NTNU – Trondheim
Norwegian University of
Science and Technology

The Influence of Ice Classification on Design of an LNG Tanker

Roy Andre Pedersen

Marine Technology (2 year)
Submission date: June 2013
Supervisor: Soren Ehlers, IMT

Norwegian University of Science and Technology
Department of Marine Technology

NTNU
Norwegian University of Science and Technology
Department of Marine Technology

Abstract

This thesis aims to identify and compare relevant ice classifications for LNG carriers, by means of a conceptual case study. The case study is approached from a stakeholder point of view, by attempting to link the present and future Arctic landscape with a rule-based method of comparing the weight and cost of targeted ice classes.

The current knowledge of the Arctic landscape is evaluated in order to select a realistic design scenario. The rule-based approach to design of vessel for ice-infested waters is reviewed, including a review of different classification societies ice-rules. The case is than finalized in selecting relevant target ice-classes for comparison.

The particle swarm optimization is selected and incorporated with a rule-based framework, which serves as a tool in the comparison analysis.

Finally the case study is performed and the comparison results are presented and discussed in light of applicable relevance and previous work.

Keywords: Ice-infested, LNG carrier, ice-classification, particle swarm optimization

Preface

This thesis report marks the conclusion of my two-year master program in Marin Structural Engineering at NTNU.

While working on this thesis topic, I have developed a fascination for Arctic engineering. I would like to thank my advisor Sören Ehlers for introducing me to this field, and for the patients he has for confused students like myself.

Also I would like to thank my fellow student David Molnes for the collaboration when writing the analysis tool. I would never have finished this task without your help.

Last but not least, I would like to thank my loving girlfriend Jenny. For helping me with all maters of life, and for taking care our precious Oliver.

Trondheim, June 10 2013

Roy Andre Pedersen

Table of contents

Figure list

Table list

Nomenclature

LOA = Length overall [m]

LPP =Length between perpendiculars [m]

B = Beam [m]

D = Depth [m]

Max T = Maximum draft [m]

Zp = Plastic section modulus (DNV)

h = Height of stiffener [mm]

t_{wn} = Net web thickness [mm]

A_{pn} = Net cross-sectional area [cm^2]

t_{pn} = Net shell plate thickness [mm]

h_w = Local frame web height [mm]

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

h_{fc} = Height of local frame measured to centre of the flange area [mm]

C = Factor depending on boundary conditions of plate field.

k_a = Correction factor for aspect ratio of plate field.

s = Stiffener spacing

l = Stiffener span

p = Design lateral pressure

σ = Nominal allowable bending stress

w_k = Correction factor for aspect ratio of plate field.

s = Stiffener spacing

l = Stiffener span

p = Design lateral pressure

σ = Nominal allowable bending stress

Ms = Stillwater bending moment [kNm]

Mw = Wave bending moment [kNm]

I_N = Moment of inertia in [cm^4] of the hull girder

z_n = Vertical distance in m from the baseline or deck-line to the neutral axis of the hull girder, whichever is relevant.

σ_c = Critical buckling stress

σ_{el} = Elastic buckling stress

σ_a = Actual stress

η = Usage factor

Z_β = Liquid height

P0 = Design vapour pressure (DNV)

$(p_{gd})_{max}$ = Maximum pressure in LNG tanks accounting for static and dynamic loads

a_β = Dimensionless acceleration

t_{net} = Thickness required for resisting ice loads

AF = Hull Area Factor

PPF_p = Peak Pressure Factor

P_{avg} = Average patch pressure [MPa]

σ_F = Minimum upper yield stress of the material [N/mm]

b = Height of design load patch [m]

l = Distance between frame supports [m]

1 Introduction

In this thesis the weight sensitivity of ice classifications for LNG carriers is performed, by means of a rule-based analysis tool. The tool was specifically written for this task, and uses a particle swarm optimization algorithm to optimize a selected midship section.

Previous studies have indicated that significant increases in structural weight can occur, when adding higher levels of ice fortification. In a study of the structural integrity of cargo containment systems in LNG carriers (Kwon, Jeon, et al., 2008), an increase of about 4-6% was found when changing scantling compliance from Baltic Class Ice 1A to IACS Polar Class 7. This is a significant increase in weight, especially since the classes are considered to have equal performance. An increase of this degree will for a merchant vessel result in a proportional reduction in payload capacity. This poses a challenge in a conceptual engineering phase, as equivalency between classifications does not necessarily translate to similar structural mass and therefore cost. In an attempt to find an approach to this complex problem, a method was suggested in a report for the Krylov Shipbuilding Research Institute (E. M. Appolonov, Nesterov, Paliy, & Timofeev, 2007). It suggests a system of determining classification equivalency, by comparing class requirements for frame cross sectional area, with one spacing plate flange width, in the ice belt. In this method the determined cross section is weighted according to area in the ice belt and averaged. The method was, amongst other things, used to compare hull mass weight. In the report it is noted: "The problem of estimating ice strengthening structure weight is especially important for ships of new types that do not have close analogies, such as large Arctic tankers and LNG carrier". This thesis aims to contribute to this area, by performing a realistic case study of the impact of ice classifications for LNG carriers. It does this by using a rule-based comparison on a complete midship section while accounting for both local and global requirements. Another approach to comparing class equivalency was performed by the Helsinki University of technology and Lloyd's Register(Bridges, Hasolt, Kim, & Riska, 2005). This study approached this problem by comparing the principal scantlings between the Russian Register Rules and the IACS unified requirements, for a selected case study in the Russian Varandey region. Similar to the previously mentioned study, this approach deals only with ice-strengthened regions. Neither of the above studies accounts for changes in local and global scantlings outside these regions. With this thesis a contribution to this area is provided, by the motivation of a case study presented in the thesis. A rule-based optimisation tool is developed, which accounts for local and global requirements both inside the ice reinforced regions and outside.

The rule-based analysis tool created during the process of this thesis is described in great detail in chapters 6-8, with the intention of serving as a manual for others whom may wish to use this tool for similar purposes. Finally the case study is performed and the comparison results are presented across classifications and class levels. The results are then discussed against previous equivalence studies and lessons learned during the process.

2 The Arctic landscape

2.1 Geographical definition

The Arctic is an area consisting of an ocean surrounded by islands and continental landmasses. Snow and ice are present on land for most of the year, while the central Arctic Ocean is consistently covered by ice. There are several geographical definitions of the Arctic boundary, such as the Arctic Circle, the treeline and the 10 degrees Celsius line. The Arctic Circle is the northernmost of the five circles of latitude surrounding the earth. North of the Arctic Circle the sun can remain above or below the horizon for 24 continues hours at least once a year. The treeline is defined by the upper limit of upright tree growth, while the 10 degrees Celsius line is defined by locations in high latitudes where the average daily summer temperature does not rise above 10 degrees Celsius. The two latter descriptions of the Arctic correspond roughly to the same geographical description.

2.2 Infrastructure

The infrastructure in the Arctic is limited in comparison with other regions of the Earth. In the following subchapters the broad concept of infrastructure will be limited to those related to marine operations. Information contained within this section is to a large extent based on the Arctic Marine shipping assessment report of 2009 (Assessment, 2009).

2.2.1 Hydrography

Hydrography is the science of surveying and charting bodies of water. Modern marine charts are compiled with hydrographical surveys and various other sources of information, including shoreline locations and conspicuous land based features. Data on navigational charts are also corrected for the movement of tides, such that the depth portrayed is normally the minimum the mariner will find under the keel. It is therefor safe to say that, in order to safely navigating any ocean; there is a need for accurate and predictable hydrographical data.

Producing accurate navigational charts is a process that can take several years and requires a significant amount of data. When compared to temperate waters, there are numerous environmental factors that make it exceptionally difficult to navigate and collect hydrographical data in the Arctic. These factors include the presence and movement of sea ice, icebergs, cold air and water temperatures. This is why large areas of the Arctic are still lacking accurate hydrographical data. The areas that have been surveyed to a greater extent are along the main trade routes: The Northern Sea Route (NSR) and the Northwest Passage (NWP). Figure 1 The Russian Federations, chart coverage of the Arctic.

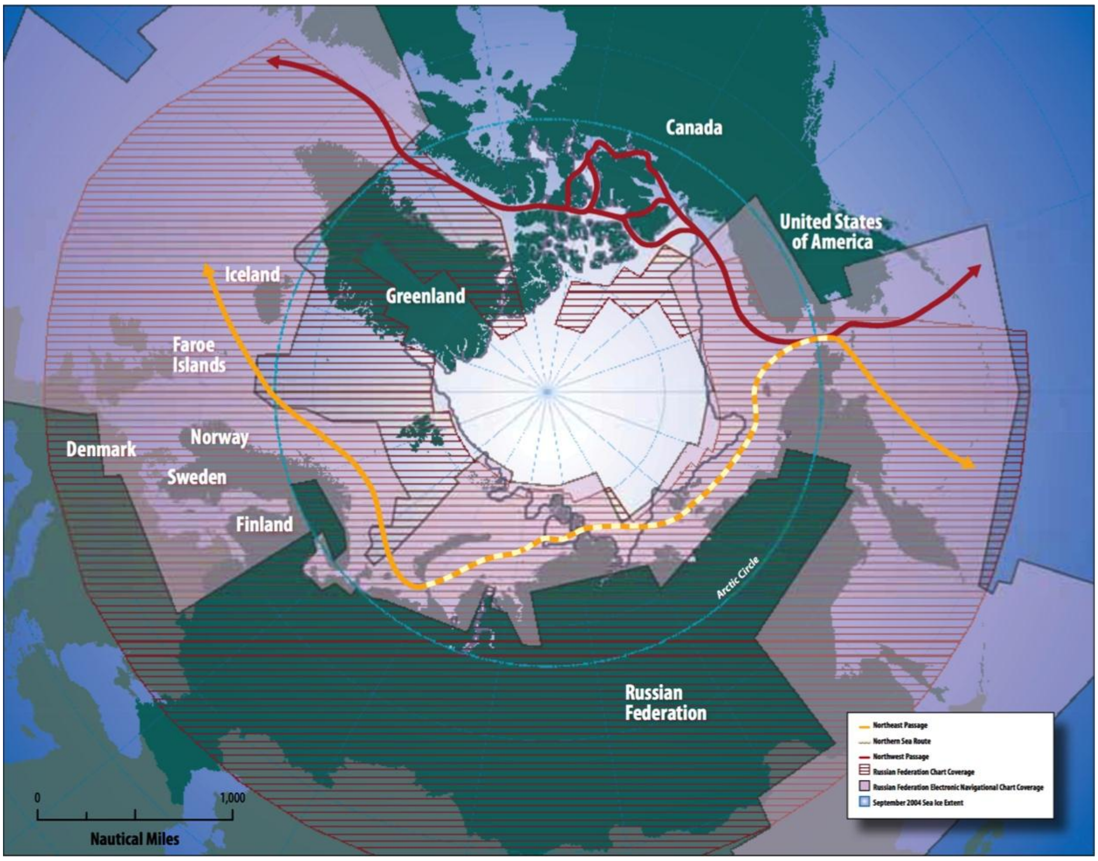


Figure 1 The Russian Federations, chart coverage of the Arctic.

2.2.2 Trade routes in the Arctic

Trade routes are pathways and stoppages used for the commercial transport of cargo. As previously mentioned, the main trade routes used for navigating ships in the Arctic are the Northern Sea Route (NSR) and the Northwest Passage (NWP). The NSR stretches along the Eurasian side of the Arctic, while the NWP is located along the American side. Due to changes in the Arctic sea ice extent, it might be possible to navigate more direct routes in the future. One such route might be across the North Pole, which has already been navigated by icebreakers during summer.

If a vessel is to navigate along the NWP, the Canadian Government has implemented regulations for the Canadian Arctic. The so-called Arctic Shipping Pollution

Prevention Regulations (ASPPR) is based on two different approaches for dealing with a vessel in different ice conditions at different times of the year. These systems are the Zone-Date System (ZDS) and the Ice Regime System (IRS). The ZDS is gives entry and exit dates for various ship types and classes into the Shipping Safety Control Zones. This is a very rigid system that does not take into account seasonal changes, which is why the Ice Regime System compliments it. The Ice Regime System determines whether or not a given vessel should precede through that a particular ice regime, based on a numerical value. This value is calculated from a simple calculation, based on quantity of hazardous ice with respect to the ASPPR classification of the vessel (Timco, Collins, & Kubat).

When navigating through the NSR the Russian Ministry of Transportation have issued rules for which vessels must be certified. This is a comprehensive certification, which is specific for season and trade route. There are different requirements for what level of ice strengthening is needed. This will depend on the sea area and at what season the vessel intend to navigate it. It should be mentioned that these ice-strengthening levels refer to the Russian Register rules. This would suggest that vessels navigating the Russian arctic needs to be designed according to these rules, or equivalent rules. This will be discussed in detail at a later point in the thesis. The rules also have draft and beam limitations for vessels. The draft limitation has been set to 15 metres due to uncertainties in their hydrographical information, and the beam limitation is set to the width of their icebreakers. In the case of wider vessels needing icebreaker support, two icebreakers will create the necessary channel width.

2.2.3 Icebreakers

Icebreakers are crucial in the development of the Arctic. Generally icebreakers perform a variety of different tasks essential to Arctic operations. Some of these tasks include maintaining shipping tracks in ice-infested waters, close escort shipping in ice, provide ice information and perform as a Science platform.
There are some 50 icebreakers in the world, where the Russian fleet is by far the largest and most powerful. Russia currently has five 75.000 shaft horsepower nuclear icebreakers, and is expanding their fleet with more in the near future.

2.2.4 Ports and intermodal transport links

For marine operations deep-water ports, places of refuge, marine rescue and adequate port reception facilities for ship-generated waste and towing services are necessary. The availability of these infrastructure components is limited in the Arctic, in comparison with temperate waters.

The distribution of deep-water ports is in general better on the Eurasian side of the Arctic then the American, but near the Bearing Strait there are very few ports on either side. On the Russian side the nearest deep-water port is Provideniya, followed by Egvekinot, Anadyr and Beringovsky, while on the American side the only deep-water port is Dutch Harbour.

On the Atlantic side of the Arctic, the number of deep-water ports is much higher. Especially on the Eurasian side of the Atlantic, where there are several ports to accommodate large vessels in Norway, Greenland, Iceland and Russia. In Russia, Murmansk is the largest deep-water port north of the Arctic Circle, which is ice-free throughout the year. The port provides intermodal access to northern European and Asian industrial centres. Other Russian Arctic ports along the Northern Sea Route include Pevek, Tiksi, Igarka, Dudinka, Dikson, Vitino, Arkhangelsk and Novy. These ports are well established and provide icebreaker support. Along the North Slope of Alaska and throughout the Canadian Archipelago there are essentially no deep-water ports, the exceptions being Tuktoyaktuk and Resolute Bay. These ports do however have some shortcomings. Tuktoyaktuk suffers from a shallow approach channel and a high degree of in-fill silting due to its proximity to the Mackenzie River, and Resolute Bay has limited port facilities and can only handle ships of 5-meter draft. In the Hudson Bay, the Port of Churchill is Canada's only northern deep-water port with well-sheltered facilities. It provides access, via rail, to the interior of Canada and North America in general. Also on the east coast of Canada is Iqaluit, which requires that ships anchor and use barges to land their cargo.

2.3 Petroleum reserves in the Arctic

2.3.1 Confirmed petroleum reserves in the Arctic

There are currently several large natural gas and oil reserves discovered within the Arctic Circle. The majority of these reserves are under the jurisdiction of four different countries, Canada, Russia, Alaska and Norway. In terms of production, Russia is by far the larges oil and gas producer in the Arctic, followed by Alaska. To illustrate the distribution of petroleum for the Arctic region, models published by Statistics Norway (Lindholt & Glomsrød, 2011) is presented in Figure 2. These models have been developed based on actual production rates, and include predictions towards 2050.

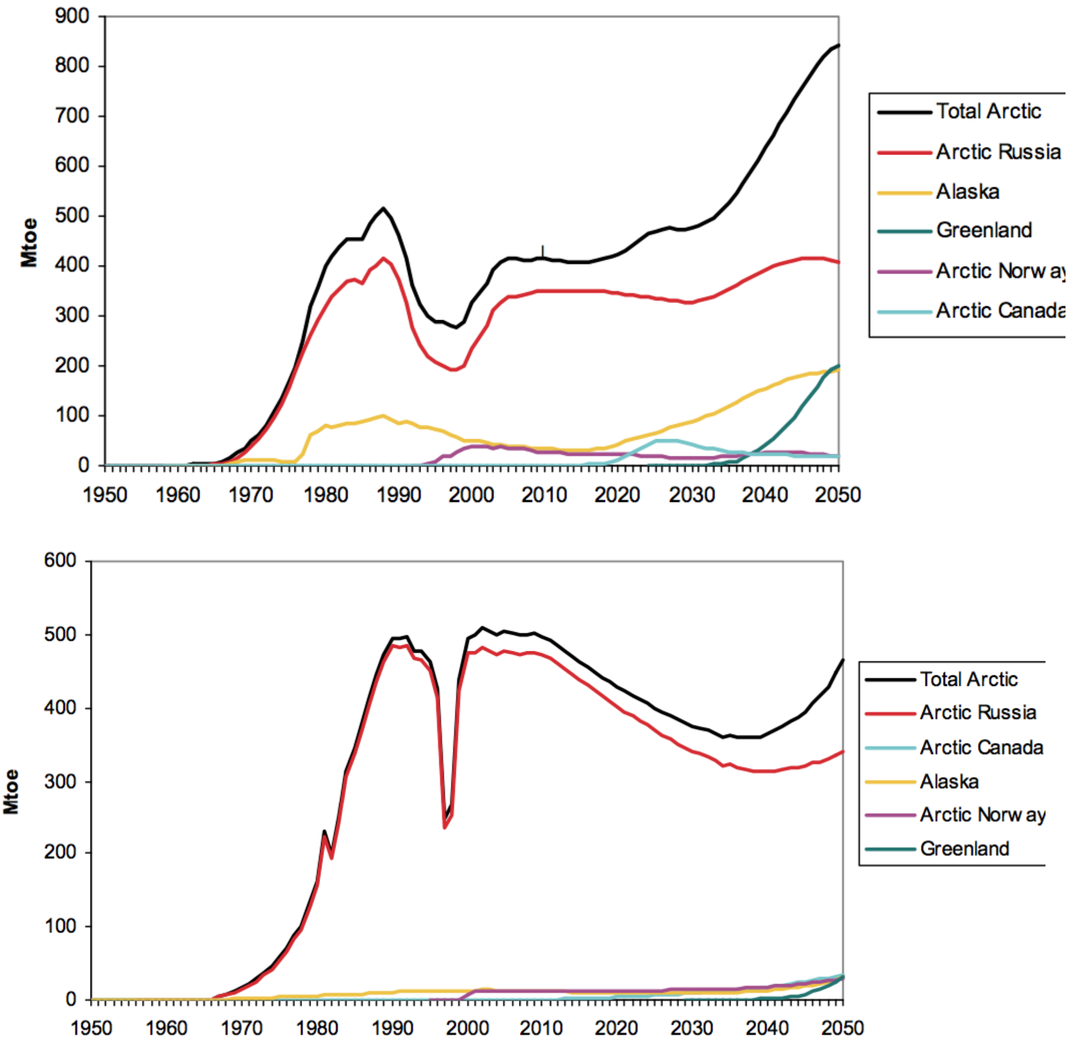


Figure 2 The annual production natural gas (bottom) and oil (top) in the Arctic

2.3.2 The future of petroleum exploitation in the Arctic

In May 2008 U.S. Geological Survey completed their evaluation of the petroleum potential of all areas north of the Arctic Circle. They concluded that about 22% of the worlds undiscovered petroleum may be located in the Arctic, mainly offshore in less then 500 meters of water.

The survey was conducted using a compiled map of Arctic sedimentary basins. This map contained more then 3 km of sedimentary date, for different geological provinces. The data was then analysed using probabilistic methodology of geological analysis and analogue modelling. The output of this survey has been presented in three maps of 25 provinces in the Arctic, showing the relative probabilities for the estimated potential for undiscovered oil and gas. These maps show the probabilistic distribution of undiscovered natural gas in the arctic. From this the survey it was determined that 70% of the mean undiscovered natural gas is located in three provinces, the West Siberian Basin, the East Barents Basin and Arctic Alaska. Further they determined that 84% of these natural gas resources are located offshore. Figure 3 gives a graphical presentation of the undiscovered petroleum in the Arctic. Darker colour represents higher concentration.

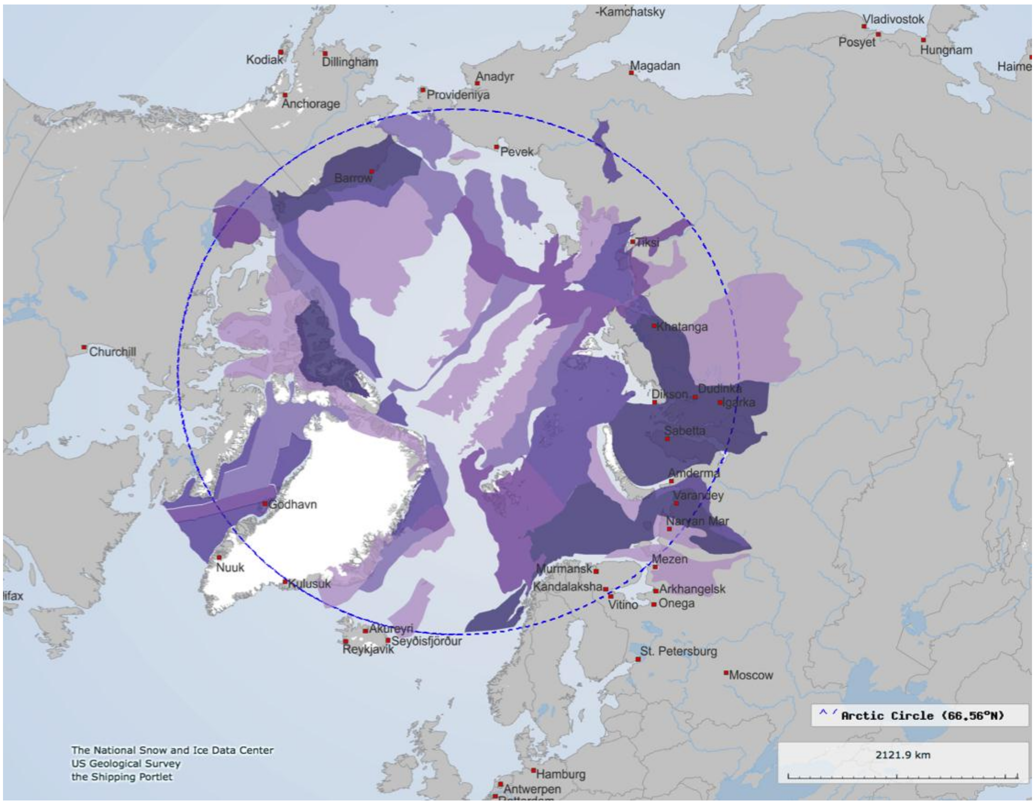


Figure 3 The distribution of undiscovered petroleum in the Arctic

According to a report by the International Energy Agency (Birol, 2011), there will be an increase in natural gas demand from 21% of the world's fuel mix in 2008 to 25% in 2035. At this rate, including the effect of decline in global coal demand, the report estimates that global natural gas demand will become the second larges fuel in the primary energy mix by 2030.

2.3.3 Transportation of natural gas

When transporting natural gas from a reserve to the intended market, two different approaches are used. The preferred method of transportation is pipelines, which require less processing than transporting the gas as liquefied natural gas (LNG). Whether the product is transported through pipelines or as LNG depends on several factors, but distance and location is the most important considerations. Even though the process of liquefying, shipping, regasification and storage is costly, this becomes cheaper than transporting natural gas in offshore pipelines for distances of more than 700 miles or in onshore pipelines for distances greater than 2,200 miles (Foss, 2007). It is also a more flexible method of transportation, which means that LNG can be transported where it is needed in a fluctuating marked.

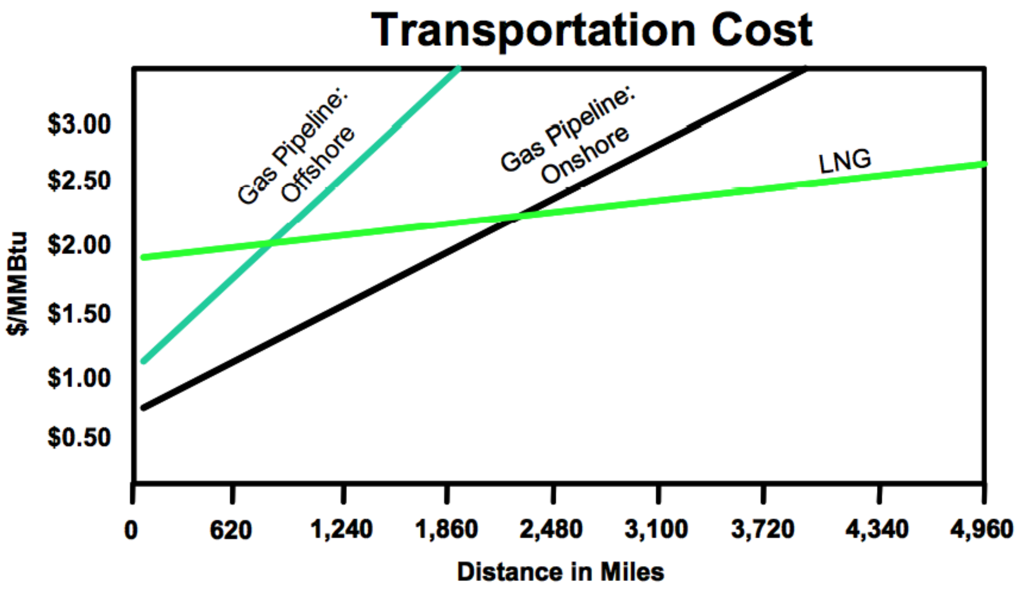


Figure 4 show the cost per distance for pipeline and LNG

2.4 Reflective summary

The Arctic holds large quantities of natural gas and oil, which is likely to gradually be developed as demand increases and more accessible sources are depleted. There are however large obstacles that need to be overcome, especially for areas with little or no infrastructure. A region of the Arctic that is likely to be developed their undiscovered recourses sooner than others, is the Russian Arctic. The reason for this is that this region already has much of the infrastructure needed for these kinds of operations, and has some of the largest undeveloped deposits of natural gas in the world. There is also reason to believe that much of this natural gas will be transported to the world markets via LNG carriers, due to the reclusive nature of the deposits. In design an LNG carrier for the Russian Arctic, it is necessary to strengthen the ships hull according to the Russian Register rules. There are however changes in the Arctic climate, which may affect these regulations in the future. In order to access these changes, an overview of historical and future predictions of the Arctic sea ice is presented.

3 Arctic sea ice

3.1 Arctic sea ice extent and annual reduction

Historical data regarding sea ice extent in the Arctic dates back to records assembled by the Vikings. They recorded the number of weeks per year that ice occurred along the north coast of Iceland. Today, scientists studying Arctic sea ice trends can rely on a fairly comprehensive record dating back to 1953, using a combination of satellite records, shipping records, and ice charts from several countries.

The change in extent of sea ice in the Arctic is a seasonal phenomenon. During the winter the sea ice usually reaches its maximum extent between February and April. After this the ice starts to melt and reaches its minimum extent between September and October. The National Snow and Ice Data Centre (NSIDC) monitors and updates these change daily. Data collected by the NSIDC for the annual minimum and maximum sea ice extent since 1979, indicates an average decline of -7.1% per decade in the Arctic (Figure 5).

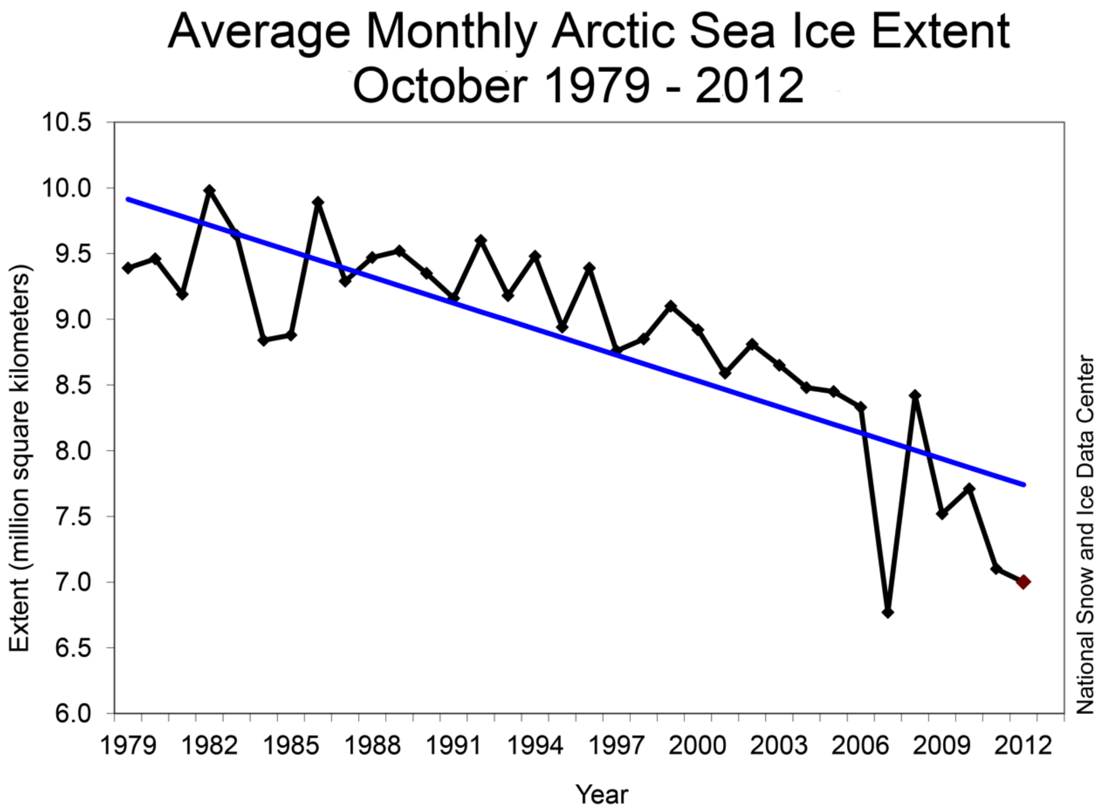


Figure 5 The average monthly Arctic Sea ice extent October 1979-2012

After the minimum ice extent the Arctic gains ice rapidly, although the ice growth rate is not the same everywhere. In 2012, the Beaufort and Chukchi seas averaged about 8,500 square kilometres per day and large areas still remain ice-free. While in the eastern part of the Arctic there was rapid ice growth in the East Siberian and Laptev seas exceeding, respectively, 28 and 18 square kilometres per day. According to NSIDC, research regarding ice growth rates indicates that the sea floor bathymetry plays an important part in the Arctic sea ice formation and extent. When the ice extent is at it's minimum, it usually corresponds to the deep/shallow water boundary at approximately 500-meter depth ("Arctic rapidly gaining winter ice," 2012).

Even though the average sea ice extent has declined significantly, this is mainly due to minimum ice extent. The maximum sea ice extent has also declined during the last decades, but to a lesser extent (approximately 2,9% reduction). This is partially due to the change in the current system from anti-cyclonic to cyclonic which occurred in 1997. This causes a large transport of ice through the Fram Strait during the melting season. The cyclonic current system also affects the ice thickness growth, due to shorter freezing time.

3.2 Sea ice thickness growth

There are two phenomena that change the thickness of sea ice, thermodynamics and dynamics. Thermodynamics is responsible for the mass growth on the upper and lover surfaces of the ice, and the mechanical process of ice dynamics causes the formation of leads and pressure ridges. If ice deformation could be neglected in a particular climatic region, the ice would grow uniformly. It would then be possible to predict the thickness by determining the thermodynamic equilibrium.

The stage of which sea ice forms starts with the formation of ice crystals on the sea surface. As these ice crystals increase in number they form a thick slush that eventually becomes what's referred to as pancake ice. Once an ice sheet is has formed the thickness increases by the freezing of water on the submerged surface. This process is due to the transfer of heat by conduction from the water to the air. The rate at which heat flows from water is proportional to the temperature difference between air and water, and inversely proportional to the thickness of the ice. Another factor important to the growth rate is the amount of snow on the ice. Snow can be an efficient insulator if it is in a non-compact form, due to the high air content.

Sea ice deformation is the main cause of extreme thickness formations. The brittle nature of ice makes it sensitive to thermal changes and forces exerted by wind and currents. These environmental factors causes ice sheets to break up and form leads of open water. When these leads close, pressure ridges are formed. Pressure ridges are divided into to parts, below and above the sea surface. The keel is the submerged part of the ridge and is typically extending 4 to 5 times further downwards then the sail, which extends upwards. The reason for this 5 to 1 ratio is because of the relative density of the ice and water. A newly formed pressure ridge does not have this ratio and is therefor in unbalance. As a result it has to sink to obtain equilibrium. Consequently pressure ridges are highest when first formed. Ridges have been observed with keel drafts of 47 meters and sails of 13 meters.

3.3 Prediction of sea ice thickness in the Arctic

When charting a vessel through ice-infested water, it is necessary to have knowledge of the expected sea ice thickness along the charted route. As previously discussed the distribution of sea ice thickness is non-uniform. The distribution of ice thickness will also, as with the sea ice extent, change during the course of a season. These changes are difficult to foresee, and several attempts on long-term and short-term predictions have been made.

The first complete research study of the distribution of sea ice thickness in the Arctic was completed in 1986 by Robert H. Bourke and Robert P. Garrett (Bourke & Garrett, 1986). They collected all the then current analysed Arctic sea ice data and compared it to data compiled from 17 submarine cruises. Before this study existing knowledge had been confined to particular regions during a given time period. With this data they made estimates of the distribution of sea ice thickness and the seasonal variations. Figure 6 shows the distribution of Arctic Sea ice as derived from submarine date in summer (left) and autumn (right). However there have been dramatic changes in the Arctic since these results were presented.

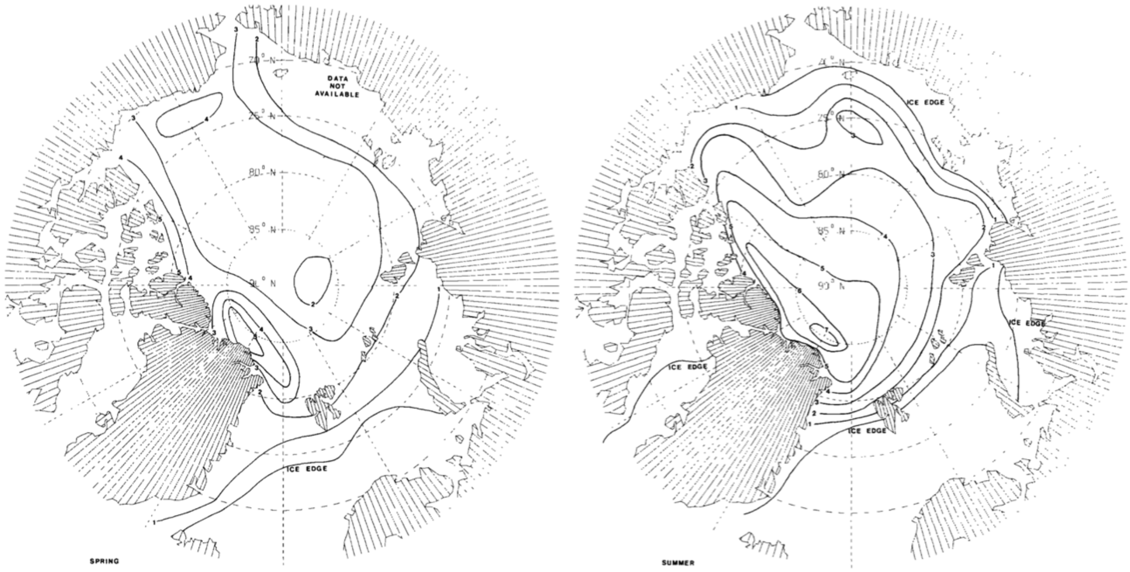


Figure 6 The distribution of Arctic Sea ice thickness 1986

Since 1986 new methods of measuring and predicting sea ice thickness have been develop. One such method is the use of satellites to estimate ice thickness. The Ice, Cloud, and Land Elevation Satellite (ICESat) use a so-called lidar to measure the freeboard of the ice. There are however an inherent uncertainty in this approach. When measuring the freeboard the lidar can’t distinguish between ice and snow, which means that rough estimates of snow depth and density has to be made. The ICESat was decommissioned in 2010 and is currently replaced by aerial observations until ICESat-2 is launched in 2016.

A more common method for predicting ice conditions in the Arctic is the use of coupled ice-ocean models. Several of these models are publicly available and can give good predictions of Arctic sea ice conditions. However, an accuracy study of coupled models (Kwok, Hunke, Maslowski, Menemenlis, & Zhang, 2008) has determined that the models have several shortcomings. The study compared four coupled models and high-resolution kinematics from satellites, concluded that the models were non-conservative in estimating deformation-related volume production.

In order to determine how the sea ice thickness in the Arctic is changing, a study where the mentioned submarine records was compared with data collected by the ICESat satellite has been performed (Kwok & Rothrock, 2009). This study determined that there has been a significant reduction in the mean average annual thickness, within the last 50 years. Comparing the average from 1980 to 2008, there has been a reduction of 1,75 meters (Figure 7). The large decrease in thickness during the last years is due to the significant reduction in multi-year ice (ice that has survived at least one melting period). It is therefor a correlation between the reduction in ice thickness and the previously discussed decrease in minimum ice extent.

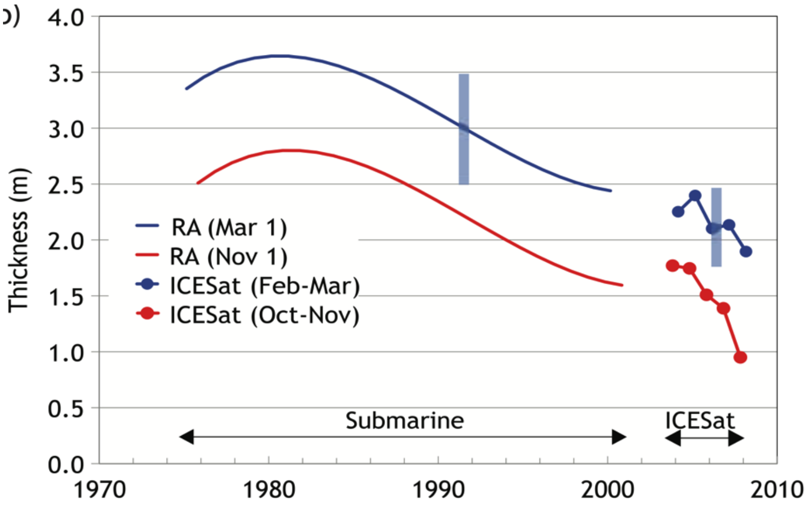


Figure 7 The collected submarine records with the ICESat data

3.4 Reflective summary

The change in the sea ice extension and the average thickness suggests that Arctic is becoming more navigational friendly then earlier. Longer ice-free periods will allow ships with lower ice-classifications to freely navigate areas for longer periods of time. For ships navigating through the Arctic during the winter season, there will still be a need for proper levels of hull strengthening and propulsion power. In order to determine how the level of ice fortification is determined and implemented the following chapter will present the current approach to the design of ships for ice-infested waters.

4 The design ice load

Designing a vessel for ice-infested waters, require that all features be designed for the task. Special considerations will have to be made to obtain adequate performance in ice and cold weather. Design of the hull is one such consideration. The hull has to enabling low resistance and manoeuvrability in ice, as well as being strong enough to resist the added load of the ice. The adequate strength of the hull is usually achieved by selecting a proper ice class for the predicted conditions along a trade route. The ice classes that determine the level of ice strengthening are different for each classification society, but the method of defining the design ice load is similar. That the design rules for ice strengthening are based on is similar for the different classification societies. But the implementation is different.

4.1 Ice loads

The interaction between sea ice and an offshore structure is commonly referred to as the ice load. The ice load is a complex process involving compressive, flexural, shearing and frictional forces. Describing this interaction has been a controversial topic in the research community, and to this day there are no accurate analytical methods implemented in classification standards. The method currently used to describe ice loads is the load patch approach.

4.1.1 The load patch

Ice loads typically arise from contact with an ice edge, which is assumed to mostly act on a load patch. This load patch is assumed to be narrow in the vertical direction and long in the horizontal direction. The actual load patch is an irregular shape, but is idealized as a rectangle for structural response calculation of local shell structures like plating, main frames, stringers and web frames (Figure 8).

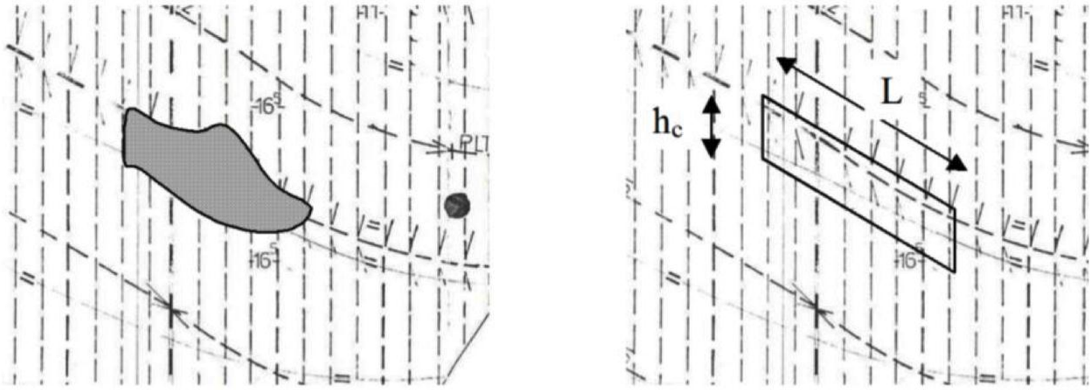


Figure 8 The actual and idealized load patch

When designing a structural member, the design load patch is placed at a location giving the largest response. As an example, for a plate the load patch would be placed symmetrically at the centre of the plate field and for a frame at the midspan. When performing this simplified approach, special attention should be given to the boundary conditions used.

Using a this simplified approach of structural idealization, is justified in the case of ice loading, as the benefits of more advanced methods disappears in the inherent uncertainty concerning the ice load values. In using the simplified patch load method there are three quantities describing the local ice pressure, the pressure p_c, load height h_c and load length.

4.1.2 Ice pressure

Methods for describing the ice pressure is specified in the individual classification rules, but a general overview of the two most common methods will be reviewed her.

A method of estimating the ice pressure is a Russian model based on the crushing of ice. The highest ice pressure values are coupled with ice failing by crushing. When analysing the flow of crushed ice, it was found that it behaved as a viscous flow.

Based on this assumption and Reynolds thin film fluid flow equation, an expression has been developed:

$$p \propto \left(\left(\frac{h_c}{2} \right)^2 - x^2 \right)^{1/4} \quad \text{Equation 1}$$

The drawback of this method is that the proportionality factor x, depends on assumptions made from empirically obtained ice strength tests done in ball drop experiments. These assumptions include viscosity, uniform film thickness and uniform source of crushed ice. This method is used in the Russian Register rules and in the unified requirements developed by the International Association of Classification Societies.

The second method for estimating the ice pressure is based on the pressure-area relationship. This relationship suggests that the average pressure on an area is dependent on the magnitude of the area. An expression has been suggested for the upper limit for this pressure-area relationship:

$$p_{av} = 8.1 \times A^{-0.57} \quad \text{Equation 2}$$

The constant and the exponent in this equation have been studied for their validity, since the expression was purposed. These studies showed that the constant varied between 2 and 10, while the exponent varied between -0,3 and -0,6. The drawback of this method, as with the first, is that it is empirically based and little physical basis exists for the area dependence.

4.1.3 Load height

As previously mentioned the dimension of the load patch is difficult to determine. As an example The Finnish-Swedish ice class (FSICR) rules have gone thru some varieties of the load height. It was first defined as the full thickness of the ice, while it is now significantly smaller. The reasoning behind the definition of load height in the FSICR is related to an extensive ice damage survey in the 1970's. The survey estimated a line load of 2 MN/m, and assumed that the load was acting over the full thickness. But this proved to underestimate the load for several structural elements. So the load height was reduced while the line load was kept ensuring that the design load increased.

4.2 Reflective summary

In defining the design ice load, the first step of understanding the approach to designing a ship for ice-infested waters has been presented. But in order to determine what classification rules and classes to use for the case study, a review of relevant classification societies will be presented in the next chapter.

5 Classification societies

5.1 The Finnish-Swedish Ice Class Rules

The Finnish-Swedish Ice Class rules (FSICR) has been developed specifically for seasonal ice in the Baltic, but have been adopted by most classification societies as the standard for ships navigating in first year ice(Agency, 2010). The FSICR are divided into three main parts that covers performance, hull strength and machinery strength of ships in ice. This review will focus only on the rules for hull strength.

5.1.1 The class system

The class system in the FSICR is divided into four ice classes: IA Super, IA, IB and IC. Where the IA super has the highest strength level, and IC the lowest. The classes corresponds to different levels of ice thickness, from 1 meter for the 1A Super to 0,6 meter for the 1C. The design scenarios these thicknesses are based on are collision with a channel edge (icebreaker escort), or/and a consolidated layer of older ridges. Table 1 shows the ice classes and the corresponding design ice thicknesses.

Ice Class	**Thickness of brash ice H_M**
1A Super	1.0 m and a 0.1 m thick consolidated layer of ice
1A	1.0 m
1B	0.8 m
1C	0.6 m

Table 1 Class description for the Finnish-Swedish ice class rules

5.1.2 Structural Requirements of the FSICR

5.1.2.1 Hull regions

To account for the differences in ice load magnitude the ship hull is divided into regions (Figure 9). There are three main regions, the bow, midbody and stern. Each of these regions then subdivided into three longitudinal regions. The different regions have a design pressure defined by a class specific hull region factor c_p. This factor is included in the design ice load, and accounts for the probability that the design ice load occurs in specified region.

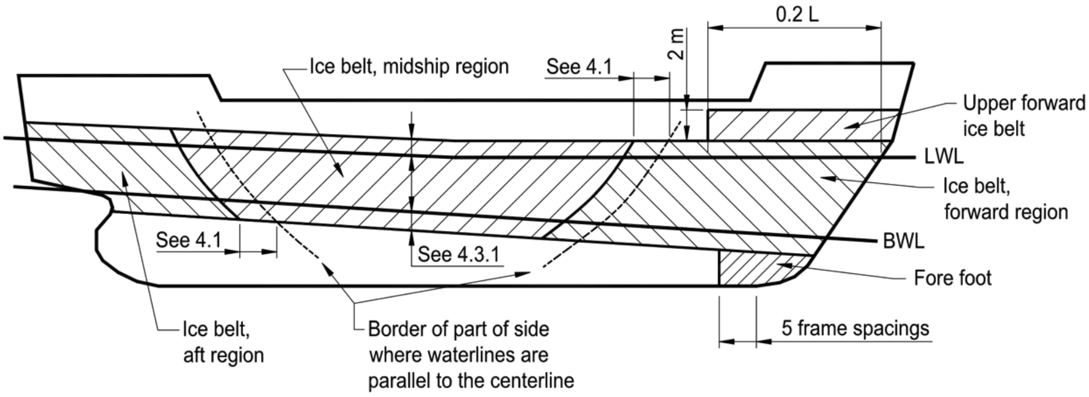


Figure 9 Hull regions according to the FSICR

5.1.2.2 Design ice loads

The design ice load is dependent on an ice pressure and a load area. To obtain the ice pressure, the nominal ice pressure is multiplied with three design factors. The nominal ice pressure has been set to the fixed value of 5,6 MPa through a series of empirical tests. The multiplication factors are then introduced to account for different design elements. Accounting for the influence of the size and engine output (c_d), the probability that the design ice pressure occurs in a certain region (c_1), the previously discussed c_p factor and the probability that the full length of the area under consideration will be under pressure at the same time (c_a). The c_d and c_1 are both determined for different regions, but the c_1 is also dependent on ice class. The c_a is a function of the load length (l_a) and determined for different structural elements.

The load area, which is determined by the load height and length, describes the area of which the ice pressure is distributed. The load height is specific for the different ice classes, and is lesser then the corresponding ice thickness. The load length is as mentioned structurally dependent.

5.1.2.3 Shell Plate Requirements

The equations in FSICR for shell requirements are similar to equations used to determine tire-loads on car decks. These equations use an elastic limit-state. The rules differentiate between transversely, and longitudinally framed regions, by use load height dependent factors. The pressure used in these equations (Equivalent pressure), is the ice pressure multiplied by a factor of 0,75. The reasoning behind this is related to the distribution of pressure over a plate panel.

5.1.2.4 Frame Requirements

The frame equations are based on classic beam theory and are therefor based on elastic formulations.

In the frame requirements for the FSICR it is distinguished between transverse frames and longitudinal frames. These share similar equations for the section modulus (Z) and the shear area (A), but the equations for longitudinal frames include factors depending upon load height and frames spacing. Other factors that is common for both are the m, which depends on boundary conditions.

Ice stringers are divided into stringer within and outside the ice belt. These have similar formulations as the longitudinal frames, but with have different distribution load factors.

For the web frames the section modulus and shear area are calculated by the load transferred by adjacent members. Additional factor given by shear area ratio and load height ratio.

5.2 The International Association of Classification Societies PC rules

The International Association of Classification Societies (IACS) is and organisation governed by a council, where each member is represented by a senior management figure. Under the Council is the General Policy Group (GPG), which is made up of a senior manager from each member. It is this group whom develops and implements actions giving effect to the policies, directions and long term plans of the Council. IACS’s technical work is undertaken generally through specialist Working Groups overseen by the GPG. Members of IACS include ABS, DNV, GL, and RMRS.

5.2.1 The class system

The IACS Unified Requirements (UR) for Polar Class (PC) ships refers to a set of seven polar classes(Societies, 2011). Where PC1 is the highest-class notation and PC7 is the lowest. The reason for having seven classes is to allow a range of operations covering both existing trades and future ones. The definition of these classes is generic, as ships from any of the classes may operate safely in a wide range of actual conditions depending on season and area. Table 2gives an overview of the design ice conditions corresponding to the different classes.

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

Table 2 The definition of the different Polar Classes according to IACS

The differences in the classification levels are mostly governed by the thickness of ice, as there is a direct connection between ice thickness and the required ice strengthening. The IACS rules are based on Arctic navigation with limited icebreaker assistance. The rules do not have explicit icebreaker classes, but provides additional requirements that assure an icebreaker notation.

5.2.2 Structural Requirements for Polar Class Ships

5.2.2.1 Hull regions

The hull is divided into regions reflecting the magnitude of the loads that expected to act upon them. This method is implemented into all the polar classes. In the longitudinal direction the hull is divided in four regions, bow, bow intermediate, midbody and stern (Figure 10). These regions are further divided into sub-regions in the vertical direction; the sub-regions are bottom, lower and ice-belt. Not all vertical sub-regions are included in the lower classes. PC4 to PC7 does not include the bottom for the midbody, and PC6 to PC7 does not include bottom for the stern.

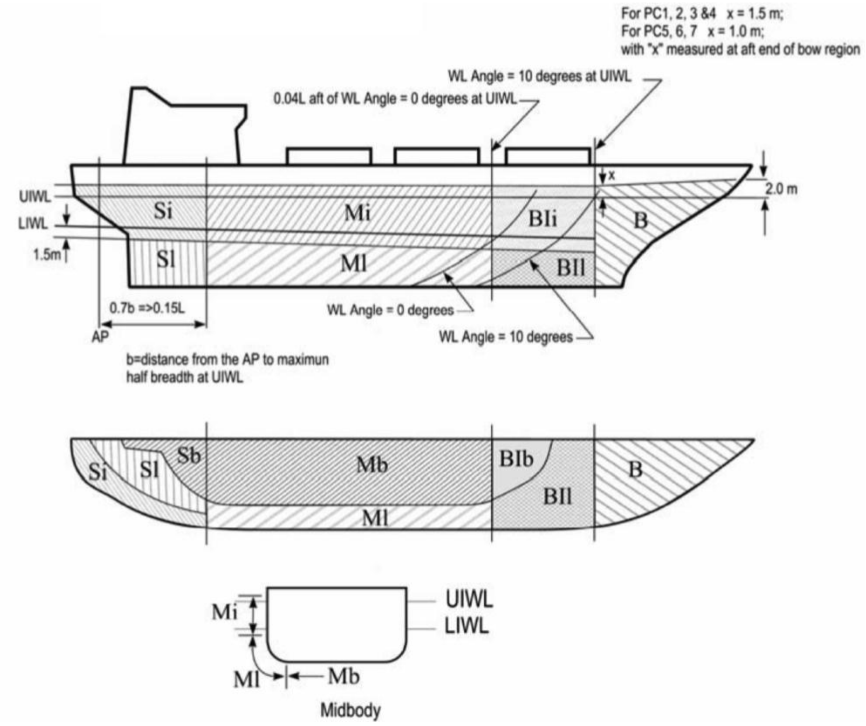


Figure 10 Hull regions according to the IACS unified requirements

5.2.2.2 Design ice loads

The design scenario for all Polar classes is a glancing impact on the bow. It is this scenario that determines the scantlings required to resist the ice loads. The design ice load is based on the average pressure (P_{avg}) uniformly distributed over a rectangular load patch. The equations used are based on an energy model, where it is assumed that the ship penetrates the ice and glances away.

The ice load parameters (P_{avg}, height (h) and width (w)) are, for the bow and intermediate bow ice-belt (PC6/7) functions of the bow shape. This is not the case for other regions, where the load parameters are calculated independently from the shape factor and with a fixed aspect ratio for the load patch (AR = 3,6). When calculating the ice load parameters for all the sub-regions in the bow, it is also required to calculate the total glancing impact force (fa_i), line load (Q_i) and pressure (P_i).

In the calculations for the shape factor, force, line load and pressure there are parameters related to the glancing impact load. These parameters are class specific and are only valid for ships with icebreaking bows. The coefficients are divided into five categories and descend in severity according to class.

Areas of higher, concentrated pressure exist within the load patch. In general, smaller areas have higher local pressures. Accordingly the peak pressure factors (PPF) have been introduced to account for the pressure concentration on localized structural members.

5.2.2.3 Shell Plate Requirements

When developing the approach for minimum plate thickness, an ultimate strength criterion was utilized. The analytical model is developed by simulating a plate in the ultimate state as a set of rigid parts connected by rectilinear plastic hinges formed by two-side corners of the plate surface kink (E. Appolonov, 2000).

The required minimum shell thickness is a sum of the thickness required to resist the ice load (t_{net}) and an added thickness against corrosion and abrasion (t_s). The t_{net} depends on the average patch pressure, orientation of the framing, location of the plate and PPF. The added thickness against corrosion and abrasion is a class specific supplement, specified by the hull areas.

5.2.2.4 Frame Requirements

In developing the design criteria for frames in the UR, a plastic design method was chosen. This is also utilized in the RMRS and the Canadian Administration. The reason for this approach was based on the methods ability to ensure a better balance of material distribution, relative weight improvement and its applicability on damage analysis.

The mathematical relationship used in the UR is directly derivable from rigid-plastic energy-based collapse analysis methods (Kendrick & Daley, 2000). This type of analysis assumes small displacements, inherently neglecting strain-hardening effects. When deriving the UR critical energy-absorbing mechanisms was chosen; a pure bending hinge, a shear hinge and a combined shear/bending hinge. The UR has also accounted for the occurrence of structural instabilities, such as buckling or tripping.

In the design approach for frames, the UR differentiates between transverse frames, longitudinal frames, load-carrying stringers and web frames. Where the area factors defined for individual sub regions accounts for the class distinguishing.

Transverse and longitudinal frames are dimensioned so the combined effect of shear and bending don't exceed the plastic strength of the member. The differences for these members are in the shear area and the plastic section modules.

Web frames and load-carrying stringer are to be dimensioned for the same combined effect of shear and bending as for transverse and longitudinal frames, but references design limit states defined by the individual member society.

Enforcing restrictions on the web height/thickness ratio prevents structural instability. On structural members where this is not practical, stiffening requirements are imposed.

5.2.2.5 Material Requirements

Plating materials for hull structures are divided into two groups: "Steel Grades for Weather Exposed Plating" (1) and "Steel Grades for Inboard Framing Members Attached to Weather Exposed Plating" (2). The rules also divides between hull structure materials below and above the waterline (+- 0,3m), where above the waterline is defined by (1) and below by the UR S6 requirements. Material class, chosen by area of exposure, subdivides them both. Inn group (1) and (2) there are class specific notations for steel grades.

5.2.2.6 Longitudinal Strength

Requirements are imposed for longitudinal strength. The combined ice loads and Stillwater loads are used to determine these requirements. The combined stresses are then compared against permissible bending and shear stresses at different locations along the ship's length. In addition, sufficient local buckling strength is also to be verified.

5.3 The Russian Maritime Register of Shipping Arctic rules

The RMRS is the principal classification society in Russia. The RMRS is a member of IACS, but has to this date not implemented the unified requirements for Polar Class ships.

5.3.1 The class system

In the RMRS the Arctic class system is divided into six classes (Shipping, 2011). They have also incorporated four additional icebreaker classes and three non-arctic classes, which will not be focused on in this review. In the Arctic class system the Arc9 is the highest ice class and Arc4 the lowest. The system is based a glancing design scenario where the ship is assumed to interact with ice floes of different thickness, age and interaction frequency. The system included a speed versus thickness recommendation, which also has been implemented into the ice passport system for the Russian Arctic. The rules also give guidance to navigational regions within the Russian Arctic, which separates between seasons and independent navigation or icebreaker escort (Table 3).

<table>
<tr><td rowspan="2">Ship category</td><td colspan="2">Permitted type and thickness of ice</td></tr>
<tr><td>Winter/spring navigation</td><td>Summer/autumn navigation</td></tr>
<tr><td>Arc4</td><td>Thin first-year</td><td>Medium first-year up to 0,9 m</td></tr>
<tr><td>Arc5</td><td>Medium first-year up to 0,8 m thick</td><td>Medium first-year</td></tr>
<tr><td>Arc6</td><td>Medium first-year</td><td>Thick first-year ice up to 1,5 m</td></tr>
<tr><td>Arc7</td><td>Thick first-year up to 1,8 m</td><td>Second year</td></tr>
<tr><td>Arc8</td><td>Multi-year up to 3,4 m</td><td>Multi year</td></tr>
<tr><td>Arc9</td><td>Multi-year</td><td>Multi year</td></tr>
<tr><td colspan="3">N o t e. The classification of ice adopted according to the "Sea Ice Nomenclature" of the World Meteorological Organization (WMO):

Ice type — Ice thickness
Multi-year — > 3,0 m
Second-year — > 2,0 m
Thick first-year — > 1,2 m
Medium first-year — 0,7 — 1,2 m
Thin first-year — < 0,7 m</td></tr>
</table>

Table 3 The definition of the different Arctic Classes according to the RR

5.3.2 Structural Requirements for RMRS Arctic Class Ships

5.3.2.1 Hull regions

The hull is divided into regions, according to the expected load magnitude. There are four main regions dividing the ship in longitudinal direction: The forward region (A), intermediate region (A_1), midship region (B) and aft region (C). These four regions are then subdivided into four vertical sub-regions: Region of alternating draughts and similar regions (I), region from the lower edge of region I to the upper edge of bilge strake (II), bilge strake (III) and region from the lower edge of bilge strake to the centre line (IV) (Figure 11). Like the IACS rules, not all vertical sub-regions are included for all classes. In Arc4 to Arc7 sub-region IV is not included for the midship. For Arc5 and Arc4 this sub-region is also not reinforced at the stern. At the stern it is also not required to include sub-region III for Arc5 and Arc4. At the midship region, Arc4 also need not strengthen sub-region II and III.

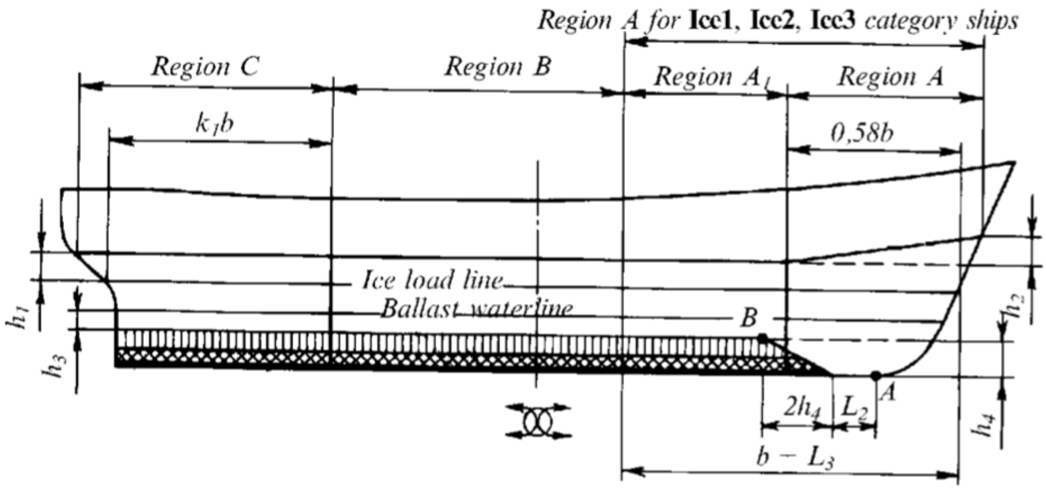


Figure 11 Hull regions according to the Russian Register rules

5.3.2.2 Design ice loads

The RMRS rules are based on a design scenario of tangential impact. An energy method, based on ultimate strength criterion is then used to determine the structures transition into a kinematic modified system called a “plastic mechanism”. The design load causing this transition is defined through the ultimate balance theory (UBT), which assumes an ideal-stiff-plastic material (E. M. Appolonov et al., 2007). The design ice load depends on three parameters: the ice pressure (P), vertical distribution of ice pressure (b) and horizontal distribution of ice pressure (l^p).

The ice pressure is determined for the different regions, by area specific formulas. For region I, the formula takes into account the summer load displacement and class specific factors. Of the sub-regions in I, AI is unique since it is taking the hull shape into account. For regions II, III and IV, the ice pressure is determined as a portion of the ice pressure in region I at the appropriate section of the ship length.

The expressions for the vertical and horizontal distribution of ice pressure are determined for each of the four main regions. As with the ice pressure, both the vertical and the horizontal distribution takes displacement and class specific factors into account. Also common is that region A, accounts for the shape of the hull.

5.3.2.3 Shell Plate Requirements

The minimum required shell-plating thickness is determined by the sum of the required thickness to withstand the ice load (S_{sp0}) and the added thickness for corrosion and abrasion (ΔS_{sp0}).

5.3.2.4 Frame Requirements

The theory behind the formulas for required geometrical characteristics of girder structure cross sections, are based on ultimate strength criterion (plastic methods). This is reflected in the expressions for the ultimate section modulus W and the web area A.

The different frame requirements have been divided into five different girder structures:

1. Conventional frames where transverse framing is used.
2. Side and intercostal stringers as part of transverse framing with deep frames.
3. Deep frames as part of transverse framing.
4. Side and bottom longitudinals as part of longitudinal framing.
5. Deep frames as part of longitudinal framing.

The class specific requirements are accounted for in the ice pressure. The ice pressure is in turn specific for the area.

5.3.2.5 Material Requirements

The choice of steel grades for hull structural members are either chose according to category or according to category, design thickness and temperature. Whether or not thickness and temperature is to be considered depends on if the structural member is to be designed for prolonged exposure to low temperatures. The latter category is class specific, and determined by the design temperature.

5.4 Classification comparison

This review has highlighted the different classification societies hull strengthening rules for ice-infested waters. There are differences between the rule sets that haven't been mentioned, since this would require a more in depth study. In this section a comparison of the different hull strengthening rules will be presented.

5.4.1 Design scenarios

There are differences in the design scenarios, which the rules are based upon. The FSICR are based on collision with a channel edge or a consolidated layer of older ridges. These rules does not state ship speed, as it is considered that speed restrictions would handicap much of the navigation in ice. The reasoning behind the design scenario is that icebreaker escort is provided throughout the Baltic Sea. Both the IACS unified requirements (UR) and the RMRS Arctic rules are based on impact scenarios with ice floes. For hull strengthening both rules use glancing impacts as the governing design scenario, but the UR include ramming when determining longitudinal strength. The difference between ramming and glancing is related to the angel of impact. Glancing is defined as an impact at an angel, and ramming as a head on impact.

5.4.2 Design limit state

The FSICR uses an elastic design limit state for both the frames and plates. This is reflected in the expressions for the section modulus (frames) and the thickness of shell plates. The design limit state for IACS and RMRS is a plastic criterion. Both IACS and RMRS have similar approaches to determining plate thickness and frame scantling. To determine the plate thickness both use an ultimate strength criterion, by assuming plastic hinges over the load patch area of the plate. The difference is that RMRS also includes a factor for planned ship life. This factor is included when calculating the added thickness for corrosion wear and abrasion. For frames the plastic criterion is reflected in the use of the plastic section modulus, for both IACS and RMRS.

5.4.3 Ice load

All three rules deals with an ice pressure and a load patch. Another common factor in the rules is that the design pressure is determined in the bow by the design scenario, and then distributed across the ship with hull factors. There is however differences in how these parameters are determined and accounted for.

In the FSICR the ice pressure is determined by an empirically obtained nominal ice pressure, which is then adjusted for engine power, region of the ship and ice class. Due to the nature of this approach the specific failure of the ice taken into account. For the RMRS the ice pressure equations does not specify a nominal pressure, as in the FSICR, but is calculated by an energy method (Bridges et al., 2005). This energy method (UBT) takes into account the failure modes of the ice, but it is not explicitly stated how they're accounted for in the rules. Instead the hull shape, summer load displacement and a class specific factor (this factor probably incorporates the ice failure criteria) are included in the ice pressure calculations.
The IACS uses an energy method similar to the RMRS, but in contrast to the RMRS the ice interaction is specifically stated by failure factor. These failure factors are included in the shape factor calculation, which is then applied to the ice force expression.

The load patch is assumed to be a rectangle with a load height and load length for all of the rules. In the FSICR the load height is defined for each region of the ship and the load length for structural elements. The RMRS includes hull shape and displacement for the load height and length in the bow, and then calculates the remaining regions in relation to these. The approach in the IACS unified requirements, calculates the load height and length from the line load. The load line is defined for the bow and non-bow regions, where the bow includes an aspect ratio defined for the individual sub-regions. This aspect ratio is the same factor included in the pressure calculations accounting for the hull shape. All of the above also includes class specific factors in their calculations.

5.5 Reflective summary

There are several differences in how the classification societies have applied the ice load to their requirements. This will most certainly affect the scantlings in a cross-classification comparison, but how these differences will impact in terms of total weight is not clear. This is a challenge for ship-designers/stakeholder when choosing the proper classification for their vessel. When choosing to apply a specific ice class for a vessel, it is desirable to keep the impact on the original design as low as possible. A stakeholder would naturally wish to transport as much of a product as possible per trip, at the same time as protecting that cargo adequately. To investigate this further a case study will be presented, where the Russian Register rules will be compared with the IACS unified requirements. The FSICR will not be included, as this would only have included one of the classes (1A super). The selected rules will be chosen according to the North Sea Route requirements. Additionally the case study will also include one class above and below, to include the possibility of requirement adjustments due to climate change. In the following chapter the selected method of optimization will be presented.

6 Structural optimization

The process of optimization is defined as the application of a systematic method for determining the design variables, which optimize a specific object while satisfying the constraints. When evaluating a ships structural constraint, it is common to divide them into two categories: Overall constraints and Strake constraints. The overall constraints are related to the global load effects, where the entire structure is evaluated as a box girder. Strake constraints consider the more localized load effects on stiffened panels, frames and girders. Mathematically it is possible to further sub-categorize these into linear and non-linear constraints. Linear constraints for are commonly enforced to balance the relationship between structural elements, so that local failures in a section are avoided. There are many non-linear constraints in welded structures, due to the non-linearity of collapse constraints such as buckling, tripping and excessive yielding. These constraints are defined by limit states, which are stated as loss of integrity (collapse) or un-serviceability (Hughes, 1980). In optimizing a structure, the first step at the conceptual phase is to calculate these constraints in accordance with service load requirements provided by the chosen classification notation. This is the level this thesis will operate at. Since there are several variables in a cross section there are several feasible solutions, which will comply with class requirements. To make sure that the feasible solutions presented in this thesis are as close to the optimum weight/constraint level as possible, an automated optimization method has been used.

6.1 Particle Swarm Optimization

A structure optimized from a general approach may satisfy structural requirements in terms of allowable stresses and deformations, but can cause unwanted side effects such as increased weight and cost. An optimization method that is capable of both satisfying structural constraints and optimizing for lowest weight and cost is the particle swarm optimization (PSO) algorithm. The PSO is a computer code, which original intent was to describe the flock behaviour of birds searching for a cornfield (Kennedy & Eberhart, 1995). When developing the algorithm the researchers Kennedy and Eberhart, realized that the rather simple PSO also could be used to find optimum solutions for more complicated problems including neural-net applications. The algorithm uses the concepts of swarm and particle. Swarm is a description of the behaviour of a population. For a structure the population could be an n-number of solutions for a strake, where the behaviour would be determined by the local and global constraints as the algorithm searches for the lowest possible weight. The particles would in this case be identified as solutions of the population, which complies with the constraints. The algorithm will then choose the particle that generates the lowest weight, and search for a “better” solution in the next generation. This process will continue till the PSO is unable to locate better solutions. The PSO has been successfully used to optimise an LNG side structure for crash-worthiness by professor Sören Ehlers at the Norwegian University of Science and Technology (Ehlers, 2010). Ehlers introduced in this procedure a constraint function that varies between -1 and 1, where particles between 0 to -1 are defined as feasible solutions and above 0 as infeasible (Hughes, 1980).

$$g_i(x) = \frac{a_i(x) - |b_i(x)|}{a_i(x) + |b_i(x)|} \quad \text{Equation 3}$$

Where $a_i(x)$ is the structural capacity of a member and $b_i(x)$ is the actual load on that member. A collision scenario run through finite element software to determine the load and the capacity was checked against the FSICR 1A ice class. On objective was defined as a function combining the highest energy per mass ratio and the lowest cost.

7 Selection of case study vessel and target ice classes

When transport natural gas in a ship it is necessary to liquefy the gas into a product commonly referred to as LNG, liquefied natural gas. To perform this process, the gas has to be cooled down to below its boiling point of -161^{0}C. In this phase the volume of the gas is reduced by approximately 600%. As a gas, the product is highly flammable, but in its liquefied state it is non-flammable. This is why the containment system on-board a LNG carrier is the most critical element. There are two main types of containment system in use today: The spherical tank (Moss tank) and the membrane tank. In spherical tank designs, the tanks are spherical aluminium tanks or prismatic-shaped stainless steel tanks. These are self-supporting within the ships hull. The membrane tank design consists of a very thin invar or stainless steel double walled insulated cargo envelope, which is supported by the ships hull (Vanem, Antão, Østvik, & de Comas, 2008).

7.1 Trends in development of LNG carrier design

With the rise in in gas production and development of new gas fields in the Arctic region, there is an increasing demand for larger LNG carriers that is capable of navigating and manoeuvring in ice. According to a report published by Lloyd's Register (Tustin, 2005), there are orders for LNG carriers capable of transporting more than 200,000 cubic metre. Not all of these will be required to operate in the Arctic, but some like the LNG carriers planed for the Yamal megaproject will. This will require the tankers to have ice capability, which will pose some major technical challenges. One major concern regarding the design of LNG tankers for ice-infested waters is the sensitivity of the cargo containment system (CCS) to large deflections of the hull. Breaching of the CCS can have severe consequences both in terms of human lives and economic loss.

7.2 Structural strength of LNG carriers for ice-infested waters

For a LNG carrier the chosen containment configuration governs the structural design. The structural detail design is then performed according the to applied classification for the vessel. In the case of a ship intended for ice-infested waters, an additional ice class is then chosen for the hull design. However for the specific case of a LNG carrier there is no particular attention, in any of the ice class rules, to added requirements for the cargo containment systems under ice impact loads. To assess the cargo containment systems for Arctic LNG carriers under ice loads, a study was performed in 2008 (Kwon, Kim, et al., 2008). Two FSICR 1A classified LNG carriers with a membrane and a spherical CCS respectively were modified to IACS PC 7 ice reinforcement. Finite elements models of the ships containments systems and including hull structures were developed then analysed using six design scenarios. It was confirmed that the ice-strengthened hull for both vessels could resist the design loads within specified requirements. One interesting side effect was noted when the ships were modified from 1A to PC 7, a notable hull weight increase of 4-6%. This is a significant increase in weight, which would reduce the payload capacity proportionally.

7.3 Suggestion of LNG carrier case study vessel

In compliance with the trends in the development of LNG carriers, a suitable LNG carrier is chosen as a suggested case study vessel (Figure 12). The Ribera del Duera

Knutsen is the first LNG tanker to be approved by Russian authorities to transit the North Sea Route. This vessel has a DNV ice class 1A, which is equivalent to the highest FSICR 1A super. Unfortunately it was not possible to acquire cross section details of this vessel. Instead the cross section configuration was obtained by scaling another similar vessel from a conference paper about the Structural Integrity Assessment of Cargo Containment Systems in Arctic LNG Carriers under Ice Loads (Kwon, Jeon, et al., 2008).

Ribera del Duera Knutsen main particulars							
LOA [m]	LPP [m]	B [m]	D [m]	Max T [m]	LNG [cbm]	Full load Displ. [t]	Deadweight [t]
290	279	45,8	26,5	12,9	173000	115000	96898

Table 4 Main particulars for the Ribera del Duera Knutsen

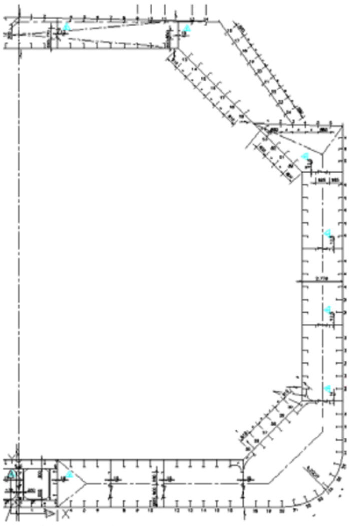


Figure 12 The Ribera del Duera Knutsen and the selected cross section layout

7.4 The selection of target ice classes

Based on the information gathered in the previous chapters, a selection of target ice classes will be presented. The Yamal Mega Project in the Kara Sea is under development, and has expressed an interest in acquiring LNG carriers to transport the natural gas to the international markets. This concurs with the assessment of Russia developing their gas recourses before other Arctic regions. By selecting this region the case study will follow the rules for NSR, enforced by the Russian Ministry of Transportation (RMT). According to Table 5, issued by the RMT, the lowest class allowed for partial navigation from November to June is Arc5. However this is only for easy ice conditions. So the comparison will also target Arc6 to Arc7, which accommodates more flexible navigation.

For vessels class Arc4 – Arc9 during navigation in the period November to December and January to June		
Ice Reinforcement Class	Ice navigation mode Independent navigation – IN With icebreaker support – IS	The Kara Sea
		E S M L
Arc4	IN	– – – –
	IS	– – – –
Arc5	IN	– – – +
	IS	– – – +
Arc6	IN	– – – +
	IS	– – + +
Arc7	IN	– – + +
	IS	+ + + +
Arc8	IN	+ + + +
	IS	+ + + +
Arc9	IN	+ + + +
	IS	+ + + +
«E» – extreme ice conditions according to the Rosgidromet official information «S» – severe ice conditions according to the Rosgidromet official information «M» – moderate ice conditions according to the Rosgidromet official information «L» – easy ice conditions according to the Rosgidromet official information «+» – Navigation is allowed «–» – Navigation is not allowed		

Table 5 The classification requirements for the Kara Sea from November to June

In order to select equivalent IACS classes, and Table 3 from the classification society chapter are used. The classes are different in their definitions, which makes it a direct comparison difficult. To support the choice of equivalent classes, a reference to a previous comparison is made. The comparison performed by the Helsinki University of technology and Lloyd's Register, which investigated equivalency between the IACS and RR rules (Bridges et al., 2005). In the report the PC4-6 was determined to be approximately comparable with the Old Russian classes LU6-4. These are now known as Arc6, Arc5 and Arc4. So based on this report, the assumption is made that PC3 will be the equivalent class to Arc7. Table 6 shows the targeted Russian Register Arctic Classes, and the assumed equivalent IACS Polar Classes.

Arctic Class		**Polar Class**	
Arc4	Thin first-year ice	PC6	Summer/autumn operation in medium first-year ice, which may include old ice inclusions
Arc5	Medium first-year ice < 0.8m	PC5	Year-round operation in medium first-year ice, which may include old ice inclusions
Arc6	Medium first-year ice	PC4	Year-round operation in thick first-year ice, which may include old ice inclusions
Arc7	Thick first-year ice < 1.8m	PC3	Year-round operation in second-year ice, which may include multi-year ice inclusions.

Table 6 The selected target ice classes for comparison

7.5 Reflective summary

In chapters 6 a case study vessel was selected, by means of predicting a need for LNG carriers for ice-infected waters due to the vast natural gas reserves in the Arctic. The selected vessel is consistent with trends in LNG carrier development, though not quite as large as the trend suggests. Furthermore eight target ice classes were chosen, to comply with the chosen trade route. In chapter 7 a method capable of optimizing a structure was introduced. This method will form part of the framework of a rule based analysis tool, which will be used in determining the difference in weight between the targeted ice classes. The development and use of this method will be presented in the following chapter.

8 The rule based analysis tool for weight comparison of ice classifications

The rule based analysis tool (Figure 13) was written in collaboration with the author, and fellow graduate student David Andre Molnes. When creating the rule based analysis tool for weight comparison of ice classifications it was decided to use two different programs. One program for the user definable inputs and one to interpret this input and calculate the necessary rules. The user input was written as an excel sheet, because it can easily be interpreted by Matlab and it is a format that most are familiar with. Matlab was chosen due to the author's familiarity with it and because the PSO script, provided by professor Sören Ehlers, was already written with this program. In Matlab several different scripts had to be written for several reasons. A cross section script interprets the cross section input, and calculates the necessary data required as an input for the rule-based scripts and the PSO. The rule-based scripts are dived into the design load script, the IACS polar class script and the Russian Register arctic class script.

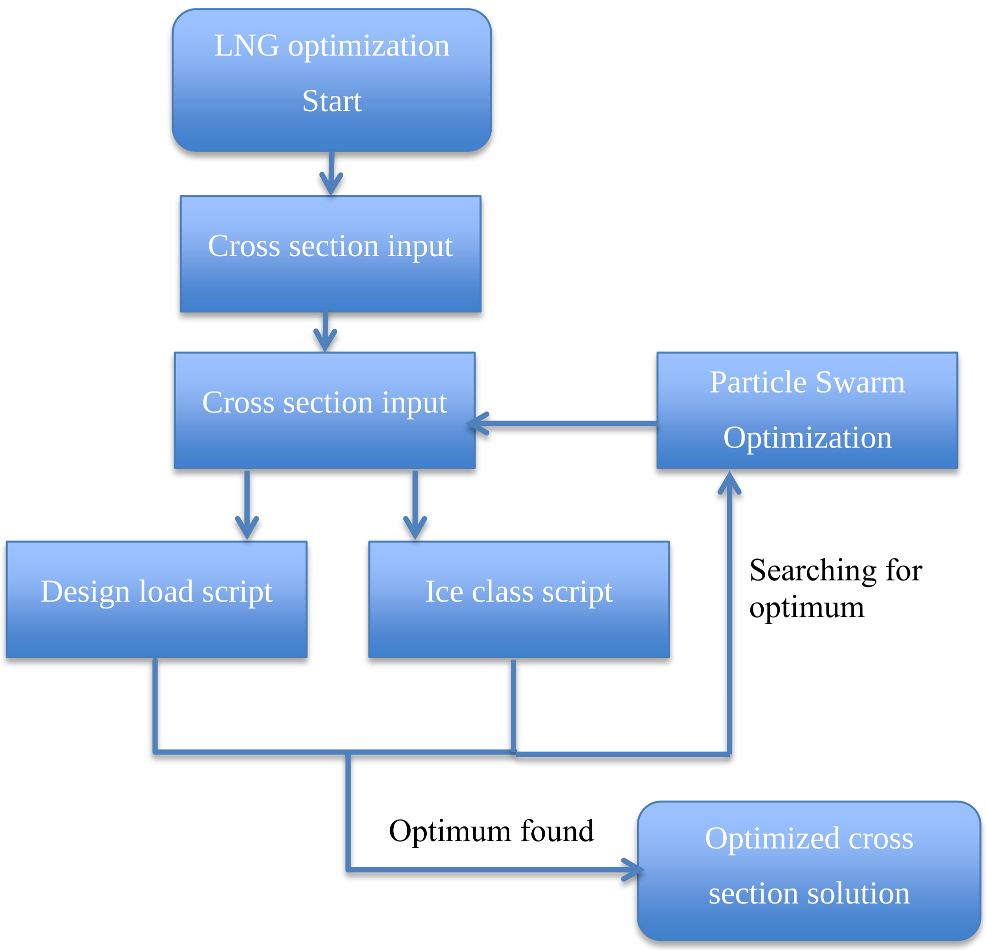


Figure 13 The rule-based analysis tool

8.1 The cross section input

For simplicity, the user input was limited to a minimum. Where it is only necessary to describe the geometry of the starboard half of the cross section. When selecting a cross-section to investigate, a location along the longitudinal axis where the curvature is minimum should be chosen. The reason for this is that the script does not mathematically interpret curves. Curves such as bilge keel are therefor simplified as inclined panels.

The first input that the user needs to input is the ships main particulars. These are to be restricted to the ships moulded breadth, length overall, length perpendicular, mean moulded summer drought, depth and displacement. All values are to be in meters or in kilograms. The input for ice class is also located in the same row. For IACS the input for this should be 1 to 7 and 9 to 1 for Russian Register.

For defining the geometry of the cross section the necessary input values was decided to be an YZ coordinate system that describes the start and end coordinates for each strake in the cross section of interest. The input coordinates are to be in millimetres in reference to origin, which has been chosen to be located at the centre line on the wet side of the keel plate. A system for this input was created, where the Y-coordinates of the strake are written in row “i” and the Z-coordinates is written in row ”i+1”. The first column will then be the strakes Y and Z start coordinate and the second column the strakes end coordinate. In addition the strakes end coordinate has to be in the YZ coordinate positive direction, which means that a horizontal strake will be inputted from left (start) to right (end) and a vertical strake from lower (start) to upper (end). Inclined panels should be inputted from left to right, but is not sensitive to input direction vertically. In which order the strakes are inputted is arbitrary, so the user can add and remove panels as pleased.

The next user input is then the unique strake id-number. This is a simple number input from 1 to number of strakes. It is important to have this input, because this is further utilized to identify the correct rule checks for each strake.

Finally there is an input for the stiffener orientation and girder id. The stiffener orientation input, is a simply 1 or 0 input, where 0 is longitudinally stiffened and 1 transversely. The girder id input is a reference to individual sections of the webframe. It is similar to the strakes input, but the unique id-number is instead consistent with each webframe sections boundary. The id-numbers are to be assigned in such a way that the boundaries that is not shared with an adjacent member is to be assigned a single digit number, and shared boundaries are to be double digits that is composed of the id-number from the two adjacent members. For example if a horizontal webframe were separated with a longitudinal side girder, the part of the webframe to the right would be identified with the id-number 1 and the left part would be identified with the number 2. The longitudinal side girder, which would be a common boundary for each webframe, would have the id-number 12. These numbers will then be interpreted by the cross section script and sorted correctly. An example of the input is shown in Table 7.

Keel plate 1					
	Start	End	ID	Orient.	Girder ID
y	0	2600	1	0	1
z	0	0			

Table 7 Cross section input example

The cross section is illustrated with a scatter chart, so that the user can confirm that the input is correct. This chart is however not robust, so the correct cells has to be edited by the user.

Both the IACS rules and the Russian rules specify the extent of the strake in the ice belt, which were accounted for in the cross section input. In the IACS rules this area is specified as fixed distances above and below the upper and lower water line, but in the Russian Rules these are variables of the beam. These variables were calculated for each Arctic Class, but since the difference between the extents for each class was small the requirement for Arc7 was used for all Arctic classes.

8.2 The cross section script

The cross section script, Cross_section_func.m, function is divided into the following categories:

- Input interpretation
- Cross-section calculations
- Webframes calculations
- Weight estimate

The input interpretation acquires its input from two primary sources. The previously discussed excel sheet, which is considered an external source, and the second source is from the PSO script. The information obtained from the excel sheet is read in its complete form directly into the matrices called Csection. From the Csection matrix the coordinates are extracted into two matrix called Csec_YZ and Webframe_YZ, which is used for numerous operations at a later point. The id-numbers and orientation is also read into their respective arrays, and also the main particulars are directly extracted into an array. It should be mentioned that due to the direct approach used for reading the excel data adjustments should be done to this Matlab script, if additional information is added below the existing main particulars data in the excel sheet. Besides this the script is quite robust and should except additional or less number of strakes. The input obtained from the PSO script is the three strake variables; plate thickness, web thickness, stiffener type and number of stiffeners. These inputs are what changes each time the PSO creates new populations. All of these inputs are uniquely defined for each strake or web and chosen by random before being read into the cross section script via individual matrices called Csec_thick, Web_thickness, Type_stiff and Stiff_num. The information from the plate thickness and web thickness inputs are in millimetres, but are immediately converted to centimetres. This might seem odd, but the choice of using millimetres was done because manufacturers of steel products tend to use millimetres when defining dimensions. The range, in which the PSO picks these, will vary for each member as the user defines them, but is usually between 10 and 30 millimetres. The stiffener type input is a reference to a multidimensional matrix created at a later point in the script called Stiff_id, which contains information for different hp and flat-bar stiffener profiles in each third dimension. How this is done will be covered later in this chapter. The final input, number of stiffeners, is as the name indicates the number of stiffeners per strake.

In the cross section calculations a variety of calculations and sub-calculations are performed. A common method used in the calculations is to differentiating between horizontal, vertical and inclined panels by comparing the changes in the start and end coordinates. This method has proved to be beneficial is a part of the robustness of the script. An area where this is utilized is the width of the strakes calculations. Here the horizontal and vertical strakes are chosen by comparing and selecting strakes where the start Y and Z coordinate is equal to the end Y and Z. Then the width is calculated by subtracting the Y-start and -end coordinate for vertical strakes, and the Z-start and -end coordinate for horizontal strakes. Inclined panels are then included separately with an “else” condition and using Pythagoras to calculate the width. In a similar fashion each strakes individual second moments of area and distance from keel/side is calculated. When dealing with stiffeners, the script only handles longitudinal stiffeners at this point. Stiffeners spacing is calculated by the formula:

$$s = \frac{C\sec\_width}{1 + Stiff\_num} \quad \textbf{Equation 4}$$

The formula divides the strake width by the number of stiffeners on that strake, plus one. This simplified approach assures that the stiffeners are evenly spaced across the width of the strake, but also inhibits solutions where non-uniformed spacing between one or more stiffeners might be desirable. By using this method, the script also limits the variation in stiffener profiles on a strake to one. This means that if a load changes over a strake the stiffeners profile complying with the largest load us used across the strake width. This simplified approach will result in a less optimized strake and will naturally increase the weight. But since the same method is utilized for every comparison, the results should be valid.

An important variable created is the Strakes three-dimensional matrix. This matrix collects all the unique information needed per strake, and stores them in the third dimension. It is also the matrix that is most frequently referenced in the subsequent rule scripts. This matrix contains the previously mentioned Stiff_id matrix, which contains the different hp or flat-bar stiffener profiles. The choice between flat-bar or hp profiles is done by commenting or uncommenting the desired profile. Unfortunately this means that a combination of these different profiles is not possible. The input Type_stiff contains numbers from 1 to the number different profiles (different hp profiles and 22 flat-bar profiles). This input will then chose the profile, and it is included in the correct Strakes matrix.

The Strakes matrix also contains the Length_stiff and Pressure array, which contains the stiffener length of longitudinal stiffeners and the pressures on each strake. The length of the stiffeners also represents the webframe spacing, which is assumed constant. This is why the Length_stiff is fixed at one cell in the array. It can however be changed manually for comparison analysis. The pressure array is uniquely defined for each case study, but is not calculated automatically by the script. Pressure calculations were performed in Excel, using the DNV rules for Liquefied Gas Carrier and ships above 100 meters. In the calculations the largest pressure was chosen per strake, and implemented in to the Pressure array. By selecting the larges pressures for each strake, the vertical strakes will be calculated more conservatively then a variable pressure would. Horizontal strakes will be unaffected by this simplified approach.

In order to add stiffeners to each strake the start coordinate for each strake was used. Then the calculated stiffeners spacing was added to this and multiplied sequentially by the number of stiffeners per strake. By doing this, the correct YZ-coordinate for where the stiffener is located on the plate is calculated. It should however be mentioned that the script only interprets what side of a plate the stiffeners are mounted on for outer shell plates, which have the same coordinates as the main particulars dictate. This will result in a small error when calculating the global neutral axis (in reference to both the vertical and horizontal base lines), which will then propagate to the global second moment of area and section modulus.

The webframes calculations start by creating a similar multidimensional matrix as Strakes. This matrix, called Girders, has the same function as the Strakes matrix in that it contains the necessary information for each webframe section. As with the Strakes matrix it also contains a multidimensional matrix, which is selected from the PSO script. This matrix, called Girder_id, is however inert at this point. It was created at an early phase and contains structural information for fifteen different girder profiles, and was intended to be part of an optimization routine for simple girders. However it was later realized that the load for these girders would be external permanent loads, which is not included in this model. These girders were subsequently removed from the script. The Girders matrix is however utilized for webframe data such as girder span and height, which are calculated at a later point in the script.

In contrast to the section of the script calculating strakes, the webframes script has to be manually adjusted for each case. The reason for this is simply that the author could not find an automated way of doing this. It was however automated to a certain degree, but it is necessary to input the correct girder id-numbers to the correct calculations and also there are some manual adjustments in order to calculate the correct area for non-rectangular webs. These adjustments are related to the order in which the coordinates for the different boundaries of non-rectangular webs are interpreted. The reason the sensitivity is that the trapz function, which is used to numerically calculate the area, needs to have the coordinates in such order that it is interpreted as a closed polygon. If this is not correct, the area will be calculated wrong. A technique used as a tool for checking this is simply to plot the coordinate matrix in question. If the plot resembles the actual web, the calculations should be correct.

One calculation that needs to be mentioned is the calculation of the plastic section modulus. An early version of the script assumed the plastic neutral axis to be the thickness of the local plate (equation 3), but was later modified to comply with the IACS polar class requirements (equation 4), The original calculation is still in use but the script evaluates what calculation to use by checking if the area of the attached effective plate flange is smaller than the area of the attached stiffener. If this turns out to be the case, the IACS calculation is used and vice versa.

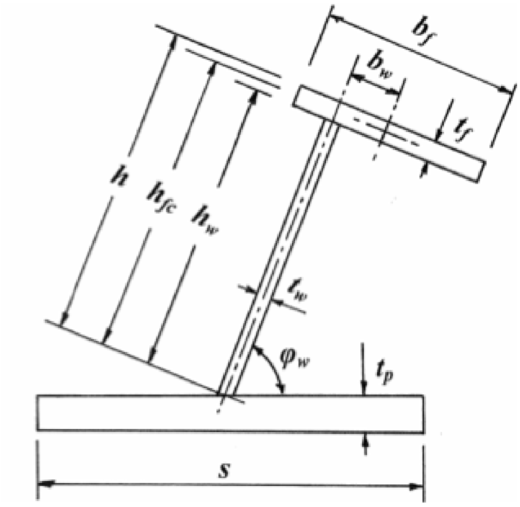
$$z_p = (Area_{Pl.flange} \times t_{P.} \times \frac{t_{P.}}{2}) + Area_{Stiff.} \times z_{NA.Stiff.} \quad \text{Equation 5}$$

$$z_p = t_{P.} \times s \times (z_{NA.} + \frac{t_{P.}}{2}) + \frac{((h_w - z_{NA.})^2 + z_{NA.}^2) \times t_{wn}}{2000} + \frac{A_{fn} \times (h_{fc} - z_{NA.})}{10} \quad \text{Equation 6}$$

Where the plastic neutral axis (Z_{NA}) is determined by equation 5:

$$z_{NA} = \frac{100 \times A_{fn} + h_w \times t_{wn} - 1000 \times t_{pn} \times s}{2 \times t_{wn}} \quad \text{Equation 7}$$

Figure 14 shows the definition of the different terms in the above equations.



- h = height of stiffener [mm]
- t_{wn} = net web thickness [mm]
- A_{pn} = net cross-sectional area [cm^2]
- t_{pn} = net shell plate thickness [mm]
- h_w = local frame web height [mm]
- A_{fn} = net cross-sectional area of local frame flange [cm^2]
- h_{fc} = height of local frame measured to center of the flange area [mm]

Figure 14 The definitions of stiffeners and frames according to DNV

To estimate the weight of the cross section, the calculations are divided into three calculations. The first calculation sums up the volume of the webframe sections, then multiplies it with the density of steel and divides it by the webframe spacing. In the second calculation the weight is calculated by means of the mass per unit length data available in the Strakes matrix. This data is given by the manufacturer, and is unique for each stiffener profile. This is then multiplied with the number of longitudinals for the correct strake and added together. The third calculation simply multiplies the cross sections total plate area, and multiplies it with the density of steel. The three results are then added up into the Weight variable, which is then used as the objective for the PSO.

8.3 Rule based scripts

The rule-based scripts for the targeted ice classes were written as two separate scripts, the IACS PC rules script and the RR Arctic rules. In addition another script was written to perform rule checks for local and global constraints not covered by the target ice classes. The design loads script is based on the DNV general requirements for ships above 100 meters. This script also contains additional requirements for LNG carriers, taken from DNV's requirements for LNG carriers. The decision of using the DNV regulations is based on the author's previous experience with the rules.

8.3.1 The design load script

When writing the design loads script, DNV's "Hull Structural Design, Ships with Length 100 metres and above, January 2012 edition" was used. For the additional LNG specific requirement the "Liquefied Gas Carriers, January 2012 edition" and "Strength analysis of hull structure in Liquefied Gas Carriers with membrane tanks, October 2008 edition" was employed.

In the design loads script the correct rules are selected by means of the strake id number and the stiffener orientation. As mentioned the cross section script does not accepts transverse stiffening of plates, but the rules for transverse oriented stiffening were incorporated into the script. This was done to accommodate future versions of the cross section script. The correct strake id number has to be manually inputted to the correct rules by the user, as well as for corresponding functions related to those rules. This includes functions that remove zeros from the minimum requirement matrixes (minimum shell thickness and so on). Below a part of the code is presented to illustrate the methodology used in the script.

```
%REQUIREMENTS FOR SIDE STRUCTURE PLATING%
for j = 1:Csec_size/2
    %LONGITUDINALY STIFFENED WITHIN 0.4L%
      if Strakes(1,21,j) = = 0;
         for i = 1:Csec_size/2
            if Strakes(1,1,i) = = 9 || Strakes(1,1,i) = =  10  || Strakes(1,1,i) = = 32
              t_side(i,1) = …..
            end
         end
      end

    %TRANSVERSLY STIFFENED WITHIN 0.4L%
      elseif Strakes(1,21,j) = = 1;
         for i = 1:Csec_size/2
            if Strakes(1,1,i) = = 9 || Strakes(1,1,i) = =  10  || Strakes(1,1,i) = = 32
              t_side(i,1) = …..
            end
          end
       end
end

for i=1:Csec_size/2
  if Strakes(1,1,i) == 9 || Strakes(1,1,i) ==   10  || Strakes(1,1,i) == 32
      t_side_check(t_side==0)=[];
      t_side(t_side= =0)=[];
  end
end
```

The local design requirement for the different cross-section areas use similar methodology but varies in design pressure, stresses and coefficients. For local thickness requirements of plating, the design calculation is based on the exposure of lateral pressure as a function of nominal allowable bending stress. The equation also accounts for the aspect ratio of the plate field, corrosion addition and the assumed boundary conditions. In the script the boundary conditions for all structural elements are assumed fixed, and the corrosion addition is neglected.

$$t = \frac{C \cdot k_a \cdot s \cdot \sqrt{p}}{\sqrt{\sigma}} + t_k \quad \textbf{Equation 8}$$

- C = factor depending on boundary conditions of plate field.
- k_a = correction factor for aspect ratio of plate field.
- s = stiffener spacing
- l = stiffener span
- p = design lateral pressure
- σ = nominal allowable bending stress

In the local requirements for longitudinals, a minimum section modulus is defined with the associated effective flange taken as the stiffener spacing. This equation uses the same lateral pressure and nominal bending stress as specified for plates and also an undefined constant that is different depending on the area checked. This factor might have a similar purpose as the C, for plates. The rules also state minimum requirements for web and flange thickness.

$$Z = \frac{83 \cdot l^2 \cdot s \cdot p \cdot w_k}{\sigma}$$ **Equation 9**

- w_k = correction factor for aspect ratio of plate field.
- s = stiffener spacing
- l = stiffener span
- p = design lateral pressure
- σ = nominal allowable bending stress

The equation above is taken from the requirement for bulkhead structures, but is similar to other areas except for the factor (83) mentioned.

Web thicknesses like longitudinal frame girders in double bottom, stringers and webframes are in general treated according to the same expression. The equation is not determined by the local pressure or a design stress, but uses instead a factor k that is determined as a percentage of the rule length L1. Besides this the equation has two constants: one that is a material factor and an initial thickness t_0 to be determined by the member location. The equation below is taken from requirements for girders on bulkheads:

$$t = 5.0 + \frac{k}{\sqrt{f_1}} + t_k$$ **Equation 10**

- k = 0.01 L1 in general
- k = 0.02 L1 for girder webs, flanges and brackets in cargo oil tanks and ballast tanks in cargo area
- k = 0.03 L1 (= 6.0 maximum) for girder webs, flanges and brackets in peaks.

Some additional requirements may occur, like for web frames were the thickness are not to be to be less than 12 times the stiffeners spacing. For this requirement the spacing is given in meters while the requirement is in millimetres. The web frames are also checked for minimum web area and elastic section modulus. In this thesis these requirements are not checked for parts of the web frame that is not rectangular.

In all cases mentioned above, a buckling check is performed. The buckling stress is somewhat simplified as it only checks for uniaxial compressional stress. The buckling formulas used were from the DNV rules, chapter.

$$\sigma_c = \sigma_f \cdot (1 - \frac{\sigma_f}{4 \cdot \sigma_{el}}) \text{ When } \sigma_{el} > \frac{\sigma_f}{2} \text{ [N/mm}^2\text{]}$$

$$\sigma_c = \sigma_{el} \text{ When } \sigma_{el} < \frac{\sigma_f}{2} \text{ [N/mm}^2\text{]}$$

Where σ_{el} is calculated by:

$$\sigma_{el} = 0.9 \cdot k \cdot \left(\frac{t}{1000 \cdot s} \right)^2 \text{ [N/mm}^2\text{]}$$

Where the k factors are dependent on the orientation of the stiffeners. For longitudinally stiffened plates it is given by:

$$k = k_l = \frac{8.4}{\psi + 1.1} \text{ For } (0 \leq \psi \geq 1)$$

And for transversely stiffened plate it is given by:

$$k = k_t = c \cdot \left[1 + \left(\frac{s}{l} \right)^2 \right]^2 \cdot \frac{2.1}{\psi + 1.1} \text{ For } (0 \leq \psi \geq 1)$$

The c factor is given by what type of stiffener profile you have chosen to use. In our case it is a bulb profile. So the c factor is 1.10. The ψ factor is the ratio between the larger and the smaller compressive stresses in the plate. It has been assumed that the compressive stresses are even over the whole plate so the $\psi = 1$. After calculating the critical buckling stress it is related to the actual compressive stress in the plate with the following formula:

$$\sigma_c = \frac{\sigma_a}{\eta} \text{[N/mm}^2\text{]}$$

η is varying from 1.0 to 0.8 depending on location in the hull and the load level in the panel. Where σ_a for plate panels subjected to longitudinal stresses are given by the formula:

$$\sigma_{al} = \frac{Ms + Mw}{I_N} \cdot (z_n - z_a) \cdot 10^5 \text{ [N/mm}^2\text{]}$$

- Ms = Stillwater bending moment [kNm]
- Mw = wave bending moment [kNm]
- I_N = moment of inertia in [cm^4] of the hull girder
- z_n = vertical distance in m from the baseline or deck-line to the neutral axis of the hull girder, whichever is relevant.

For the buckling check of the stiffeners the actual compressive stresses are calculated in the same way as for the plates, the critical stress as well. But the σ_{el} that is calculated in differently:

When performing the buckling check for stiffeners, the moment of inertia and cross sectional area is calculated with an effective flange 80% of the stiffener spacing. This is in accordance with the rules.

The script checks the allowable stress of the plate or stiffener towards the critical buckling stress. If the critical buckling stress is lower than the allowable stress in the plate, the critical stress replaces the allowable stress in the requirement equations above.

$$\sigma_{el} = 0.001 \cdot E \cdot \frac{I_A}{A \cdot l^2} \text{ [N/mm}^2\text{]}$$

- I_A = moment of inertia in [cm^4] about the axis perpendicular to the expected direction of buckling.
- A = cross sectional area in [cm^2]
- l = length in [m] for the stiffener
- E = $2.06 \cdot 10^5$ [N/mm^2] for steel.

In the additional requirements for LNG carriers, specific design rules is stipulated for plates and stiffeners of inner hull supporting membrane tanks. These rules are similar to the thickness requirements for plates and section modulus requirements for stiffeners on the design rules. The main difference is the pressures used. The pressure for these calculations, p_{eq}, accounts for slushing effects in the tank and is calculated by acceleration and liquid height parameters. The actual equation for the tank pressure is the sum of the design vapour pressure p_0 and the liquid pressure $(p_{gd})_{max}$.

$$p_{eq} = p_o + (p_{gd})_{\max} \text{ [bar]}$$

The design vapour is a constant value usually set to 0.25 [bar], but the liquid pressure is variable of the dimensionless acceleration aβ and the liquid height Z_β. The acceleration results from gravitational and dynamic loads, in an arbitrary direction β, while the liquid height is the largest liquid height [m] above the point where the pressure shall be determined measured from the tank shell in the β direction.

$$p_{gd} = \frac{a_b Z_b r}{1.02 \times 10^4} \text{[bar]}$$

The dimensionless acceleration is defined as the distance from a point on the elliptic curve formed by relationship between vertical and transverse accelerations in the tank, to a unit height above the z-axis. In order to find the $(p_{gd})_{max}$, it's necessary to find the largest value the angel β. When this is achieved the dimensionless acceleration aβ will be the distance to this point. When calculating the different values for Zβ, the tank dome is considered as part of the accepted volume of liquid. The illustration below shows the definition of dimensionless acceleration and liquid height (Figure 15).

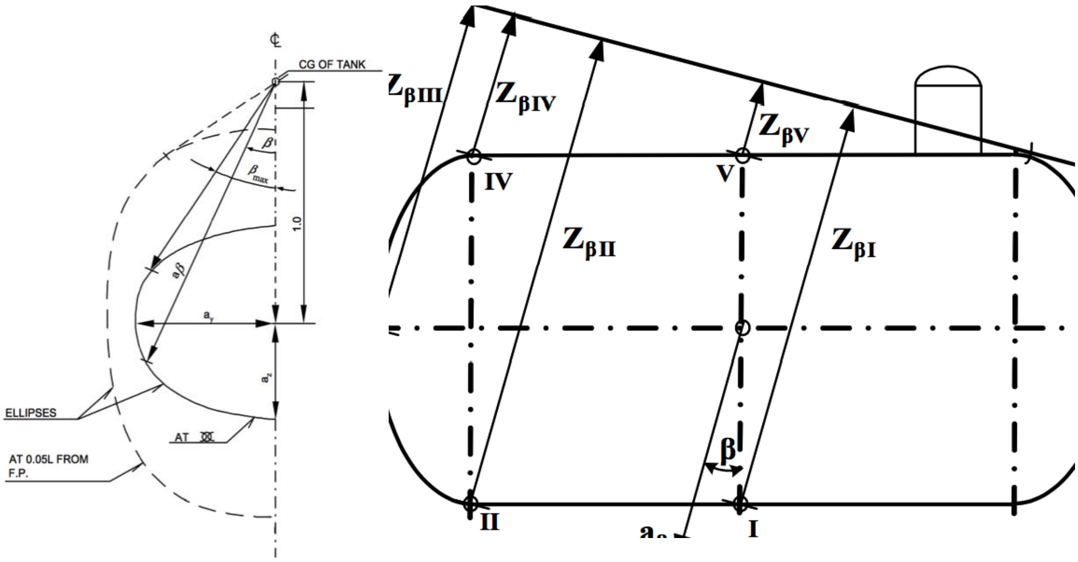


Figure 15 Definitions of the dimensionless acceleration and liquid height

In order to create normalized constraint values to be evaluated by the PSO, the equation introduced by Hughes is used:

$$g_i(x) = \frac{a_i(x) - |b_i(x)|}{a_i(x) + |b_i(x)|} \quad \text{Equation 3}$$

In the script $a_i(x)$ represents the respective requirement and $b_i(x)$ the structural value checked. The script also checks for global requirements, such as the section modulus of the hull girder, but no harmonisation between adjacent strakes is performed.

In order to calibrate the cross section script, a test case was run using a fixed input of one feasible solution. This test case was created using the DNV software Nauticus hull. The software suggests scantlings for a desired cross section according to the same rules used here. It was than possible to force the script to run this one case, so calibration could be done (appendix A3).

8.3.2 The IACS Polar Class script

In the IACS PC script a similar approach as in the design load script was used to identify correct stiffener orientation and strakes. One difference is the choice of class specific coefficients, which is selected separately. The method is simple, as the coefficients are selected by column location according to class. A part of the code is show below for the selection of crushing failure factor:

```
CFc = [17.69 9.89 6.06 4.50 3.10 2.40 1.80];          %Crushing failure class factor

if Isklasse == 1
            CFc = CFc(1,1) ;
if Isklasse == 2
           CFc = CFc(2,1) ;
.
.
end
```

The different coefficients determine the magnitude of the load for the different classes and regions. These will not be listed here, since it would contribute to the study. However local requirements of shell plating, web area and section modulus will be mentioned.

Shell plate requirements are in the rules defined as; the thickness required for resisting ice loads (t_{net}), plus a corrosion and abrasion addition. In this thesis the latter is neglected. The formulation for t_{net} is slightly different depending on the framing orientation and relative angel of the shell plate. In the script both requirement for longitudinal and transverse framing is included, but as mentioned the scope of this thesis does not include transverse framing.

$$t_{net} = 500 \times s \times \sqrt{\frac{AF \times PPF_p \times P_{avg}}{\sigma_f}} \times \frac{1}{1 + s/(2 \times l)} \text{ [mm]}$$

- s = longitudinal frame spacing in longitudinally-framed ships [m]
- AF = Hull Area Factor
- PPF_p = Peak Pressure Factor
- P_{avg} = Average patch pressure [MPa]
- σ_F = minimum upper yield stress of the material [N/mm] ((355 MPa used for this script)
- b = height of design load patch [m]
- l = Distance between frame supports [m]

The requirements for longitudinals are the effective sheer area and the effective plastic modulus.

$$A_l = 100^2 \times (AF \times PPF_s \times P_{avg}) \times 0.5 \times b_1 \times a / (0.557 \times \sigma_F)$$ **Equation 11**

$$Z_{pL} = 100^3 \times (AF \times PPF_s \times P_{avg}) \times b_1 \times a^2 \times A_4 / (8 \times \sigma_F)$$ **Equation 12**

- PPFs = Peak Pressure Factor
- b1 = ko·b2 [m]
- ko = 1-0.3/b'
- b' =b/s
- b = height of design ice load patch [m]
- s = spacing of longitudinal frames [m]
- b2 = b(1-0.25·b') [m], if b'< 2 – s [m], if b' ≥ 2
- a = longitudinal design span [m]
- A4 = 1 / (2 + kwl·[(1 - a42) $^{0.5}$ - 1])
- a4 = Al/Aw
- Aw = net effective shear area of longitudinal [cm]
- kwl = 1 / (1 + 2·Afn / Aw)
- Afn = Net cross-sectional area of local frame flange [cm]

For load carrying stringers and web frames similar expressions are used for checking effective sheer area and the effective plastic modulus. A difference is that these expressions also includes factors for sheer response and uses a usage factor (0.9). The web thickness of these members is also checked, though this is only required for members were it is not practical to calculate the effective sheer area and the effective plastic modulus. The reason it was done for this thesis is that thickness of web is the only variable available in the optimisation.

$$t_{wn} = 2.63 \times 10^{-3} \times c_1 \times \sqrt{(\sigma_F / (5.34 + 4 \times (c_1 / c_2)^2))} \text{ [mm]}$$

- c_1 = hw-0.8h [mm]
- hw = web height of stringer/web frame [mm]
- h = height of framing member penetrating the member under consideration (0 if no such framing member) [mm]
- c_2 = spacing between supporting structure oriented perpendicular to the member under consideration [mm]

Buckling checks are performed for all members in accordance with previous described method. The way it is implemented into the rules are however different. Instead of evaluating towards the design load, it is evaluated towards the yield stress.

8.3.3 The RR Arctic Class script

This script uses some of the same methodology as the IACS script, but does not include the check for stiffener orientation as rules for transverse framing is not included. Instead an improvement was done in selecting correct strakes for different ice classes. Instead of just using the ice class id numbers for the different class specific factor, it is also used them to select the correct strakes. The strake id numbers must still be written in manually for each case, but it is no longer necessary to include or exclude numbers for higher or lower class comparisons. The method is shown below:

```
for i = 1:Csec_size/2
    if  Isklasse == 5 || Isklasse == 6 || Isklasse == 7
        if Strakes(1,1,i) == 21 || Strakes(1,1,i) == 22
        …..
        end
    elseif Isklasse == 4
        if Strakes(1,1,i) == 21 || Strakes(1,1,i) == 22
        …..
        end
    elseif Isklasse == 3 || Isklasse == 2 || Isklasse == 1
        if Strakes(1,1,i) == 21 || Strakes(1,1,i) == 22
        …...
        end
    end
end
```

The Russian requirements are, somewhat difficult to interpret. Most requirements contain several variables that are integrated into sub-calculations, which the author finds hard to explain. Some of the requirements used in the script will be presented, though not all variables will be included.

The expression used for checking the shell plating consists of the thickness required for resisting ice loads (S_{sp0}) and an addition for corrosion and abrasion addition. The latter is determined by the planned ship life (in years) and an annual reduction factor. In contrast to the IACS rules this is included in the script. In retrospect this should have been excluded from the calculations, and will be considered a source of error in the comparison.

$$S_{sp} = S_{sp0} + \Delta S_{sp0}$$ **Equation 13**

$$S_{sp0} = 15.8 \times a_o \times \sqrt{\frac{p}{R_{eH}}}$$ **Equation 14**

$$\Delta S_{sp0} = T \cdot u$$ **Equation 15**

$$a_o = \frac{a}{1 + 0.5 \times \frac{a}{c}}$$ **Equation 16**

- p = ice pressure in the region under consideration [kPa]
- *c* =*l* where the grillage is longitudinally framed in the region under consideration;
- *b*= vertical distribution of ice pressure in the region under consideration [m]
- *l* = distance between adjacent transverse members [m]
- *a*= spacing of main direction girders, in m
- *T*= planned ship life, in years;
- *u*= annual reduction of shell plating thickness (taken from table in rules)
- R_{eH} = Yield stress [MPa] (355 MPa used for this script)

Longitudinals, girders and web frames are as in the IACS rules checked against ultimate capacity criteria. The RR rules do however offer two approaches for this; an iterative approach and one simplified. Both of these serve the same purpose of assuring a minimum residual capacity of the structural member. For this script the simplified approach was chosen. The approach is reflected in calculations for minimum ultimate section modulus of web frames, girders and longitudinals. By using this approach it is however imposed an additional criteria of the actual web area to be at least 10% higher than the requirement. The equations defining the requirements are similar for the different structural members though not entirely. There are differences in additional factors, which is not described in the rules. The requirements for ultimate section modulus and web area of longitudinals are show further down. Longitudinals are also checked for minimum web thickness, flange width and stiffener spacing.

$$W_l = W_{l0} \cdot k_l \quad \text{Equation 17}$$

$$W_{l0} = \frac{125}{R_{eH}} \cdot p \cdot b_1 \cdot (l - 0.5 \cdot a) \cdot c^2 \cdot w_l \quad \text{Equation 18}$$

$$A_l = \frac{8.7}{R_{eH}} \cdot p \cdot b_1 \cdot l \cdot c \cdot k_l + 0.1 \cdot h_l \cdot \Delta s \quad \text{Equation 19}$$

- k_l = 0.63 (simplified)
- p = ice pressure in the region under consideration [kPa]
- $b_1 = k_0 b_2$
- a = spacing of longitudinals [m]
- l = spacing of floors and deep frames [m]
- c = 1 for longitudinals
- ω_l = 1.15 63 (simplified)
- b_2 = function of vertical distribution of ice pressure in the region under consideration [m]

9 Results

Before optimizing of the individual classes could commence, feasible populations had to be created. The feasible populations were created for each class by letting the PSO create 2000 random versions of the cross section for a fixed web frame spacing of 3 meters. A small peace of code then wrote the feasible solutions to a text file. From this text file, 125 feasible solutions were chosen as the initial feasible solution to be optimized. This number has to be equal to the number of strakes (38) multiplied by the number of variables per strake (3), plus the number of web frame sections (11). The optimization was then run four times, with 250 generations per run. This was done to in order to get as many data points as necessary to get an conversion towards an average optimum weight per class. To illustrate the process of optimization, the best results for each class were plotted in the same graph. In Figure 16 and Figure 17, the objective function is on the y-axis and the number of generations on the x-axis. In the first generations one can see that it quickly finds feasible solutions were better weights are calculated. After about 100 generations the graph starts to level out, as most constraints are optimized.

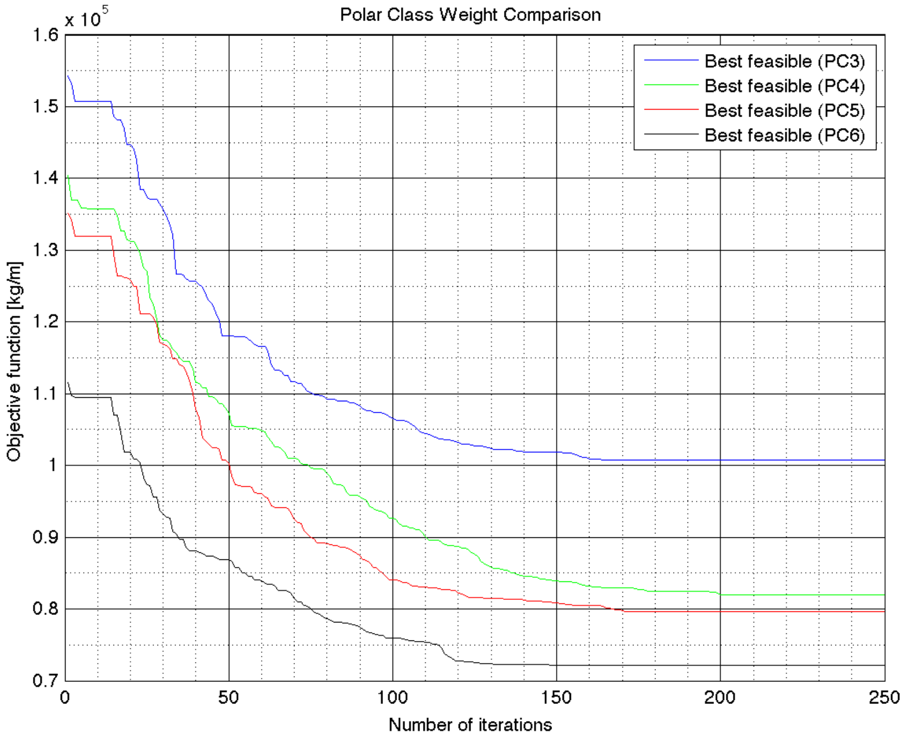


Figure 16 The development of Polar Class optimization

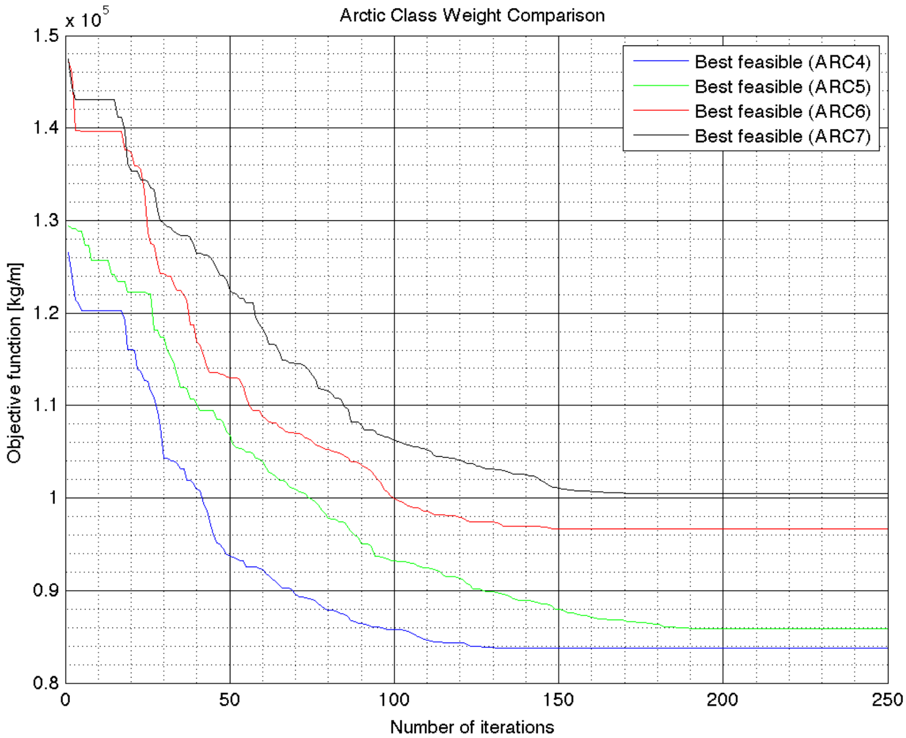


Figure 17 The development of Arctic Class optimization

	Arc7 [kg/m]	Arc6 [kg/m]	Arc5 [kg/m]	Arc4 [kg/m]
Run1	111770	98218	97066	83744
Run2	103070	103260	85905	84363
Run3	100450	96698	93910	89327
Run4	108250	94376	90520	85871

Table 8 The Arctic Class data scatter

	PC3 [kg/m]	PC4 [kg/m]	PC5 [kg/m]	PC6 [kg/m]
Run1	104080	92106	80086	72208
Run2	103920	89395	79690	77462
Run3	100800	81970	85585	77265
Run4	112390	93782	85091	78104

Table 9 The Polar Class data scatter

The tables above (Table 8, Table 9) show the obtained data scatter for the different runs. As seen here some of the classes, like Arc6, have values with varying up to 8%. This is why at least 4 runs are required in order to get a convergence towards an average. In Table 10 the optimum average values obtained for each Arctic Class, is compared with its equivalent Polar Class. The values are presented as absolute value and as percentage value. Also the percentage increase between the higher and lower class is included.

Arctic Class	Averaged weight [kg/m] and percentage increase	Polar Class	Averaged weight [kg/m]	Difference [%]
Arc4	85826	**PC6**	76260	11.15
	7%		8%	-
Arc5	91850	**PC5**	82613	10.06
	6%		8%	-
Arc6	98138	**PC4**	89313	8.99
	7%		15%	-
Arc7	105885	**PC3**	105298	0.55

Table 10 The average values created by optimization.

These results show that the weights generated for the Arc4-7 are in general about 10% higher than the equivalent Polar Class results. The exception being the Arc7 and PC3, where an average difference of only 0.55% was found. When comparing the results from Arc4-7, there is an even increase between 6% and 7%. This is as expected as the main difference between the classes is the load determining parameters, except for Arc4 where the bilge is not included in the requirements. Between PC6-4 we can see the similar effect as for the Arctic Classes, with a steady increase of 8%. A notable exception is the increase from PC4-3, were a significant increase of 15% is calculated. This is of course due to the bottom strakes and floors being included in the rules.

Between the lower classes there is an increase of between 6-8% when compared with the above class. A notable difference is found between PC4 and PC3, where the weight increases with 15%. The reason for this is that PC3 also has requirements for the bottom.

In order to investigate how the weight is distributed in Arctic Classes compared with the Polar Classes, the scantlings of strakes covered by ice rules are compared. As with the weight comparison, all the variables were averaged before compared (Appendix: A2). When comparing the results, it was surprising to find that the scantlings between the classes were surprisingly similar. In fact several of the strakes of the Polar Classes, which has an overall lower weight than the Arctic Class, had larger scantlings. The only strake that had significant increase in scantling compared to the Polar Class was the ice belt. The requirement that drives this is the plastic section modulus, which results in both larger profiles and a significantly higher number of stiffeners per strake. The difference in scantlings is shown in the appendix (A1), but Table 11 shows the scantlings for the ice belt.

Strake number 8 – Ice belt	PC 3	Arc 7	PC 4	Arc 6	PC 5	Arc 5	PC 6	Arc 4
Thickness [mm]	39	33	36	38	25	43	29	27
Stiffener type	20	22	11	22	11	18	11	9
Number of stiffeners per strake	30	65	36	33	36	49	31	43

Table 11 The scantling for the ice belt

When comparing the web frames results, the average thickness for the web was significantly higher for the PC3 class than for the Arc7. In fact the PC rules are in general higher than the Arctic Class.

Girder number	PC3	Arc7	PC4	Arc6	PC5	Arc5	PC6	Arc4
1	51	-	-	-	-	-	-	-
2	60	-	-	-	-	-	-	-
3	53	-	-	-	-	-	-	-
4	59	-	-	-	-	-	-	-
5	35	14	23	12	23	11	18	12
6	50	19	55	14	55	10	55	15

Table 12 The web thickness requirements

10 Discussion

This thesis has performed a case motivated study of the sensitivity of ice classifications for LNG carriers. A relevant region of the Artic was determined by reviewing the current and future of the Arctic landscape. In accordance with this the thesis targeted ice rules, which covered a range of navigation by todays regulations. These classifications sets were integrated into a rule-based analysis tool that optimizes the chosen midship cross-section for lowest weight. This method was motivated by previous studies indicated significant differences in weight for apparently equivalent classifications.

In the results the average optimum weight indicated that there is a significant increase in hull mass when opting a Russian Register Arctic Class compared to an equivalent IACS Polar Class. Since the difference between these two classifications were very consistent, with the exception of PC3 vs. Arc7, it was expected that the scantlings covered by of the Arctic Classes rules would be generally greater than the PC covered ones. This turned out to be a false assumption. The only area, which produced consecutively larger scantlings for Arc than PC, was the ice belt (Strake 8). It is most likely that this is due to the high plastic section modulus requirements in this region, which would explain why it was necessary to select large stiffener profiles, many stiffeners and thick plates. When considering the expression for the section modulus for longitudinal framing in the Russian rules we can see that it is a function of the strake width, which would explain why the results for this strake became so large. This strake for the Russian case study is 8.7 meters. The reason for the large width of this area, known as region of alternating drafts, is calculated by minimum and maximum drafts. This result in the strake width used in this case study. The rules do however require additional framing of strakes longer than 2 meters, but this was neglected as this is intended to be a conceptual study. It is assumed that even though the solution is non-realistic, the weight comparison will still be relevant. The sensitivity the ice-belt section modulus has to the hull mass, would suggest that the method suggested in the report referenced in the introduction is justified at least in this scenario (E. M. Appolonov et al., 2007).

In the process of running the analysis it became apparent that the optimization approach has weaknesses, which needs to be dealt with before sensible results can be obtained. The particle swarm optimization is a quick method of optimization but since the script only uses one constraint, less optimized solutions can occur. What happens in these cases is that a governing constraint might be very close to an optimum value (close to 0), but this does not mean that the other constraint will be anywhere near the optimum. Times where the author experienced this repeatedly was when optimizing for the higher Arctic classes. What occurred was that the calculated requirements were so high, that only the larges values in the available range produced feasible results. This meant that this constraint was always the dominating the optimization, and overly conservative solutions for the rest of the cross section were selected. The remedy was simply to increase the range, which is why scantlings for the highest PC and Arctic Classes are non-realistic.

11 Conclusion

The stated hypothesis of a relation between the applied ice class and the structural weight of an LNG carrier has been confirmed in this thesis. This has the potential to impact the decision of classification level from a stockholder point-of view. Where choosing a classification level might be an evaluation of navigational flexibility with less payload, and reduced navigational freedom and a higher profit per trade. There are changes in the Arctic climate, which may also allow flexible navigation for these lower classes. Also this thesis confirmed what previous studies has indicated that the Russian Register Arctic rules residual capacity of strength members in the ice belt, ads additional mass in comparison with IACS Polar Class rules.

12 Further work

The method used in this thesis has a lot of potential for more applicable and realistic scenarios than introduced here. One way of doing this would be to integrate the optimization with finite element software. This has already been done for collision scenarios, the author also envision this to be used as an efficient pre-engineering tool. It is important for ship designers to be able to estimate the steel weight at a very early stage, as this is used for engineering purposes and for pricing a vessel correctly. However this would require an implementation of some sort of local strakes personification and ability to handle all types of framing. Also the input for the cross section should be improved in terms of handling curvature and the user interface. The selection of constraints would also need to be improved, maybe with a more evaluated method for selecting the best constraint.

13 References

Agency, The Finnish Transport Safety. (2010). Finnish-Swedish Ice Class Rules.

Appolonov, E.M., Nesterov, A.B., Paliy, O.M., & Timofeev, O.Ya. (2007). A System Of Forming Fundemental Engineering Solutions On Assurance Of Ice Strength And Safe Ship Service In Russian Arctic. *Arctic Shipping*.

Appolonov, Evgeny. (2000). Shell Plating.

Arctic rapidly gaining winter ice. (2012). *Arctic sea ice and analysis.* Retrieved June 4, 2013

Assessment, Arctic Marine Shipping. (2009). Arctic Marine Infrastructure.

Birol, Fatih. (2011). World energy outlook. *International Energy Agency*.

Bourke, Robert H., & Garrett, Robert P. (1986). Sea ice thickness distribution in the Arctic ocean.

Bridges, R., Hasolt, S., Kim, MS., & Riska, Kaj. (2005). Current hull and machinery ice class rules, requirements and impact of IACS Polar rules.

Ehlers, Sören. (2010). A procedure to optimize ship side structures for crashworthiness. *Proceedings of the Institution of Mechanical Engineers, Part M: Journal of Engineering for the Maritime Environment, 224*(1), 1-11. doi: 10.1243/14750902jeme179

Foss, Michelle Michot. (2007). Introduction To LNG. http://www.beg.utexas.edu/energyecon/lng/documents/CEE_INTRODUCTION_TO_LNG_FINAL.pdf: Center For Energy Economics.

Hughes, Owen F. (1980). A Practical Method for the Rational Design of Ship Structures.

Kendrick, Andrew, & Daley, Claude. (2000). Shell Framing.

Kennedy, James, & Eberhart, Russell. (1995). *Particle Swarm Optimization*. Paper presented at the ICNN'95 - International Conference on Neural Networks.

Kwok, R., Hunke, E. C., Maslowski, W., Menemenlis, D., & Zhang, J. (2008). Variability of sea ice simulations assessed with RGPS kinematics. *Journal of Geophysical Research, 113*(C11). doi: 10.1029/2008jc004783

Kwok, R., & Rothrock, D. A. (2009). Decline in Arctic sea ice thickness from submarine and ICESat records: 1958–2008. *Geophysical Research Letters, 36*(15). doi: 10.1029/2009gl039035

Kwon, JinChil, Jeon, ByungYeong, Kim, JaeHyun, Bo Wang, Han Yu, Basu, Roger, Lee, Hoseong, . . . Kendrick, Andrew. (2008). *Structural Integrity Assessment of Cargo Containment Systems in Arctic LNG Carriers under Ice Loads*. Paper presented at the Fourth Annual Arctic Shipping 2008 Conference, St. Petersburg, Russia.

Kwon, JinChil, Kim, Byung Yeong Jeon JaeHyun, Wang, Bo, Yu, Han, Basu, Roger, Lee, Hoseong, . . . Kendrick, Andrew. (2008). Structural Integrity Assessment of Cargo Containment Systems in Arctic LNG Carriers under Ice Loads.

Lindholt, Lars, & Glomsrød, Solveig. (2011). The role of the Arctic in future global petroleum supply.

Shipping, Russian Maritime Register Of. (2011). Rules for The Classification And Construction Of Sea-Going Ships (Vol. Volume 1): Saint-Petersburg.

Societies, International Association Of Classification. (2011). IACS polarclasses requirements.

Timco, G.W., Collins, A., & Kubat, I. An approach for including polar class vessels in the canadian arctic shipping regulations.

Tustin, Robert. (2005). Recent developments in LNG and ice-class tanker design and the potential application to future Arctic LNG ships.

Vanem, Erik, Antão, Pedro, Østvik, Ivan, & de Comas, Francisco Del Castillo. (2008). Analysing the risk of LNG carrier operations. *Reliability Engineering & System Safety, 93*(9), 1328-1344. doi: 10.1016/j.ress.2007.07.007

14 Appendix

A1

ID		Arc7	%	PC3	Arc6	%	PC4-
1	Thick.	28	0.55	13	29	0.17	24
	Type	15	-0.19	17	17	0.36	11
	Number	6	-0.48	9	6	-0.22	7
2	Thick.	25	0.51	12	25	-0.19	29
	Type	13	-0.52	19	16	0.34	10
	Number	9	-0.83	16	10	-0.29	12
3	Thick.	25	-0.01	25	21	0.00	21
	Type	13	-0.22	16	15	0.20	12
	Number	7	-0.86	13	8	-0.16	9
4	Thick.	25	0.50	12	21	-0.18	25
	Type	14	-0.09	16	16	0.11	14
	Number	14	-1.00	27	15	-0.24	18
5	Thick.	22	0.00	22	19	-0.11	21
	Type	14	-0.19	17	17	0.07	16
	Number	4	-0.27	5	4	0.59	2
6	Thick.	19	0.14	16	17	-0.44	24
	Type	17	0.13	15	16	-0.25	20
	Number	18	-0.15	21	14	0.19	12
7	Thick.	25	-0.14	29	26	-0.13	30
	Type	14	-0.23	17	14	0.18	12
	Number	4	-1.86	10	6	-0.36	9
8	Thick.	33	0.12	29	38	0.05	36
	Type	22	0.08	20	22	0.51	11
	Number	65	0.53	30	33	0.02	32
9	Thick.	12	-0.15	13	13	0.17	11
	Type	14	0.02	14	15	0.18	12
	Number	9	-0.46	13	12	-0.02	12
10	Thick.	10	-0.15	12	16	-0.22	20
	Type	16	-0.12	18	13	0.13	11
	Number	3	0.00	3	2	-3.67	11
11	Thick.	22	0.34	15	15	0.02	15
	Type	14	-0.38	19	16	0.27	11
	Number	2	0.00	2	4	0.07	3
12	Thick.	25	0.20	20	15	0.10	14
	Type	13	0.10	12	11	-0.07	11
	Number	8	-0.03	8	19	0.41	11
13	Thick.	19	-0.09	21	15	-0.83	28
	Type	12	-0.39	16	13	0.13	11
	Number	4	-0.40	5	6	0.63	2
14	Thick.	13	0.09	12	14	-0.18	17
	Type	12	0.15	10	13	0.23	10
	Number	13	0.42	8	13	-0.15	15
15	Thick.	17	0.26	13	19	0.08	17
	Type	18	0.00	18	12	0.33	8
	Number	2	0.56	1	8	0.37	5

16	Thick.	18	0.14	16	20	-0.04	21
	Type	13	-0.28	16	13	-0.25	16
	Number	6	0.24	5	7	0.59	3
17	Thick.	16	-0.54	25	16	-0.25	20
	Type	13	0.08	12	15	0.14	13
	Number	7	-0.22	8	7	0.46	4
18	Thick.	12	-0.85	22	21	0.19	17
	Type	11	-0.24	14	14	0.07	13
	Number	6	0.30	4	6	-0.71	10
19	Thick.	14	-0.28	18	18	0.27	13
	Type	11	-0.91	21	15	0.14	13
	Number	7	0.42	4	13	-0.04	14
20	Thick.	12	-1.21	27	16	-0.48	23
	Type	14	-0.16	16	15	0.33	10
	Number	5	0.00	5	7	0.19	6
21	Thick.	24	-0.27	31	18	-0.46	26
	Type	18	-0.03	18	16	-0.28	21
	Number	10	0.66	3	5	0.40	3
22	Thick.	39	0.59	16	17	-0.09	19
	Type	16	0.03	15	16	-0.18	19
	Number	9	0.38	5	10	0.73	3
23	Thick.	16	-0.02	16	12	-0.70	20
	Type	12	-0.29	16	16	-0.10	17
	Number	5	-0.11	5	5	0.50	2
24	Thick.	12	-0.48	18	12	-0.15	14
	Type	13	0.00	13	13	0.16	11
	Number	2	-0.50	3	10	0.71	3
25	Thick.	24	0.12	21	21	0.34	14
	Type	16	-0.19	19	14	-0.42	20
	Number	2	0.43	1	6	0.32	4
26	Thick.	14	0.20	11	22	0.29	16
	Type	15	0.34	10	14	-0.29	18
	Number	9	0.69	3	2	-1.29	4
27	Thick.	17	-0.62	28	15	-0.80	28
	Type	16	0.15	13	11	0.09	10
	Number	4	0.44	2	3	-1.36	7
28	Thick.	25	0.37	16	13	0.12	12
	Type	12	-0.13	14	13	0.04	12
	Number	11	0.56	5	8	-0.27	10
29	Thick.	13	-1.31	30	15	-0.12	17
	Type	14	0.16	12	12	0.00	12
	Number	7	-0.34	10	8	0.20	6
30	Thick.	11	-0.09	12	12	-0.06	13
	Type	13	0.13	11	13	0.13	12
	Number	10	0.05	9	11	0.11	10
31	Thick.	14	0.16	12	21	0.05	20

	Type	12	-0.02	13	13	0.02	13
	Number	6	-0.04	6	4	-0.81	7
32	Thick.	11	-0.57	17	12	-0.49	18
	Type	13	0.18	10	13	0.15	11
	Number	16	0.09	15	15	0.44	8
33	Thick.	16	-0.11	18	13	-0.12	14
	Type	12	-0.02	12	12	-0.40	17
	Number	15	0.43	8	16	0.40	10
34	Thick.	11	-0.87	21	13	0.02	13
	Type	13	0.25	10	14	0.28	10
	Number	6	-0.35	8	11	0.42	6
35	Thick.	15	0.29	11	17	0.39	10
	Type	12	-0.19	14	13	0.21	11
	Number	12	0.26	9	21	0.49	11
36	Thick.	15	-0.08	16	11	-0.02	11
	Type	17	0.30	12	15	0.07	14
	Number	8	0.00	8	9	-0.03	9
37	Thick.	24	0.54	11	19	0.25	14
	Type	12	0.09	11	17	-0.14	20
	Number	2	-1.83	4	3	0.62	1
38	Thick.	18	0.31	13	15	-0.41	21
	Type	18	0.42	11	13	-0.21	16
	Number	1	-2.40	4	5	0.57	2
1	Web□t.	19	-1.66	51	20	-0.49	30
2	Web□t.	13	-3.60	60	17	-0.08	18
3	Web□t.	27	-0.94	53	16	0.16	13
4	Web□t.	15	-2.85	59	13	0.15	11
5	Web□t.	14	-1.55	35	12	-0.94	23
6	Web□t.	19	-1.67	50	14	-2.93	55
7	Web□t.	16	0.02	16	19	0.14	16
8	Web□t.	16	-0.60	25	16	0.02	16
9	Web□t.	16	0.25	12	21	0.42	12
10	Web□t.	13	-0.13	15	15	-0.57	24
11	Web□t.	19	-0.19	23	14	-0.69	23
	Total	105885	0.01	105298	98138	0.09	89313

ID		Arc5	%	PC5	Arc4	%	PC6
1	Thick.	24	-0.09	27	25	0.11	22
	Type	22	0.51	11	19	0.41	11
	Number	4	-0.80	7	5	-0.90	10
2	Thick.	23	-0.03	23	25	-0.10	27
	Type	13	-0.23	16	17	0.37	11
	Number	7	-0.31	9	18	0.41	10
3	Thick.	28	0.04	27	33	0.29	23
	Type	13	0.04	13	13	0.29	9
	Number	7	-0.04	7	9	-0.24	11
4	Thick.	28	0.14	24	22	-0.03	23
	Type	16	0.34	11	10	0.32	7
	Number	12	-0.80	21	12	0.04	11
5	Thick.	28	0.35	19	25	0.03	24
	Type	13	0.20	10	11	-0.58	18
	Number	1	-3.25	4	4	0.67	1
6	Thick.	14	-0.22	17	19	0.17	16
	Type	12	0.13	11	12	0.28	9
	Number	16	0.05	16	10	-0.59	16
7	Thick.	16	-0.32	22	21	0.29	15
	Type	13	0.08	12	15	0.08	14
	Number	5	-0.14	6	8	0.09	8
8	Thick.	43	0.42	25	27	-0.08	29
	Type	18	0.40	11	17	0.32	11
	Number	49	0.27	36	43	0.28	31
9	Thick.	12	-0.04	13	10	-0.12	12
	Type	14	-0.11	15	12	0.26	9
	Number	11	0.19	9	15	0.32	10
10	Thick.	14	-0.04	15	12	-0.14	14
	Type	15	-0.10	16	12	-0.04	13
	Number	2	-1.89	7	8	0.50	4
11	Thick.	12	-0.71	21	23	0.00	23
	Type	11	-0.42	16	13	0.29	9
	Number	6	0.57	3	6	-0.17	7
12	Thick.	14	0.13	12	17	0.27	12
	Type	15	0.22	11	12	0.20	9
	Number	8	-0.03	8	15	0.37	10
13	Thick.	27	0.21	21	21	0.35	14
	Type	17	0.32	12	11	0.44	6
	Number	2	-2.50	7	6	-0.26	7
14	Thick.	13	-0.02	13	12	0.00	12
	Type	16	0.31	11	10	0.00	10
	Number	8	-1.73	21	12	0.22	9
15	Thick.	23	0.02	23	13	-0.81	24
	Type	14	-0.39	20	12	0.04	12
	Number	4	0.76	1	2	-1.71	5

16	Thick.	23	-0.04	24	21	0.01	21
	Type	13	0.18	10	11	0.51	6
	Number	12	0.50	6	4	-2.00	12
17	Thick.	24	0.40	15	14	0.09	13
	Type	12	0.10	11	16	0.38	10
	Number	7	-0.25	9	4	-1.93	11
18	Thick.	20	0.05	19	17	0.18	14
	Type	11	0.07	11	17	0.45	9
	Number	3	-0.31	4	3	-1.46	8
19	Thick.	19	0.03	19	12	0.00	12
	Type	14	-0.02	14	15	0.20	12
	Number	4	0.12	4	8	0.16	7
20	Thick.	12	-0.20	15	13	-0.40	19
	Type	14	0.05	13	12	0.32	8
	Number	8	0.55	4	7	-0.25	9
21	Thick.	17	0.33	11	30	0.58	13
	Type	16	0.00	16	16	0.55	7
	Number	5	-0.74	8	4	-2.27	12
22	Thick.	22	0.10	20	26	0.55	12
	Type	15	-0.02	15	15	0.67	5
	Number	7	-0.04	7	5	-1.10	11
23	Thick.	22	0.47	12	25	0.47	13
	Type	14	0.21	11	10	0.20	8
	Number	7	0.37	4	4	0.24	3
24	Thick.	16	0.26	12	20	0.11	18
	Type	20	0.41	12	18	0.61	7
	Number	3	-0.77	6	2	-6.63	15
25	Thick.	17	-0.45	24	11	-0.60	18
	Type	12	-0.85	21	16	0.38	10
	Number	1	-0.25	1	4	-0.53	6
26	Thick.	27	0.30	19	12	-0.29	16
	Type	13	0.18	11	12	0.34	8
	Number	3	-0.92	6	1	-2.80	5
27	Thick.	12	-0.57	18	14	-0.36	19
	Type	13	0.10	12	16	0.44	9
	Number	7	0.57	3	3	-0.83	6
28	Thick.	26	0.43	15	16	0.19	13
	Type	11	0.09	10	11	0.36	7
	Number	4	-0.29	5	4	-2.81	15
29	Thick.	13	-0.88	24	14	0.13	12
	Type	10	-0.83	19	13	-0.04	13
	Number	13	0.83	2	8	0.10	7
30	Thick.	21	0.38	13	16	0.19	13
	Type	10	-0.15	12	15	0.12	13
	Number	10	0.24	7	7	-0.24	9
31	Thick.	10	-0.93	20	24	0.39	15

	Type	15	0.10	13	13	0.16	11
	Number	12	0.54	5	3	-1.73	8
32	Thick.	10	0.02	10	12	-0.22	15
	Type	12	-0.15	14	11	-0.05	11
	Number	13	0.02	13	13	0.35	8
33	Thick.	16	0.28	12	13	-0.08	14
	Type	14	0.06	13	10	0.37	7
	Number	9	-1.05	19	10	-1.21	22
34	Thick.	13	-0.26	16	11	-0.39	15
	Type	10	-0.05	11	13	0.47	7
	Number	6	-0.59	9	7	0.08	6
35	Thick.	13	-0.08	14	20	0.04	20
	Type	11	-0.30	14	15	0.55	7
	Number	10	0.25	8	10	-0.05	11
36	Thick.	23	0.55	11	13	0.25	10
	Type	15	0.31	10	11	0.36	7
	Number	11	-0.30	14	10	-0.05	10
37	Thick.	16	0.29	11	18	-0.06	19
	Type	11	0.02	11	14	0.23	11
	Number	3	-2.70	9	2	-0.14	2
38	Thick.	18	-0.41	25	30	0.38	19
	Type	12	-0.19	14	13	0.36	9
	Number	1	-3.75	5	4	0.76	1
1	Web�t.	15	-0.05	16	15	0.14	13
2	Web�t.	15	-0.39	21	13	-0.20	15
3	Web�t.	13	0.02	12	19	0.08	17
4	Web�t.	17	0.09	15	18	-0.07	19
5	Web�t.	11	-1.14	23	12	-0.55	18
6	Web�t.	10	-4.50	55	15	-2.71	55
7	Web�t.	15	0.10	14	13	-0.51	19
8	Web�t.	18	-0.24	22	14	-0.40	19
9	Web�t.	14	0.07	13	16	0.08	14
10	Web�t.	18	-0.70	30	16	0.14	14
11	Web�t.	17	-0.55	26	17	-0.17	19
	Total	91850	0.10	82613	85826	0.11	76260

Strake number		PC3	Arc7	PC4	Arc6	PC5	Arc5	PC6	Arc4
1	t [mm]	13	-	-	-	-	-	-	-
	Type	17	-	-	-	-	-	-	-
	Numb.	9	-	-	-	-	-	-	-
2	t [mm]	12	-	-	-	-	-	-	-
	Type	19	-	-	-	-	-	-	-
	Numb.	16	-	-	-	-	-	-	-
3	t [mm]	25	-	-	-	-	-	-	-
	Type	16	-	-	-	-	-	-	-
	Numb.	13	-	-	-	-	-	-	-
4	t [mm]	12	-	-	-	-	-	-	-
	Type	16	-	-	-	-	-	-	-
	Numb.	27	-	-	-	-	-	-	-
5	t [mm]	22	22	-	19	-	28	-	-
	Type	17	14	-	17	-	13	-	-
	Numb.	5	4	-	4	-	1	-	-
6	t [mm]	16	19	24	17	17	14	16	-
	Type	15	17	20	16	11	12	9	-
	Numb.	21	18	16	14	16	16	16	-
7	t [mm]	29	25	30	26	22	16	15	18
	Type	17	14	12	14	12	13	14	15
	Numb.	10	4	6	6	6	5	8	4
8	t [mm]	39	33	36	38	25	43	29	27
	Type	20	22	11	22	11	18	11	9
	Numb.	30	65	36	33	36	49	31	43
21	t [mm]	31	24	26	18	11	17	13	30
	Type	18	18	21	16	16	16	7	16
	Numb.	3	10	8	5	8	5	12	4
22	t [mm]	14	39	19	17	20	22	12	26
	Type	15	16	19	16	15	15	5	15
	Numb.	5	9	3	10	7	7	11	5

A3

Section modulus for stiffeners comparison, included effective flange

Structural element	ID-number	Strake number	Calculated (Cross_section) [cm3]	Rule (Nauticus) [cm3]	Calculated rule requirement (Design_load) [cm3]
Keel	1	1	1243.71	1265	1631.58
Bottom	2	2	1222.07	1037	1400.56
Bilge	3	3	1216.77	-	842.04
Center girder	11	4	833.00	863	993.94
Side girder	12	5	816.22	845	993.94
Inner plating	4	6	1247.38	1251	1197.50
Stringer	4	7	448.29	447	1057.09
Side plating	6	8	829.93	833-679	885.95
Side plating	6	9	830.15	833-454	718.99
Side plating	6	10	459.31	500-567	718.99
Strength deck	8	11	396.98	420	1076.45
Strength deck	8	12	394.71	397	1068.90
Stringer	9	13	359.89	363	-
Bulkhead plating	10	14	964.75	978	803.60
Inner side plating	10	15	700.51	708-363	718.99
Inner side plating	10	16	365.68	385-459	718.99
Bulkhead plating	10	17	565.10	972-330	827.31