
t_s = increment for abrasion and corrosion [mm]	$t_s = 2$	$t_s = 4$	$t_s = 2$	$t_s = 4$	$t_s = 2$	$t_s = 4$	$t_s = 2$	$t_s = 4$
$t = t_{net} + t_s$ [mm]	***t=27 mm***	***t=29 mm***	—	—	—	—	***t=24 mm***	***t=26 mm***
$t = t_{net} + t_s$ [mm]			***t=27.5 mm***	***t=29.5 mm***	***t=31 mm***	***t=33 mm***	—	—

'Popov' Glancing Impact

Note that all the physical values (class parameters) and class factors are presented in Table VIII-2.

- Determination of the oblique collision force

$$KE_n = IE$$

$$IE_{crush} = \int_0^{\delta} F_n(\delta) \cdot d\delta$$

$$F_i = P_{av} \cdot A = P_0 \cdot A^{1+ex}$$

where

$$A = \delta^2 \cdot \tan(\frac{\varphi}{2}) / (\cos^2(\beta') \cdot \sin(\beta'))$$

and

$$\delta_m = 1/2 \cdot M_e \cdot V_n^2 \cdot (3 + 2ex) / (P_o \cdot k_a^{1+ex}))^{1/(3+2ex)}$$

where

$$k_a = \tan(\varphi / 2) / (\cos^2(\beta') \cdot \sin(\beta')).$$

Then,

$$F_n = P_o^{(1/3+2ex)} \cdot k_a^{(1+ex)/(3+2ex)} \cdot (1/2 \cdot M_e \cdot V_n^2 \cdot (3 + 2ex))^{(2+2ex)/(3+2ex)}$$

Note that in the equations,

$$M_e = M_{ship}/C_o,$$

in order to calculate the total ice Force, the mass reduction coefficient should be estimated.

Hull angles at point P:

a = waterline at point P
β = frame angle
$\beta' = \theta$ = normal frame angle,
γ = sheer angle

The various angles are related as follows,

$$tan(\beta) = tan(a) \cdot tan(\gamma)$$

$$tan(\beta') = tan(\beta) \cdot tan(a)$$

Based on these angles, the direction cosines, l,m,n are

$$l = sin(a) \cdot cos(\beta')$$

$$m = cos(a) \cdot cos(\beta')$$

$$n = cos(\beta')$$

and the moment arms are

$$\lambda l = ny - mz \text{ (roll moment arm)}$$

$$\mu l = lz - nx \text{ (pitch moment arm)}$$

$$nl = mx - ly \text{ (yaw moment arm)}$$

The added mass terms are as follows (from Popov),

$$AM_x = \text{added mass factor in surge} = 0$$

$$AM_y = \text{added mass factor in sway} = 2T/B$$

$$AM_z = \text{added mass factor in heave} = 2/3 \cdot (B \cdot C_{wp}/2)/(T \cdot (C_b \cdot (1+C_{wp})))$$

$$AM_{rol} = \text{added mass factor in roll} = 0.25$$

$$AM_{pit} = \text{added mass factor in pitch} = B/((T \cdot (3-2 \cdot C_{wp}) \cdot (3-C_{wp}))$$

$$AM_{yaw} = \text{added mass factor in yaw} = 0.3 + 0.05 \cdot L/B$$

The mass radii of gyration (squared) are

$$rx^2 = C_{wp} \cdot B^2/(11.4 \cdot C_m) + H^2/12 \text{ (roll)}$$

$$ry^2 = 0.07 \cdot C_{wp} \cdot L^2 \text{ (pitch)}$$

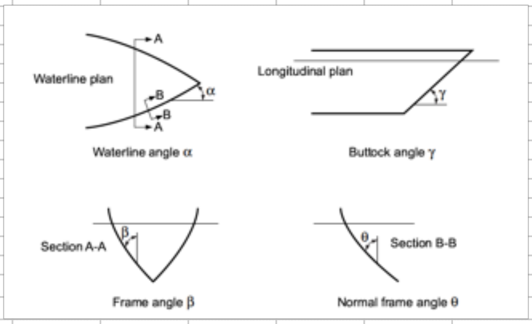
$$rz^2 = L^2/16 \text{ (yaw)}$$

With the above quantities defined, the mass reduction coefficient is

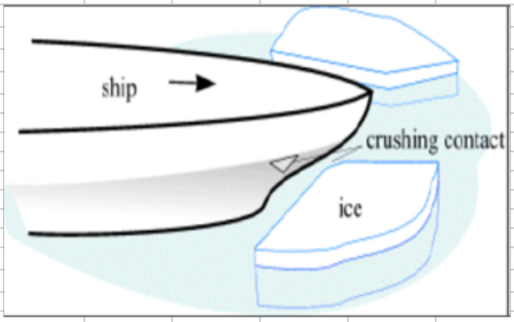
$$C_o = l^2/(1+AM_x) + m^2/(1+AM_y) + n^2/(1+AM_z) +$$
$$+\lambda l^2/(rx^2(1+AM_{rol})) + \mu l^2/(ry^2(1+AM_{pit})) + nl^2/(rz^2(1+AM_{yaw}))$$

Frame 164			
Popov Glancing Collision (Wedge Edge)			
Ship Main Parameters			units
Ship Name	SN	Lena River	text
Length	L_{WL}	279.20	m
Beam	B	44.20	m
Draft	T	12.9375	m
Height	H	26.00	m
Block Coef.	CB	0.749125	nd
Waterplane Coef	Cwp	0.851425	nd
Midship Coefficient	Cm	0.9953	nd
Mass	M	121201	tonnes
Ship Speed	Vs	1.750	m/s
Hull Angles and coordinates			
Alpha	α	15.00	deg
Beta	β	18.00	deg
Beta prime	β'	17.42	deg
gamma	γ	45.00	deg
Alpha	α	0.2618	rad
Beta	β	0.3142	rad
Beta prime	β'	0.3041	rad
gamma	γ	0.7854	rad
Symmetrical		no	text
x coordinate	x	131.06	m
y coordinate	y	1.5	m
z coordinate	z	0	m
Ice Crushing Terms			
Ice strength term	Po	1.25	Mpa
Ice exponent (process PA)	ex	-0.1	nd
Wedge angle	ϕ	150	deg
Wedge angle	ϕ	2.62	rad
form factor 1	fx	2.80	nd
form factor 2	fa	10.54	nd
Popov Terms			
x dirn cosine	l	0.2469	nd
y dirn cosine	m	0.9216	nd
z dirn cosine	n	0.2994	nd
roll moment arm	λl	0.4492	m
pitch moment arm	μl	-39.2440	m
yaw moment arm	ηl	120.4102	m
Surge Added Mass	Amx	0.0000	nd
Sway Added Mass	Amy	0.5854	nd
Heave Added Mass	Amz	1.1905	nd
Roll Added Mass	Amrol	0.2500	nd
Pitch Added Mass	Ampit	1.2258	nd
Yaw Added Mass	Amyaw	0.6158	nd
roll gyrad(squared)	rx2	202.9327	m2
pitch gyrad(squared)	ry2	4645.96	m2
yaw gyrad(squared)	rz2	4872.04	m2
Mass Reduction Coef.	Co	2.6291	nd
Effective mass	Me	46100373	kg
Normal Speed	Ve	0.432	m/s
Kinetic Energy	KEe	4304697	kg-m2/s2
Impulse	Ie	19922257	kg-m/s
Results			
pen(n)	ζn	0.969	m
Normal Force	Fn	12.44	MN
Maximum Force Flexural Strength	Fn,lim	16.280022	MN
Design Force	Fmin	12.442	MN
Aspect Ratio	AR	2.235	
Length	w	3.24	m
Height	b	1.45	m
Average pressure	p_{avg}	2.637	Mpa

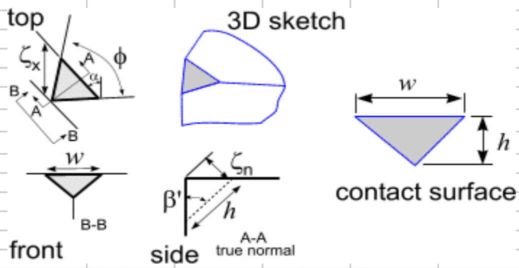
Hull Angles



Scenario

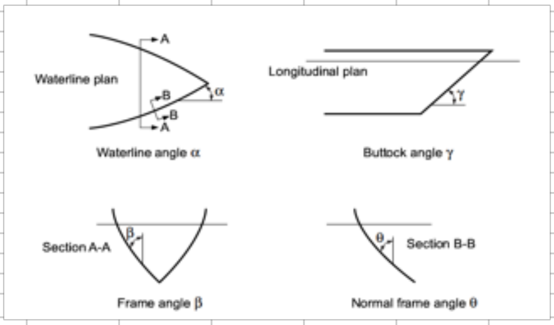


Indentation Geometry

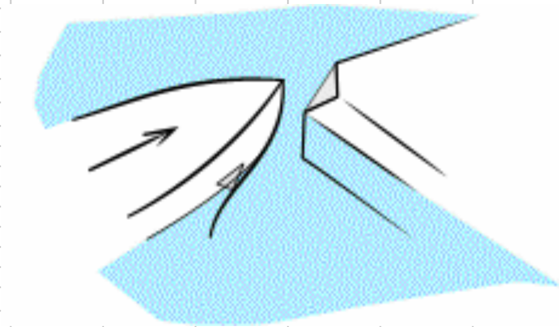


	Frame 151			
Popov Glancing Collision (Wedge Edge)				
Ship Main Parameters				units
	Ship Name	SN	Lena River	text
	Length	L_{WL}	279.20	m
	Beam	B	44.20	m
	Draft	T	12.9375	m
	Height	H	26.00	m
	Block Coef.	CB	0.749125	nd
	Waterplane Coef	Cwp	0.851425	nd
	Midship Coefficient	Cm	0.9953	nd
	Mass	M	121201	tonnes
	Ship Speed	Vs	1.750	m/s
Hull Angles and coordinates				
	Alpha	α	26	deg
	Beta	β	19.00	deg
	Beta prime	β'	17.20	deg
	gamma	γ	54.78	deg
	Alpha	α	0.4538	rad
	Beta	β	0.3316	rad
	Beta prime	β'	0.3001	rad
	gamma	γ	0.9561	rad
	Symmetrical		no	text
	x coordinate	x	120.66	m
	y coordinate	y	5.80	m
	z coordinate	z	0	m
Ice Crushing Terms				
	Ice strength term	Po	1.25	Mpa
	Ice exponent (process PA)	ex	-0.1	nd
	Wedge angle	ϕ	150	deg
	Wedge angle	ϕ	2.62	rad
	form factor 1	fx	2.80	nd
	form factor 2	fa	10.64	nd
Popov Terms				
	x dirn cosine	l	0.4188	nd
	y dirn cosine	m	0.8586	nd
	z dirn cosine	n	0.2956	nd
	roll moment arm	λl	1.7147	m
	pitch moment arm	μl	-35.6711	m
	yaw moment arm	ηl	101.1674	m
	Surge Added Mass	Amx	0.0000	nd
	Sway Added Mass	Amy	0.5854	nd
	Heave Added Mass	Amz	1.1905	nd
	Roll Added Mass	Amrol	0.2500	nd
	Pitch Added Mass	Ampit	1.2258	nd
	Yaw Added Mass	Amyaw	0.6158	nd
	roll gyrad(squared)	rx2	202.9327	m2
	pitch gyrad(squared)	ry2	4645.96	m2
	yaw gyrad(squared)	rz2	4872.04	m2
	Mass Reduction Coef.	Co	2.1150	nd
	Effective mass	Me	57305299	kg
	Normal Speed	Ve	0.733	m/s
	Kinetic Energy	KEe	15388716	kg-m2/s2
	Impulse	Ie	41996546	kg-m/s
Results				
	pen(n)	ζn	1.522	m
	Normal Force	Fn	28.313	MN
	Flexural strength	σ_f	0.65	Mpa
	Maximum Force Flexural Strength	Fn,lim	16.489	MN
	Design Force	Fmin	16.489	MN
	Aspect Ratio	AR	2.207	
	Length	w	3.60	m
	Height	b	1.63	m
	Average pressure	p_{avg}	2.810	Mpa

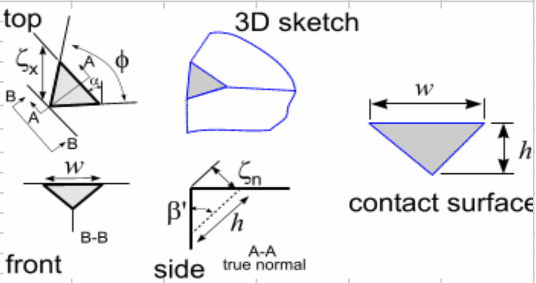
Hull Angles



Scenario

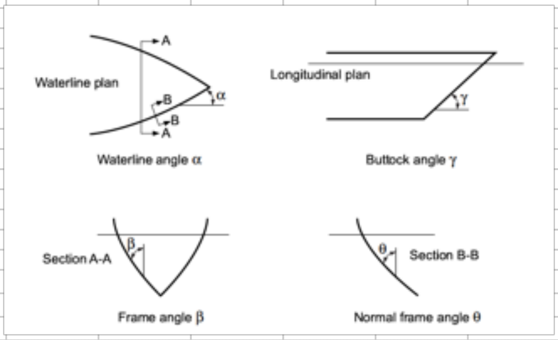


Indentation Geometry

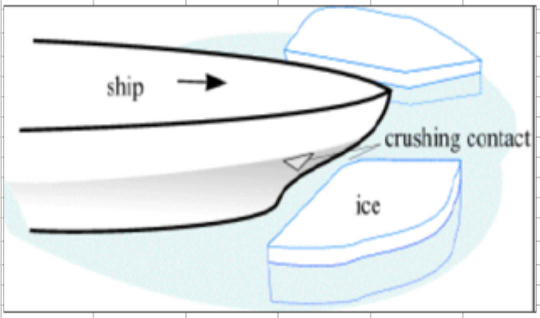


	Frame 145			
Popov Glancing Collision (Wedge Edge)				
Ship Main Parameters				units
	Ship Name	SN	Lena River	text
	Length	L_{WL}	279.20	m
	Beam	B	44.20	m
	Draft	T	12.9375	m
	Height	H	26.00	m
	Block Coef.	CB	0.749125	nd
	Waterplane Coef	Cwp	0.851425	nd
	Midship Coefficient	Cm	0.9953	nd
	Mass	M	121201	tonnes
	Ship Speed	Vs	1.750	m/s
Hull Angles and coordinates				
	Alpha	α	26	deg
	Beta	β	22.00	deg
	Beta prime	β'	19.96	deg
	gamma	γ	50.40	deg
	Alpha	α	0.4538	rad
	Beta	β	0.3840	rad
	Beta prime	β'	0.3483	rad
	gamma	γ	0.8796	rad
	Symmetrical		no	text
	x coordinate	x	115.86	m
	y coordinate	y	8.1	m
	z coordinate	z	0	m
Ice Crushing Terms				
	Ice strength term	Po	1.25	Mpa
	Ice exponent (process PA)	ex	-0.1	nd
	Wedge angle	ϕ	150	deg
	Wedge angle	ϕ	2.62	rad
	form factor 1	fx	2.80	nd
	form factor 2	fa	9.62	nd
Popov Terms				
	x dirn cosine	l	0.4120	nd
	y dirn cosine	m	0.8448	nd
	z dirn cosine	n	0.3413	nd
	roll moment arm	λl	2.7648	m
	pitch moment arm	μl	-39.5445	m
	yaw moment arm	ηl	94.5386	m
	Surge Added Mass	Amx	0.0000	nd
	Sway Added Mass	Amy	0.5854	nd
	Heave Added Mass	Amz	1.1905	nd
	Roll Added Mass	Amrol	0.2500	nd
	Pitch Added Mass	Ampit	1.2258	nd
	Yaw Added Mass	Amyaw	0.6158	nd
	roll gyrad(squared)	rx2	202.9327	m2
	pitch gyrad(squared)	ry2	4645.96	m2
	yaw gyrad(squared)	rz2	4872.04	m2
	Mass Reduction Coef.	Co	1.9898	nd
	Effective mass	Me	60911244	kg
	Normal Speed	Ve	0.721	m/s
	Kinetic Energy	KEe	15835497	kg-m2/s2
	Impulse	Ie	43921745	kg-m/s
Results				
	pen(n)	ζn	1.593	m
	Normal Force	Fn	27.83	MN
	Flexural strength	σ_f	0.65	Mpa
	Maximum Force Flexural Strength	Fn,lim	14.28	MN
	Design Force	Fmin	14.282	MN
	Aspect Ratio	AR	2.548	
	Length	w	3.58	m
	Height	b	1.40	m
	Average pressure	p_{avg}	2.827	Mpa

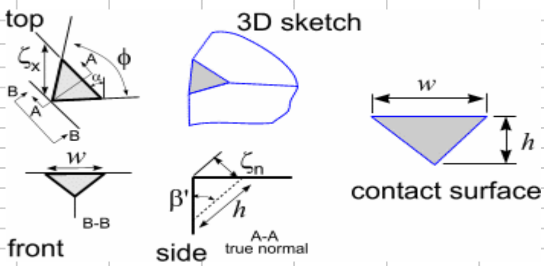
Hull Angles



Scenario

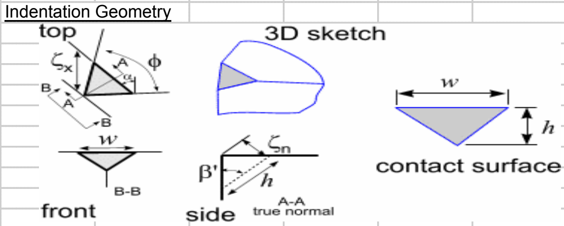


Indentation Geometry

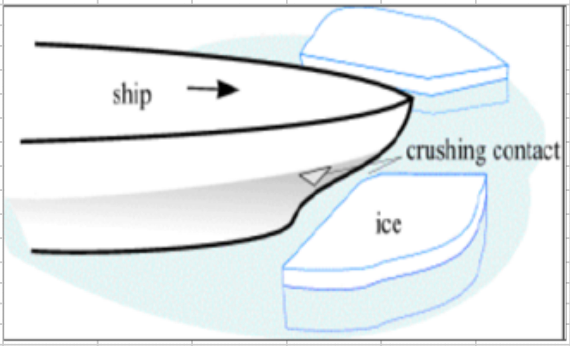


	Frame 140			
Popov Glancing Collision (Wedge Edge)				
Ship Main Parameters				units
	Ship Name	SN	Lena River	text
	Length	L_{WL}	279.20	m
	Beam	B	44.20	m
	Draft	T	12.9375	m
	Height	H	26.00	m
	Block Coef.	CB	0.749125	nd
	Waterplane Coef	Cwp	0.851425	nd
	Midship Coefficient	Cm	0.9953	nd
	Mass	M	121201	tonnes
	Ship Speed	Vs	1.750	m/s
Hull Angles and coordinates				
	Alpha	α	26	deg
	Beta	β	24.00	deg
	Beta prime	β'	21.81	deg
	gamma	γ	47.60	deg
	Alpha	α	0.4538	rad
	Beta	β	0.4189	rad
	Beta prime	β'	0.3807	rad
	gamma	γ	0.8308	rad
	Symmetrical		no	text
	x coordinate	x	111.86	m
	y coordinate	y	10.4	m
	z coordinate	z	0	m
Ice Crushing Terms				
	Ice strength term	Po	1.25	Mpa
	Ice exponent (process PA)	ex	-0.1	nd
	Wedge angle	φ	150	deg
	Wedge angle	φ	2.62	rad
	form factor 1	fx	2.80	nd
	form factor 2	fa	9.12	nd
Popov Terms				
	x dirn cosine	l	0.4070	nd
	y dirn cosine	m	0.8345	nd
	z dirn cosine	n	0.3715	nd
	roll moment arm	λl	3.8639	m
	pitch moment arm	μl	-41.5570	m
	yaw moment arm	ηl	89.1059	m
	Surge Added Mass	Amx	0.0000	nd
	Sway Added Mass	Amy	0.5854	nd
	Heave Added Mass	Amz	1.1905	nd
	Roll Added Mass	Amrol	0.2500	nd
	Pitch Added Mass	Ampit	1.2258	nd
	Yaw Added Mass	Amyaw	0.6158	nd
	roll gyrad(squared)	rx2	202.9327	m2
	pitch gyrad(squared)	ry2	4645.96	m2
	yaw gyrad(squared)	rz2	4872.04	m2
	Mass Reduction Coef.	Co	1.9023	nd
	Effective mass	Me	63713211	kg
	Normal Speed	Ve	0.712	m/s
	Kinetic Energy	KEe	16160356	kg-m2/s2
	Impulse	Ie	45379030	kg-m/s
Results				
	Normal Penetration Depth pen(n)	ζn	1.636	m
	Normal Force	Fn	27.65	MN
	Maximum Force Flexural Strength	Fn,lim	13.12	MN
	Flexural strength	σ_f	0.65	Mpa
	Design Force	Fmin	13.122	MN
	Aspect Ratio	AR	2.773	
	Length	w	3.57	m
	Height	b	1.29	m
	Average pressure	p_{avg}	2.846	Mpa

Indentation Geometry



Scenario



Hull Angles