Master's thesis

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Structural Optimisation of an Ice-Strengthened Yacht Vessel

Masters' thesis in Ship Design
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Abstract

The purpose of the thesis was to perform two different methods for structural optimisation of ice-strengthened yacht vessel changing class notation from Ice Class C to Polar Class 6. The problem statement is given by Marin Teknikk AS.

The first method of the thesis used Microsoft Excel to create an application calculating element dimensions for two class notations. The application consists of input, calculation and result sheets.

The second method uses Siemens NX for parametric panel design and finite element analyses. The first part of the method tests an output panel from the calculation application, and by tuning the input parameters, the panel satisfies the requirements of its classification. The panel is localised in the midship ice-belt. In the second part, a case study is completed to investigate if a minimum addition to the Ice Class C panel could make it satisfy the requirements of a polar classification; Polar Class 6. After studied five different cases, a satisfying panel for polar classification is found.

At the end of the thesis, a comparison of the two methods implemented is carried out, focusing on when to apply the different methods and the additional weight for the respective methods.

Sammendrag

Dette prosjektet ble delt inn i to ulike metoder for strukturell optimalisering av en is-klassifisert yacht som skulle bytte klassenotasjon fra isklasse C til polarklasse 6. Oppgaven ble gitt av firmaet Marin Teknikk AS.

I metode én, ble Microsoft Excel benyttet for å utvikle en kalkulasjonsapplikasjon med hensikt å regne ut dimensjoner for elementer inkludert i to ulike klassenotasjoner. Den ferdige applikasjonen består av ark for input, kalkulasjoner og resultatvisning.

I den andre metoden, ble applikasjonen Siemens NX brukt til å gjennomføre en parametrisk model og "finite element" analyse. I del én av metoden testes et beregnet panel fra kalkuleringsapplikasjonen, og ved små justeringer av input tilfredsstiller panelet kravet til sin egen klassenotasjon. Panelet er lokalisert i midtskips isbelte. I del to gjennomføres en studie med ulike tester for å finne minimumsendring av isklasse C-panelet for å møte kravene for islasten polarklasse 6-panelet må tåle. Etter fem ulike tester, ble det funnet et minimumstillegg som gjorde at panelet tilfredsstilte kravet for den høyere klassenotasjonen.

Avslutningsvis i oppgaven vises det en sammenligning av de to gjennomførte metodene, fokusert på gjennomføring og vekt.

Master Agreement

Structural Optimisation of an Ice-Strengthened Yacht Vessel

Background

Over the coming decades the shipping traffic of the arctic environment is estimated to grow significantly, and between 2012 and 2050 by 50%. Because of Global warming, the thinning of polar ice has increased, which leads to an increasing number of ships using the polar environment for their voyages. Due to a growing market for polar exploration yachts, Marin Teknikk AS now wants to study how a change of notation will affect the structural components and how crucial these changes will be.

Scope

There are a lot of requirements to be studied in such theses, but to narrow it down, the student will mainly look at the structural challenges and how ice loads will affect the structural components of a vessel. As a result of changes in structural elements, the student also needs to study how these changes will affect the ship due to weight.

Objectives

The main objective of this thesis is to investigate and analyse how the requirements for structural dimension will be affected due to ice loads in baltic/polar waters. The thesis will focus on the use of two different methods:

1. Rule-based Method
2. Finite Element Method

Research Questions

Research questions were made to narrow down the problem stated in the scope and objectives. These will be used as guidance for the thesis' development.

1. Based on the rule-based design, which class notations are important?

2. Is it possible to add a small amount of structure, or is it needed to modify the original structure to fulfil the higher requirements? **Minimum change**.
3. If the solution is to add more structure or change of the original, how will the optimised panel be constructed due to steel structure weight?

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Preface

This master thesis ends a two-year Master's degree programme for Ship Design at The Norwegian University of Science and Technology, Aalesund. The thesis constitutes the basis for evaluation of the subject "IP501909 MSc thesis, discipline-oriented", and counts 30p.

A special thanks to my supervisor Karl Henning Halse. Halse has facilitated a good dialogue throughout the project period and has laid a solid foundation for the implementation of this project.

I will also thank Ronny Olsen and Christian Vasstrand at Marin Teknikk, for great supervising throughout the whole project period. Without our close cooperation during the project period, the resulting product would not have been as good as it became.

I'm also grateful to my family, who have helped me throughout the rough time with Covid-19 virus in Norway, and let me use all the needed space at home. They have also been great dialogue partners when it was not allowed to move back to school and discuss with other fellow students.

Finally, I would like to thank all the lecturers during my five years at NTNU Aalesund for great talks, functional teaching environments and all help. Maybe our paths will meet again.

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Contents

List of Figures

List of Tables

Part I:

Introduction

1 Introduction

1.1 Problem

Navigation for ships in Baltic and Polar waters has, for a long time being, been a popular travel destination for hunting. In the later years, exploration has also become more and more popular, and yacht vessels are now being classified with cold climate classifications. By classifying vessels for cold climate, new changes may appear in the structural part of the design procedure.

During the navigation in ice-covered waters, the structure of a vessel is exposed to extreme conditions. This can be conditions such as ice loads, icing, compressive ice, ice loads on the propeller, additional ice resistance and change of material properties (Warntjen et al., 2018). In this master thesis, the student will study together with Marin Teknikk AS how a change of class notation will affect the structural elements in the ship hull. Figure 1.1 illustrates the reference ship used in this thesis. The vessel is designed by Marin Teknikk and its name is MT 5006 Mk II Ulysses.

Figure 1.1: MT 5006 Mk II Ulysses (Marin Teknikk AS, 2016).

1.2 Motivation

An important factor in this master thesis is the field of study; hull structure and class notation. A subject as hull structure will lead to a good understanding of the structural segment, which is required to see the bigger picture. The change of class notation is also a topic that has been more and more interesting in the later years for exploring vessels. As Baltic and Polar classification is a topic which is still researched, this motivates the student to look further into the consequences (e.g. change of ice belt, the dimension of plates and cost) of classifying a ship in the specified notation. With higher knowledge of how this affects the hull structure, the procedure of designing a vessel for cold climates becomes easier.

1.3 Scope of work

In ship design, structural dimensioning is a challenge for ship engineers. This is because of all the different type of structures, various loads and ice-/sea-pressures on the hull. Especially in the starting phase of a new design, the dimensions are unclear, and the designers are using rough estimates, personal experience and comparisons to set dimensions on structural elements.

For this master thesis, Marin Teknikk suggested the following: "A study of how a change in the class notation for a vessel will affect the structural design, and how it can be optimised to fulfil the requirements of a higher class notation".

The student is to:

Complete two methods of structural optimisation for a yacht vessel changing class notation from Ice Class C(Hereafter abbreviated as ICE(C)) to Polar Class 6(Hereafter abbreviated as PC(6)). As a result of the research, an excel application calculating new structural dimensions, and finite element analyses to find a minimum change of a panel is to be done. Supervisor at NTNU is Karl Henning Halse. Supervisors at Marin Teknikk is Ronny Olsen and Christian Vasstrand.

1.4 Objective:

The objective of this thesis is divided into two different phases. At first, the thesis will establish a calculation application for structural elements of the ship hull. Secondly, the thesis will focus on creating a panel analysis to find the minimum change required to fulfil a higher class notation.

Structural calculation application

The application should provide a comparison between the structural elements of the hull when the vessel changes from one class notation to another one. The application should include:

- Ice loads
- Plate dimensions
- Stiffener dimensions
- Primary support member dimensions

Finite Element Analysis

The finite element analysis should investigate the minimum change required for a panel of the ship hull. In this part, the analysis will look further into different cases for a better structural optimised panel design. The analysis should include:

- Parametric panel design
- Mesh sensibility study
- Analyse of different cases

1.5 Research questions:

To narrow down the problem stated in the scope and objective, some research questions were established. These were used as guidance for the thesis' development.

1. Based on the rule-based design, which class notations are important?
2. Is it possible to add a small amount of structure, or is it needed to modify the original structure to fulfil the higher requirements? **Minimum change**.

3. If the solution is to add more structure or change of the original, how will the optimised panel be constructed due to steel structure weight?

1.6 Previous work

During the start-up of this thesis, a meeting with a supervisor from NTNU Trondheim was held. He helped this thesis by showing earlier completed theses. The theses were written by Herman Holm (2012), Roy-Andre Pedersen(2013) and David Andre Molnes (2013).

Herman Holm was creating a finite element study of the bow part of KV Svalbard. With this finite element study, he was able to map the stress which the bow part was subject to in 102 different load cases. At the end of his thesis, he compared the results from his finite element study against eleven measurements from the full-scale trials of KV Svalbard.

The other thesis, written by Roy Andre Pedersen(2013), created a rule-based analysis tool to locate the weight sensitivity on an ice classified LNG carriers midship section. His thesis aimed to identify and compare relevant ice classifications with a rule-based method of comparing the weight and cost of targeted ice classes.

A tool which searches after the optimum structural arrangement for different ice classes were made of David Andre Molnes(2013). He used the tool for different types of vessel to see if there was any difference in ice classification of various ships and the choice of ice class.

These three theses have been great to study in the start-up phase of my work. The theses helped me with the understanding of ice-load and how they act on the ship hull.

Part II:

Theoretical Basis and Methods

2 | Ice properties

2.1 Ice loads acting on the hull

Ice loads acting on the hull can be divided into Global and Local loads. Loads coming from single-site ice contacts at different parts or a high load on a particular hull element can be described as local loads. Global loads can be described as the total load from an ice cover acting on the larger elements, such as the entire hull girder or the side shell plating longitudinally (Ghosh S., 2019).

When the vessel is operating in ice, the load response on the hull is time-varying reaction forces that occur due to various load incidence processes.

These loads are:

- Crushing of ice
- Bending of ice
- Submersion of ice floes
- Turning of ice floes
- Sliding of ice floes along the hull

The crushing and bending of ice will primarily occur at the waterline in the bow part of the vessel. The submersion, turning and sliding of ice floes will, including to happen in the waterline of the ship, also be dependent on the submerged hull shape (Warntjen J., 2018).

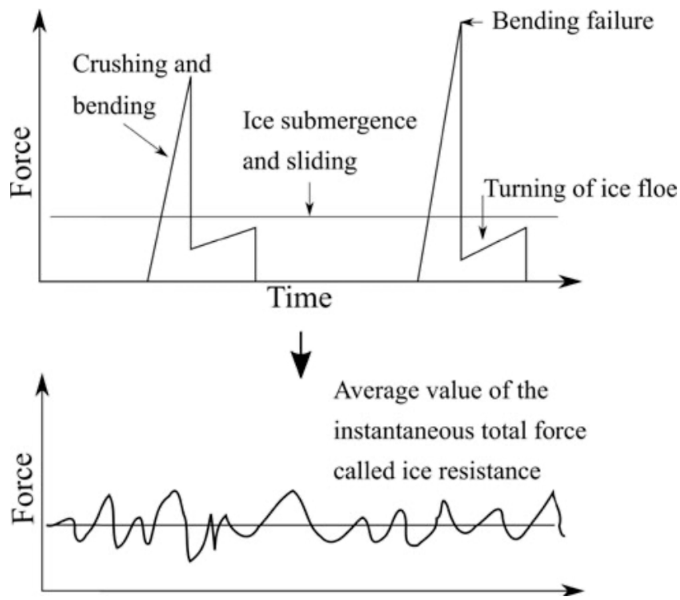


Figure 2.1: Time history of ice forces contributing to ice resistance (Warntjen J., 2018).

Figure 2.1 illustrates how a peak of an ice load distribution varies over time by Suyuthi (2012) is looking. Looking at the ice load in a short term perspective, this may vary from voyage to voyage. Looking at long term perspective, it may differ from winter to winter.

Due to various ice pressure, it is hard to map how the hull will be subject to the ice load. The ice load can be assumed to be like a loaded patch, which is narrow in the vertical direction and long in the horizontal direction (Pedersen R.A., 2013). In real life operations, the vessel will be subject to an irregular load patch, but for structural calculations, the load patch is assumed to be rectangular. The load patch is illustrated in Figure 2.2.

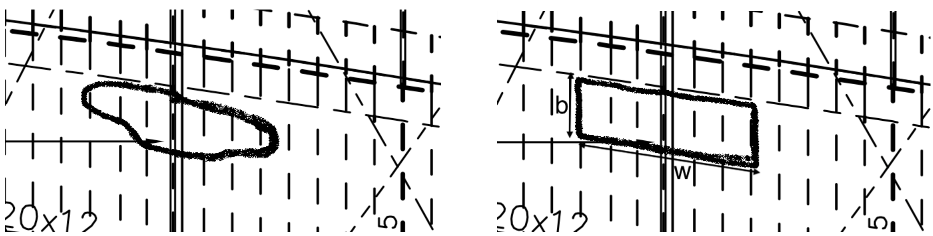


Figure 2.2: Real life vs. calculation friendly load patch.

While looking at the rules made by classification societies, the rectangular load patch assumption is used for structural calculations. The load patch is subject to the maximum pressure, maximum line load and maximum force calculated (DNV GL, 2019):

$$w_{bow}(Horisontal) = \frac{F_{bow}}{Q_{bow}} \tag{2.1}$$

$$b_{bow}(Vertical) = \frac{Q_{bow}}{P_{bow}} \tag{2.2}$$

$$w_{nonbow}(Horisontal) = \frac{F_{nonbow}}{Q_{nonbow}} \tag{2.3}$$

$$b_{nonbow}(Vertical) = \frac{w_{nonbow}}{3.6} \tag{2.4}$$

2.2 Ice thickness

One of the most crucial parts of calculating the ice loads is the ice thickness. The sea ice systems are considered to be vulnerable to climate change (Comiso, 2004), and during a 100-year time series in the 20th century, the length of ice season has decreased by 14-44 days in the last century (Jevrejeva et al., 2004). In the Baltic regions, the ice-covered area would decrease by about 45,000 km^2 for each degrees Celsius increase in the average temperature(Meier, 2002). The sea ice is classified by stages of development that relate to thickness and age (NSIDC, 2020). The different stages can be divided into:

- New Ice
- Young Ice
- First-Year Ice
- Multi-Year Ice

The New ice refers to an ice thickness of less than 100 millimetres. Young ice is the next stage and refers to an ice thickness between 100 and 300 millimetres, and can be divided into two subclasses; grey-ice (100 to 150 millimetres) and grey-white ice (150 millimetres). The two ice thickness classes that are subject for this thesis is the first-year- and the multi-year ice. The first-year ice is dependent on freezing time, wind speed, snow type, and air temperature, and has not survived a summer melt season. The thickness of this type is higher than 300 millimetres. Multi-year ice is dependent on a combination of thermal growth and consolidation of pressure ridges. It has survived at least one summer melt season and is much thicker than the other ones. Normally the thickness of Multi-year ice will be ranging from 2 to 4 meters (Timco and Weeks, 2010)(NSIDC, 2020).

3 | Classification of ships

3.1 Introduction

Commercial vessels operating around the world needs to be classified by a classification society. These societies generate rules for structural elements, painting, furniture, cut-outs, superstructure etc. The most traditional societies in Norway is DNV-GL, Lloyd's Register and American Bureau of Shipping.

To get a higher knowledge about the classification of ships which is operating in Baltic and Polar regions, the rules and classifications made by DNV GL will be used. DNV GL is a classification society that is making rules and regulation for different types of vessels. This thesis will focus on the rules for the classification of ships navigating in cold climate (DNV GL, 2019). As written in the Scope of the project, Section 1.3, the main topic is the change of class notation from Ice(C) to PC(6). As the change of class notation is Ice(C) to PC(6), there are only two different regions which will be included in this thesis:

Baltic regions: "Ice strengthening for the Northern Baltic Pt.5 Ch.1 Sec.3"

General Polar regions: "Polar class Pt.5 Ch.1 Sec.8"

3.2 Class system

As the thickness of ice will vary across areas, the societies are dividing the rules and regulations into different regions. As commented above, the regions included in this thesis is Baltic and Polar, where the Polar region has the most strict rules. For both Baltic and Polar regulations, these are divided into different individual notations. The Baltic region is divided into Ice(1A*), Ice(1A), Ice(1B), Ice(1C) and Ice(C), where the Ice(1A*) is the most strict class notation, and the Polar region is divided into PC(1), PC(2), PC(3), PC(4), PC(5), PC(6), PC(7), where PC(1) is the most strict class notation.

3.3 Hull areas

To be able to calculate the elements of different sections in the hull of the vessel, the rules and regulations are divided into different hull areas. For the Baltic region, the rules only include the rules for the ice-belt area, while the other areas are calculated based on rules for regular vessels. On the other hand, the rules for Polar region is divided into several regions. Including the ice-belt area, these rules are also including other areas of the vessel; ice-belt, lower and bottom. In Figure 3.1 and 3.2, illustration of the different hull areas can be viewed.

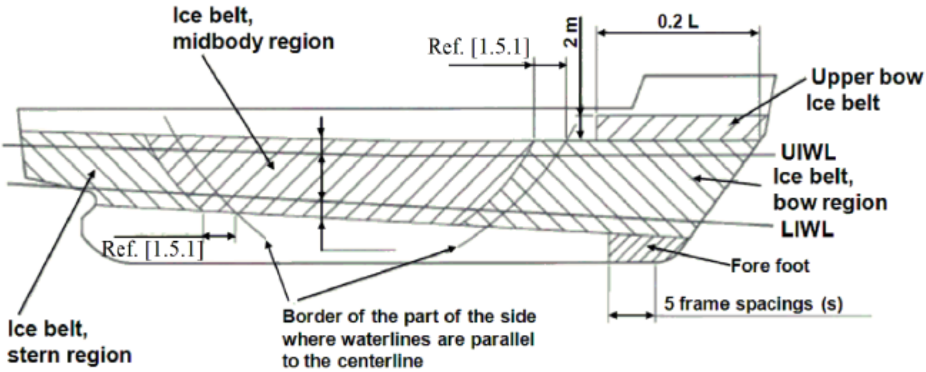


Figure 3.1: Hull areas for Baltic classification (DNV GL, 2019).

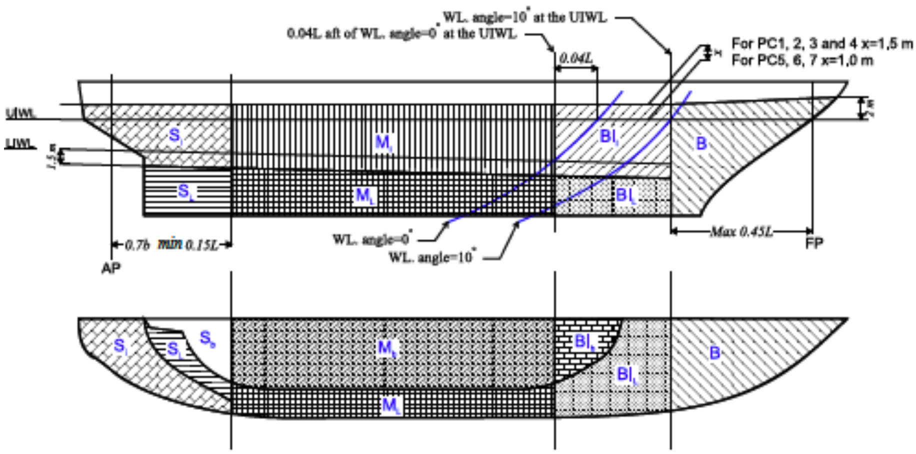


Figure 3.2: Hull areas for Polar classification (DNV GL, 2019).

3.4 Baltic regions

3.4.1 Ice loads

The ice loads in the Northern Baltic area are defined by the formula:

$$p = 5600\, c_d\, c_1\, c_a\, (kN/m^2) \tag{3.1}$$

, where:

c_d	The influence of the size and engine output of the ship.
c_1	The probability that the design ice pressure occurs in a certain region of the hull.
c_a	The probability that the full length of the area under consideration will be under pressure at the same time.

To calculate the c_d factor, the formula used is:

$$c_d = \frac{ak+b}{1000} \tag{3.2}$$

$$k = \frac{\sqrt{\Delta_f P_{min}}}{1000} \tag{3.3}$$

, where:

Δ_f	Displacement of the ship(t) on the maximum ice class draught.
P_{min}	Machinery output(kW)

The value of a and b is defined in Figure 3.3:

Table B6 Values of a and b

	Region			
	Bow		*Midbody and Stern*	
	k ≤ 12	k > 12	k ≤ 12	k > 12
a	30	6	8	2
b	230	518	214	286

Figure 3.3: Values for a and b.

The second factor, c_1, is decided based on the values in Table 3.1. The table presents the values used in the formula divided into Bow-, Midbody- and Stern part. For Ice C classification, the rules state that c_1 is equal to 0.55 in all regions.

Ice Class	Bow	Midbody	Stern
ICE-1A*	1.0	1.0	0.75
ICE-1A	1.0	0.85	0.65
ICE-1B	1.0	0.70	0.45
ICE 1C	1.0	0.50	0.25
ICE C	0.55	0.55	0.55

Table 3.1: Values for c_1-factor.

The last factor used in formula 3.1 is the c_a. This one is defined by:

$$c_a = \sqrt{\frac{l_0}{l_a}} \tag{3.4}$$

Where:

l_0 = 0.6
l_a Given by Table 3.2

Structure	Type of framing	l_a
Shell	transverse	frame spacing
	longitudinal	1.7 * frame spacing
Frames	transverse	frame spacing
	longitudinal	span of frame
Ice stringer		span of stringer
Web frame		2 * web frame spacing

Table 3.2: Value of l_a.

For both Northern Baltic and Polar Classification, it is essential to remember that an Ice-strengthened ship is not the same as an Ice-breaker, and is designed to travel behind an ice-breaker in the brash ice channel. The ice-strengthened vessel is by this assumed to operate in ice-thickness not exceeding h_0 (Figure 3.4). As an average of the ice thickness, the design ice height will be given as h (Figure 3.4)(Warntjen J., 2018).

Ice class	h_o *(m)*	*h (m)*
ICE-1A*	1.0	0.35
ICE-1A	0.8	0.30
ICE-1B	0.6	0.25
ICE-1C	0.4	0.22

Figure 3.4: Values for ice height.

3.4.2 Plating requirements

Ice class	*Region*	*Above UIWL (m)*	*Below LIWL (m)*
ICE 1A*	Bow	0.60	1.20
	Midbody		
	Stern		1.0
ICE 1A	Bow	0.50	0.90
	Midbody		0.75
	Stern		
ICE 1B and **ICE 1C**	Bow	0.40	0.70
	Midbody		0.60
	Stern		

Figure 3.5: Vertical extension of ice belt.

The shell plate thickness for transverse framing is defined by the formula:

$$t = 21.1 s \sqrt{\frac{f_1 p_{PL}}{R_{eH}}} + t_c \tag{3.5}$$

The shell plate thickness for longitudinal framing is defined by the formula:

$$t = 21.1 s \sqrt{\frac{p}{f_2 R_{eH}}} + t_c \tag{3.6}$$

, where:

p_{PL}	$= 0.7\text{p}$
p	Given by Equation 3.1
f1	$= 1.3 - \frac{4.2}{(h/s + 1.8)^2}$
f2	$= 0.6 + \frac{0.4}{(h/s)}$, when $h/s \leq 1$
	$= 1.4 - 0.4(h/s)$, when $1 \leq h/s < 1.8$
	$= 0.35 + 0.183(h/s)$, when $1.8 \leq h/s < 3$
	$= 0.9$, when $h/s > 3$
R_{eH}	Yield stress of the material
t_c	Increment for abrasion and corrosion
h	Given in Figure 3.4

3.4.3 Stiffener requirements

Transverse frames

The gross section modulus of the transverse frames is given by the formula:

$$Z_{gr} = \frac{P s_1 h l}{m_t R_{eH}} 10^3 \tag{3.7}$$

, and the gross shear area is calculated by:

$$A_{gr} = \frac{8.7 f_3 P h s_1}{R_{eH}} \tag{3.8}$$

, where:

P	Given by equation 3.1
h	Given in figure 3.4
m_t	$= \frac{7 * m_0}{7 - \frac{5h}{l}}$
f_3	Factor takes into account the maximum shear force versus the load location and the shear stress distribution, $f_3 = 1.2$
m_0	$= 5.7$

Longitudinal frames

The gross section modulus of the transverse frames is given by the formula:

$$Z_{gr} = \frac{f_4 P h l^2}{m_1 R_{eH}} 10^3 \tag{3.9}$$

, and the gross shear area is calculated by:

$$A_{gr} = \frac{8.7 f_4 f_5 P h l}{R_{eH}} \tag{3.10}$$

, where:

f_4	= (1-0.2 h/ s_1)
f_5	= 2.16
P	Given by Equation 3.1
h	Given in Figure 3.4
m_1	= 13.3 for continous beam, 11. for frames without brackets

3.5 Polar regions

3.5.1 Ice loads

For ships of all polar classes, a glancing impact on the bow is the design scenario for determining the scantlings required to resist the ice load. In the bow area of the vessel, the ice load parameters are functions of the actual bow shape. For other areas of the vessel, these were independent of the hull shape and was based on a fixed load patch aspect ratio (Pt.6 Ch.6 Sec 4. DNV GL ,2019).

Before calculating the Ice Load pressure, some values need to be found or assumed, based on empirical data. In Figure 3.6, the different angles required for ice load calculation is presented. In this figure, β' is the normal frame angle at upper ice waterline, α is the upper ice waterline angle, and γ is the buttock angle at the upper ice water line.

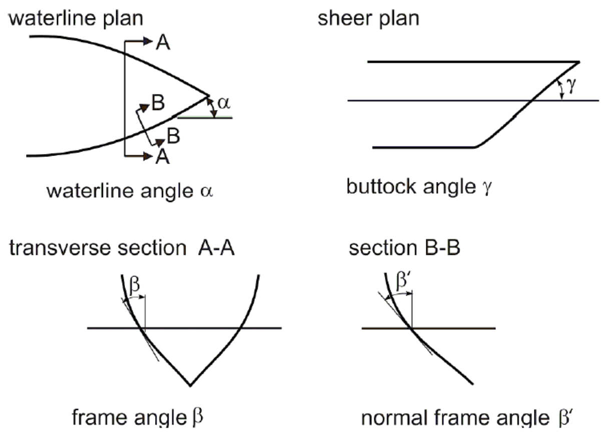


Figure 3.6: Definition of hull angles (DNV GL, 2019).

In Table 3.3 the class factors used in the calculations are given.

Polar Class	Crushing failure class factor(CF_C)	Flextural failure class factor(CF_F)	Load patch dimensions class factor(CF_D)	Displacement class factor(CF_{DIS})	Longitudinal strength class factor(CF_L)
PC(1)	17.69	68.60	2.01	250	7.46
PC(2)	9.89	46.80	1.75	210	5.46
PC(3)	6.06	21.17	1.53	180	4.17
PC(4)	4.50	13.48	1.42	130	3.15
PC(5)	3.10	9.00	1.31	70	2.50
PC(6)	2.40	5.49	1.17	40	2.37
PC(7)	1.80	4.06	1.11	22	1.81

Table 3.3: Class Factors.

The bow area load characteristics are defined by the shape coefficient; fa_i. The coefficient can be found by:

$$fa_i = Minimum(fa_{i,1}; fa_{i,2}; fa_{i,3}) \tag{3.11}$$

, and:

$$fa_{i,1} = \frac{(0.097 - 0.68(x/L_{wl} - 0.15)^2)\alpha_i}{\beta_i^{0.5}} \tag{3.12}$$

$$fa_{i,2} = \frac{1.2CF_F}{sin(\beta_i)CF_C\Delta_{tk}^{0.64}} \tag{3.13}$$

$$fa_{i,3} = 0.60 \tag{3.14}$$

, where:

i	Sub-Region considered
L_{wl}	Ship length measured on the upper ice waterline (UIWL)
x	Distance from forward perpendicular (FP) to station under consideration
α	Waterline angle
β	Normal Frame angle
Δ_{tk}	Ship displacement at UIWL
CF_C	Crushing Faliure Class Factor from Table 3.3
CF_F	Flexural Failure Class Factor form Table 3.3

Using the given equations, the total bow force can be expressed as:

$$F_i = fa_i\, CF_C\, \Delta_{tk}^{0.64} \tag{3.15}$$

For other areas than the bow part, the force will be given as follows:

$$F_{NonBow} = 0.36 * CF_C * DF \tag{3.16}$$

, where:

DF Ship Displacement Factor
$= \Delta_{tk}^{0.64}$ if $\Delta_{tk} \leq CF_{DIS}$
$= CF_{DIS}^{0.64} + 0.10(\Delta_{tk} - CF_{DIS})$ if $\Delta_{tk} > CF_{DIS}$

When the forces are calculated, the Load Patch Aspect Ratio, the Line Load and the Patch Pressure can be calculated

Load Patch Aspect Ratio:

$$AR = 7.46\, sin(\beta_i) \geq 1.3 \tag{3.17}$$

Line Load:

$$Q_i = \frac{F_i^{0.61} CF_D}{AR_i^{0.35}} \tag{3.18}$$

$$Q_{NonBow} = 0.639\, F_{NonBow}^{0.61} CF_D \tag{3.19}$$

, where:

CF_D Load Patch Dimension Class Factor from Figure 3.3

Patch Pressure:

$$P_i = F_i^{0.22} CF_D^2 AR_i^{0.3} \tag{3.20}$$

3.5.2 Plating requirements

The required minimum shell plate thickness t is given by:

$$t = t_{net} + t_s \tag{3.21}$$

t_{net} Plate thickness required to resist ice loads according to the following equations
t_s Corrosion and abrasion allowance according to Figure 3.7

Hull area	t_s [mm]					
	With effective protection			Without effective protection		
	PC(1) PC(2) PC(3)	**PC(4) PC(5)**	**PC(6) PC(7)**	**PC(1) PC(2) PC(3)**	**PC(4) PC(5)**	**PC(6) PC(7)**
Bow; bow intermediate ice belt	3.5	2.5	2.0	7.0	5.0	4.0
Bow intermediate lower; midbody and stern ice belt	2.5	2.0	2.0	5.0	4.0	3.0
Midbody and stern lower; bottom	2.0	2.0	2.0	4.0	3.0	2.5

Figure 3.7: Corrosion/abrasion additions for shell plating.

Transversely-framed Plates:

$$t = 500s\sqrt{\frac{AF \cdot PPF_p \cdot P_{avg}}{R_{eH}}}\ \frac{1}{1+\dfrac{s}{2b}} \tag{3.22}$$

Longitudinal-framed plating, when b ≥ s

$$t = 500s\sqrt{\frac{AF \cdot PPF_p \cdot P_{avg}}{R_{eH}}}\frac{1}{1+\dfrac{s}{2l}} \tag{3.23}$$

Longitudinal-framed plating, when b < s

$$t = 500s\sqrt{\frac{AF \cdot PPF_p \cdot P_{avg}}{R_{eH}}} \cdot \sqrt{2\frac{b}{s} - \left(\frac{b}{s}\right)^2} \cdot \frac{1}{1+\dfrac{s}{2l}} \tag{3.24}$$

, where:

s	Transverse frame spaving in transversely-framed ships or longitudinal frame spacing in longitudinally-framed ships
AF	Given by Figure 10.1 and 10.2 in Appendix 4
PPF_p	Peak pressure factor found in Figure 10.3 in Appendix 4
P_{avg}	$= F/(b \cdot w)$
F	F_{Bow} or F_{NonBow}
P_{Bow}	Maximum pressure in the bow area, in MN/m
b_{Bow}	$= Q_{Bow}/P_{Bow}$
b_{NonBow}	$= w_{NonBow}/3.6$
w_{Bow}	$= F_{Bow}/Q_{Bow}$
w_{NonBow}	$= F_{NonBow}/Q_{NonBow}$
b	Height of design load patch, where $b \leq (l - s/4)$ in the case of transversely framed plating
l	Distance between frame supports
R_{eH}	Minimum upper yield stress of the shell plate in way of the framing member.

3.5.3 Stiffener requirements

Transverse frames

Actual net effective shear area of the frame:

$$A_t = \frac{100^2\, 0.5\, LL\, s\, (AF\, PPF_t\, P_{avg})}{0.577\, R_{eH}} \tag{3.25}$$

, where:

LL	Length of loaded portion of span, lesser of a and b
a	Frame span
b	Height of design ice load patch
s	Spacing of local frame
AF	Hull area factor
PPF_t	Peak pressure factor
P_{avg}	Average pressure within load patch

Table 3.4: Parameters of net effective shear area formula.

, and the actual net effective plastic section modulus is calculated by:

$$Z_{pt} = \frac{100^3\ LL\ Y\ s\ AF\ PPF_t\ P_{avg}\ a\ A_1}{4\ R_{eH}} \tag{3.26}$$

, where:

AF,PPF_s,P_{avg}, LL, b, s and a equal as Table 3.4

Y	= 1-0.5(LL/a)
A_1	Maximum of A_{1A} and A_{1B}
A_{1A}	$= \dfrac{1}{1 + j/2 + k_w\ j/2((1-a_1^2)^{0.5} - 1)}$
A_{1B}	$= \dfrac{1 - 1/(2a_1 Y}{0.275 + 1.44k_z^{0.7}}$
j	1 or local frame with one simple support outside the ice-strengthened areas 2 for local frame without any simple supports
a_1	$= A_t/A_w$
A_t	Minimum shear area of the local frame
A_w	Effective shear area of the local frame
k_w	$= \dfrac{1}{1 + 2A_{fn}/A_w}$
k_z	$= z_p/Z_p$
z_p	Sum of individual plastic section modulus of flange and shall plate $= \dfrac{b_f t_{fn}^2/4 + b_{eff} t_{pn}^2/4}{1000}$
b_f	Flange breadth
t_f	Net flange thickness
t_p	The fitted net shell plate thickness
b_{eff}	Effective width of shell plate flange, 500s
Z_p	Net effective plastic section modulus of the local frame

Longitudinal frames

Actual net effective shear area of the frame:

$$A_L = \frac{100^2\, 0.5\, b_1\, a\, AF\, PPF_s\, P_{avg}}{0.577\, R_{eH}} \tag{3.27}$$

, where:

AF	Hull area factor
PPF_s	Peak pressure factor
P_{avg}	Average pressure within load patch
b_1	$=k_0\, b_2$
k_0	= 1-0.3/b'
b'	= b/s
b	Height of design ice load patch
s	Spacing of local frame
b_2	Corrected load height
	= b(1-0.25 b') if b' < 2
	= s if b'≥2
a	Longitudinal design span

Table 3.5: Parameters of net effective shear area formula.

, and the actual net effective plastic section modulus is calculated by:

$$Z_{pL} = \frac{100^3\, b_1\, a^2\, A_4\, AF\, PPF_s\, P_{avg}}{8\, R_{eH}} \tag{3.28}$$

, where:

AF,PPF_s,P_{avg}, b_1 and a equal as Table 3.5

$$A_4 = \frac{1}{2 + k_{wl}((1 - {a_4}^2)^{0.5} - 1)}$$

a_4 $= A_L / A_w$

A_L Minimum shear area for longitudinals

A_w Net effective shear area of longitudinals

k_{wl} $= 1/(1+2\ A_f / A_W)$

A_f Net cross-sectional area of local frame flange

4 | Rule-Based Calculation Application

The following chapter provides information about how the structural dimension application was designed and developed. Section 4.1 covers the method used and Section 4.2 how the application was built. In appendix 3, the assumptions made while creating the application will be included.

4.1 Method

Many different classification societies like DNV GL, Lloyd's Register and American Bureau of Shipping are creating rules and classifications for different types of vessels, and naval architects are using these all over the world for shipbuilding. The most common one in Norway is DNV GL; Det Norske Veritas and Germanischer Lloyd. This is also the classification society used in this thesis.

When creating a rule-based calculation application, there are a lot of features needed to be discussed. Which parameters should be given by the user, which parameters should be assumed and how to combine these in proper ways? One should also narrow down the problem statement to which class notations that are important for the application.

Some steps were early written down as a summary of the method, to create a template of how the application should be and how it should work.

First Point

The first step was to categorise the inputs in tables, which gives you a brief overlook and establishes a fundament for the data analysis. The purpose of the application was to provide the user with an estimate of the dimensions needing lesser inputs. The user shall also be able to choose two different kinds of class notations and get an impression of how the structural components will vary.

Second Point

When inputs are specified, the application should automatically provide an estimation of how the vessel will be divided into aft-section, mid-section and for-section/bow-section. Each of these sections will also be divided into frames regarding given frame spacing.

Third Point

As the vessel will operate in Baltic/Polar environments, the application should be able to find where the Ice-belt of the vessel will be located. For both classes, each section will be divided into the bottom-, lower- and ice-belt area.

Forth Point

When the calculations are done, the user should be able to print a report giving a summary of the estimates and a comparison of the two different class notations given.

4.2 Application

The application used for these calculations was Excel, that is a spreadsheet software developed by Microsoft, which includes features like calculation, graphing tools and macro programming language. It became the preferred application for these calculations due to its ability to create a calculation application without any further background of programming.

4.2.1 Input

The main dimensions of the vessel were chosen as the primary input. By main dimensions; length, breadth, depth, draft and frame spacing were included. The next most crucial input was to give the highest and lowest waterline of the vessel. These waterlines would, together with an assumed value, provide how large the ice belt should be. Along with the waterlines, the height of where the deck would appear was needed. This would help the application to map at which height the structural components should be dimensioned, regarding ice loads or just normal sea pressure. At last, a chose of which class notation the vessel should be designed for, the orientation of plating and stiffeners, material class, etc. had to be done. Illustration of the input sheet from excel will find a place in Appendix 5.

4.2.2 Variables

For correct calculations of ice pressure, different angles were needed to be assigned to the vessel. Figure 4.1 illustrates some of these angles used in the calculation.

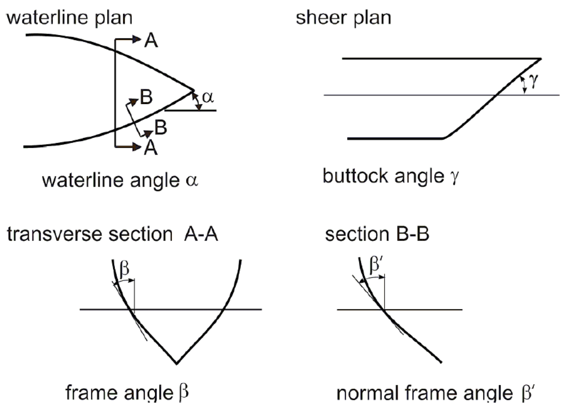


Figure 2 Definition of hull angles

β'	=	normal frame angle at upper ice waterline, in degrees
α	=	upper ice waterline angle, in degrees
γ	=	buttock angle at upper ice waterline (angle of buttock line measured from horizontal), in degrees
$tan(\beta)$	=	$\tan(\alpha)/\tan(\gamma)$
$tan(\beta')$	=	$\tan(\beta)\cos(\alpha)$.

Figure 4.1: Definition of hull angles (DNV GL, 2019).

4.2.3 Calculations

The excel sheet divides the calculation part into different topics;

- Hidden Variables
- Ice loads PC(6)/Ice(C)
- Plates PC(6)/Ice(C)
- Stiffeners PC(6)/Ice(C)
- Girders PC(6)/Ice(C)

Hidden Variables

Hidden variables were the sheet where all the assumed values and values based on input was calculated. The calculations were based on the input pages, choice of class notation, material factor, hull angles etc. Including all these calculations.

For the whole vessel to be divided correctly into three/four different sections, a feature of dividing percentage was included in the application. This was a percentage which was assigned to the LOA and gave the application how many frames the aft-, mid-, fore- and bow-section would consist of. With all these features, the vessel would be assumed in the application to look as well as illustrated in Figure 4.2.

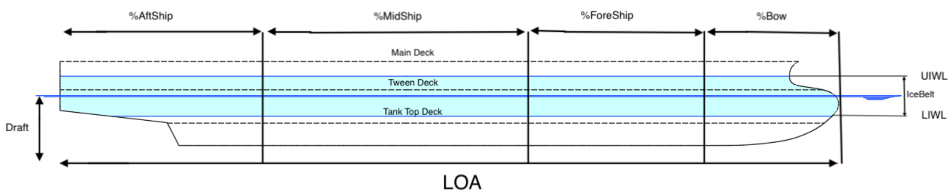


Figure 4.2: Illustration of vessel.

Ice Loads

For the ice loads, these were calculated based on the input given. For the polar classification, the ice load is given by an average pressure for each bow-, forward-, mid- and aft-section. In each section, different hull area factors were given, which were multiplied with the average pressure to get the right pressure for each area. Formulas can be seen in Chapter 3.

Plates PC(6)/Ice(C)

By using rules from Chapter 3 the plates were determined. As it was possible to choose the direction of the plates in the input page, the application would automatically choose different rules of relevance, calculating new plate thicknesses.

Stiffeners PC(6)/Ice(C)

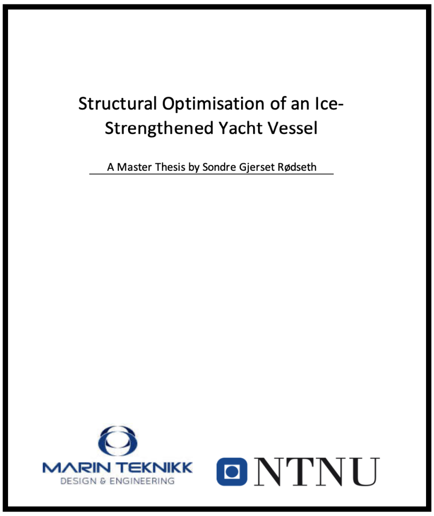
In the input sheet, the direction of the stiffener, longitudinal or transversal, could be chosen. This feature was also divided into ice belt vs other areas, which made it possible to choose two different directions for stiffeners.

Girders PC(6)/Ice(C)

In the rules and regulations for Polar and Baltic regions, there were no extra strict rules made for girders. Hence, the regulations from regular ships were used, but the pressure applied was equal to the Baltic and Polar calculated pressure to get the right dimension.

4.2.4 Summary report

At last, the application made it possible to print out a report. This report provides the user with all information of the inputs used, the different pressures, and all the calculated dimensions.


Structural Optimisation of an Ice-Strengthened Yacht Vessel

A Master Thesis by Sondre Gjerset Rødseth

Figure 4.3: Summary report frontpage.

5 | Panel optimisation with Finite Element Analysis

The objective of the second part of the thesis was to investigate the minimum of structural addition to the Ice(C) classified panel that had to be done to meet a higher required class; PC(6). The analyses will use the method of finite element, and the following chapter will describe how the method was applied.

5.1 Siemens NX - Parametric modelling

The chosen software analysis tool for modelling and testing was Siemens NX (Siemens PLM Software, 1973). In Siemens NX, the user can model a structure in an early stage of the process and make a complete analysis of the given structure. This will provide the engineers with an indication of the final product design, as well as how it will react when it is subject to load and constraints. To create a model that is modular and easily changed to suit other analyses, Siemens has created a feature called expressions. In this feature, one can assign functions/parameters for different elements. This will help the engineer to carry out several analyses based on the same model, but with minor changes to, e.g. the dimensions, in a smaller amount of time. A simple example of how the expression feature can be used while modelling follows in the next paragraph.

First, a 2D drawing of the design has to be made. It can be smart to insert geometrical constraints to make the design stick to the place, preventing problems when adding expressions later. In Figure 5.1, a 2D-girder design was made with a geometrical constraint in the bottom centre, which will keep it in the same position.

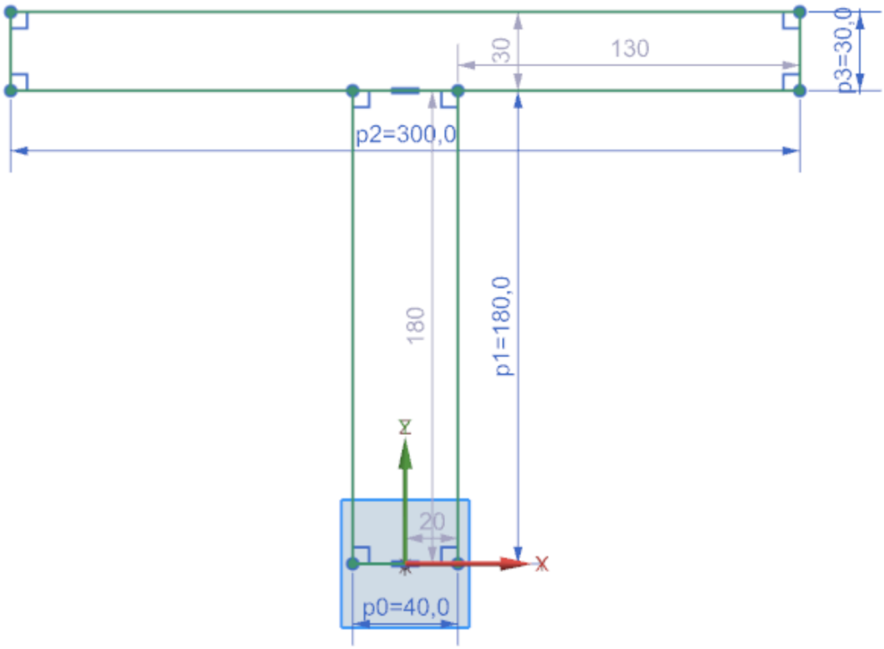


Figure 5.1: Create sketch.

Second, expressions have to be made. In these expressions, the user assigns lengths to the elements. These expressions could make it possible to change the parameters of the design without having to open each sketch.

	↑ Name	Formula	Value	Units
1	> Default Group			
9	⌄ Girder			
10	FlangeHei...	30	30 mm	mm
11	FlangeWidth	400	400 mm	mm
12	GirderLength	3000	3000 mm	mm
13	WebHeigth	180	180 mm	mm
14	WebThickn...	30	30 mm	mm

Figure 5.2: Create expressions.

Third, the expressions have to be assigned to the model, as illustrated in Figure 5.3.

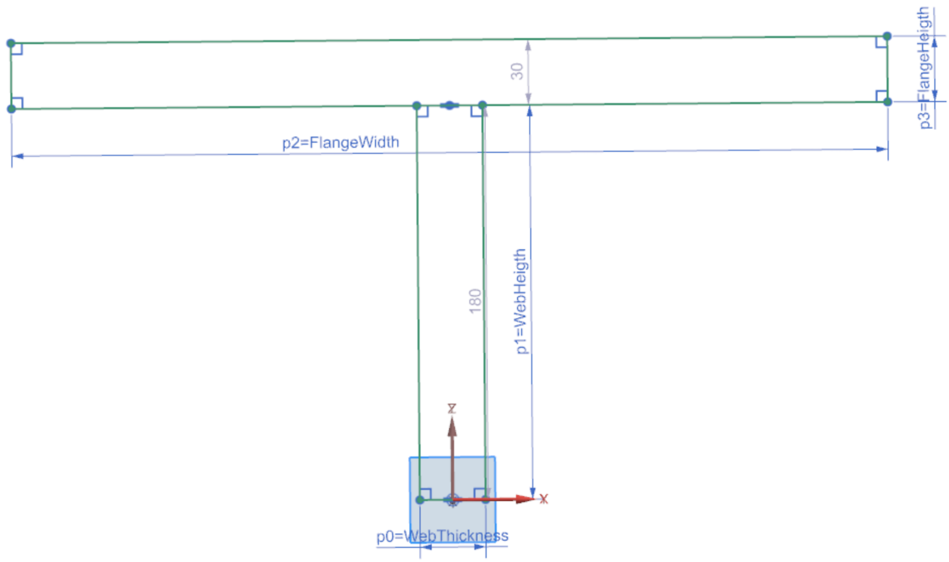


Figure 5.3: Assign expressions.

After assigning the expressions to the model, the last stage is to finalise the model. Figure 5.4 illustrates the result of a girder after extruding it using the expression "GirderLength".

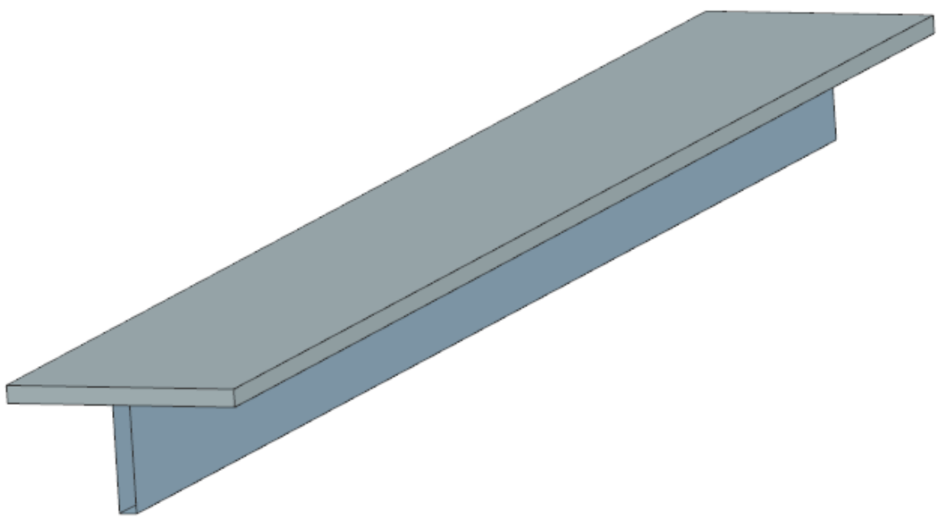


Figure 5.4: Extrude.

5.2 Method

The idea of finite element method consists in modelling the field studied, and through several elements connected, solve the most diverse problems of solid mechanics (Ion and Ticu, 2015). For the analyses in this method, a parametrical design was used. This structures the work, making it easy to have control over what has been done and what needs to be done.

The first step of the method was to choose a panel for testing and assign loads to this panel. For this problem, the user was, in the calculation application, able to select a part of the vessel and get the information needed for modelling the section. In this feature, the user can get all the structural dimensions and ice loads which the section was a subject to.

Further, the dimensions calculated in the application were applied to a panel designed as a parametric model in Siemens NX.

5.2.1 Panel design

The panel was assembled by a plate, stiffeners and girders. A panel of the midship ice-belt section was the target part of the testing. To avoid curvature, the panel was assumed to be flat-sided during the analyses.

The plate was assigned a height and length. The two parameters can be changed depending on which ship one would like to analyse the panel for, and how much of the section should be examined. Since the panel that was going to be analysed in this thesis was a sub-part of the midsection, the ice-belt, it was assumed that the plate would have the same thickness all over. Due to the same thickness, the plate is assigned only one thickness parameter.

For the stiffeners, more parameters had to be assigned. Using the calculation application made in excel, all the needed output parameter values were calculated for the panel design.

The last component of the panel was the girder, and this was based on two different elements; web and flange. Both web and flange had a height/breadth and a thickness. Since the plate was already modelled, and the girder was mounted on the plate, there was not assigned parameters for the lower flange of the girder.

Including the dimension of the structural elements, the correct spacing between the elements was needed. As the panel modelled was assumed to be having fixed boundaries at all sides, better explained in Section 5.3, no structural elements were modelled at the edges. A function to distribute the stiffeners and girders along with the length/height of the plate, but with a margin space from the edges, was made.

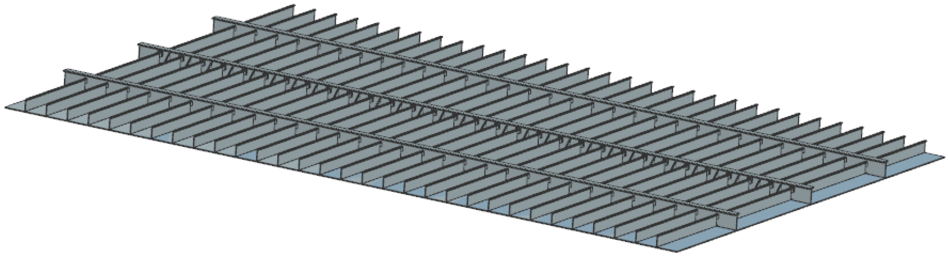


Figure 5.5: Designed parametric panel.

5.3 Boundaries

For the boundary conditions, the general rules in a case of local loads are that the constraints shall be placed as far away as possible from where the loads are applied. To satisfy this, the structural elements were placed such that there was a gap between the edge of the plate and the first structural element.

The vertical height of the panel represents the space between two decks, thus making the upper and lower edge fixed. The horizontal length of the panel represents the distance between two bulkheads, which makes it possible to consider the ends of the horizontal length as fixed. Hence, all of the panel sides are fixed. The way of constraining panels will depend on where it is located. Other places the constraint can, e.g., be free in some directions.

5.4 Mesh

For the meshing of the panel, a correct balance between a fine mesh and computational effort was essential. With a larger Finite element model, the more computational effort was needed, and if an advanced mesh was applied to the model, an analysis would take a lot of time. A smaller model with larger elements could influence the quality of the study, making the results less accurate. To make the meshing and analyses more computational efficient, the elements of the panel was generated into using only the mid-surfaces. This made it possible to use 2D QUAD8-elements for the meshing process and caused a decrease of time during the later solving.

5.4.1 Sensitivity study of the mesh

To get an excellent solvable panel, a mesh sensitivity study had to be done. The goal of the sensitivity study of the mesh was to find the best compromise between finer mesh and the amount of computational effort. To reach the goal, the study started off using significant elements (50x50mm). With this mesh, a simulation only used 120 seconds to give a possible solution to the panel design. Due to significant elements, the solution varied a lot between all of the elements, and very high stress could be found in one element while much lesser in neighbouring elements. Further, in the sensitivity study, the areas where the highest stress occurred were examined, and to cope with the stress, refinement for the mesh was used in these areas.

In Figure 5.6 illustrates stress concentration. In this figure, the elements were 50x50mm, and the difference of stress was very high between the cells.

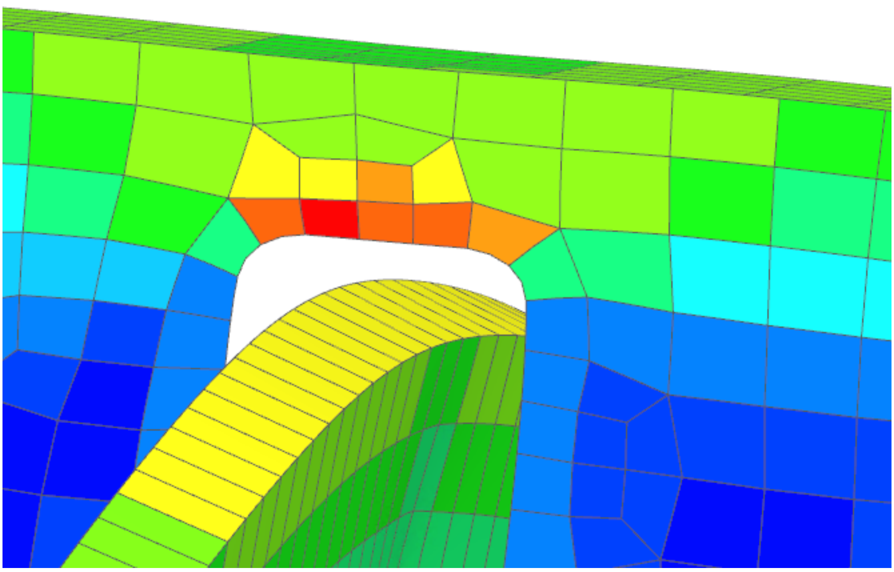


Figure 5.6: Stress concentration.

In the next test, an element size of 20x20mm was applied to the model, but the same result appeared. With this in mind, a refinement was created in the area around the cut-out. When creating a refinement, the transition between the refinement zone and the other area must be smooth. With this in mind, the mesh was designed with two squares for refinement. In Figure 5.7, the inner refinement has an element size of 5mm, the outer refinement of 10mm and the elements surrounding has an element size of 10mm.

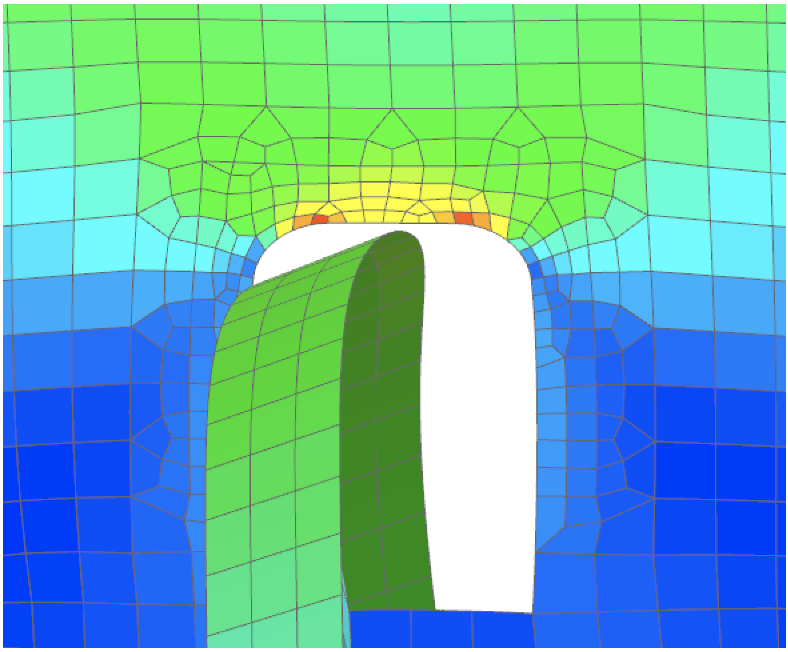


Figure 5.7: Illustration of the refinement zone.

With this refinement, the transition between elements was smoother, but still, some stress concentration was found at the edge of the cut-out. The simulation of this mesh used 791 seconds, which is approximately 11 minutes more than the simulation with 50x50mm elements. By comparing Figure 5.6 and Figure 5.7 one can see how a finer mesh can give a more precise answer than using larger cell size, despite the small amount of time the simulation takes in that case.

The fourth test used a finer mesh; element size of 1x1mm in the inner refinement, 5x5mm at the outer refinement and 10x10mm at the surrounding elements. This refinement is illustrated in Figure 5.8

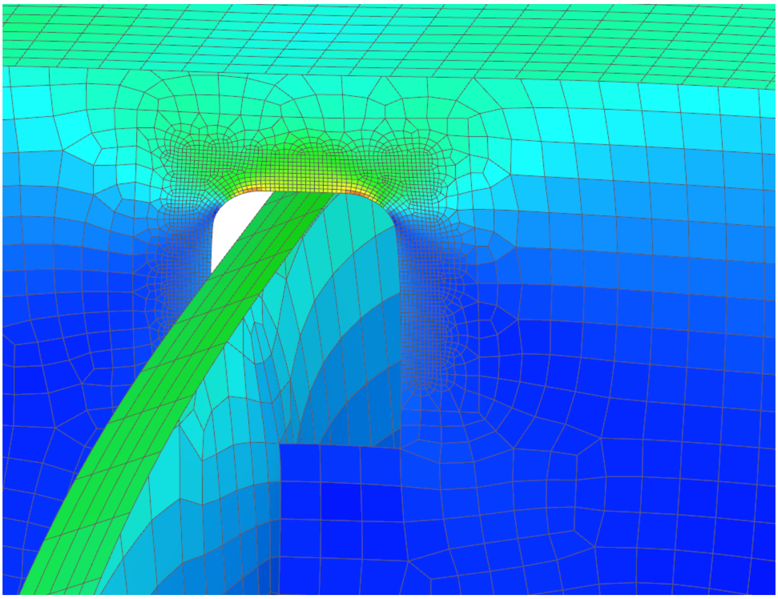


Figure 5.8: Illustration of the refinement zone.

For this mesh, the solution took approximately the same time as the last one. This shows that there were a lot of factors that came into play. The first test with this previous mesh took 1710 seconds, while the second only took 821 seconds, which was under half of the time.[1]

With this last test, the variance of stress between each cell was decreased a lot. This means that the mesh was of much better quality, and the case study was ready to be started. Below in Table 5.1, the results of time used during sensitivity study can be viewed.

Test	Mesh size inner refinement	Mesh size outer refinement	Mesh size surrounding elements	Time[sec]
1	50	50	50	120
2	20	20	20	275
3	5	10	10	791
4	1	5	10	821

Table 5.1: Summary of sensitivity study.

[1]Because of Covid-19, the simulations had to be done on a virtual machine. And with an unstable internet connection, the simulation can vary a lot.

Part III:

Case study, Conclusion and Future Work

6 | Structural dimension application

In this chapter, the final product of structural dimension application will be described. As mentioned in Section 4.2.4, the final product of the application was a summary report. This report includes several results for structural elements in both Ice(C) and PC(6) classification. The main sections in this report were:

- Ice loads
- Plates
- Stiffeners
- Primary Support Members

The structural dimension application is an application which shall be used for calculating basic hull members. By this, it was meant that only plates(transverse/longitudinal), stiffeners(transverse/longitudinal) and primary support members were calculated.

The final summary report can be viewed in appendix 1.

6.1 Loads

The first section of the summary report gave information of which loads the vessel was subject to. For the polar rules and ice class rules, there were two different ways of calculating the pressure. The polar rules were given as an average pressure for the whole section, which in the later calculation was multiplied with a hull area factor to provide the right pressure for the right element. This hull area factor was given by ice belt, lower area and bottom area. For the ice-class pressure, this was also divided into different sections, but this pressure was given for different types of structural elements. The Ice class rules were calculating the pressure inside the ice-belt, and for structural components outside the ice-belt, regular rules were used. In Table 6.1, the pressures calculated in the two different class rules can be viewed.

Class	PC(6)	Ice(C) - Shell Transverse	Ice(C) - Shell Longitudinal	Ice(C) - Frames Transverse	Ice(C) - Frames Longitudinal
Bow	2.50 MPa	0.91 MPa	0.69 MPa	0.91 MPa	0.52 MPa
Forship	2.68 MPa	0.91 MPa	0.69 MPa	0.91 MPa	0.52 MPa
Midship	2.68 MPa	0.57 MPa	0.44 MPa	0.57 MPa	0.33 MPa
Aftship	2.68 MPa	0.57 MPa	0.44 MPa	0.57 MPa	0.33 MPa

Table 6.1: Summary of pressures.

For the polar class, the rules were divided into bow area and non-bow area. The ice-class is divided into foreship and mid-/aft- ship.

6.2 Plates

In the next section the plate thicknesses, both for PC(6) and Ice(C) are illustrated (Table 6.2).

<table>
<tr><th colspan="6">Class Notation</th></tr>
<tr><td rowspan="11">Sections</td><td colspan="2"></td><td>PC(6)</td><td>Ice(C)</td><td>Comparison</td></tr>
<tr><td colspan="2">Bow</td><td>36mm</td><td>21mm</td><td>15mm</td></tr>
<tr><td rowspan="3">Forship</td><td>Ice-Belt</td><td>36mm</td><td>21mm</td><td>15mm</td></tr>
<tr><td>Lower</td><td>27mm</td><td>11mm</td><td>16mm</td></tr>
<tr><td>Bottom</td><td>21mm</td><td>11mm</td><td>10mm</td></tr>
<tr><td rowspan="3">Midship</td><td>Ice-Belt</td><td>25mm</td><td>18mm</td><td>7mm</td></tr>
<tr><td>Lower</td><td>19mm</td><td>11mm</td><td>8mm</td></tr>
<tr><td>Bottom</td><td>11mm</td><td>11mm</td><td>0mm</td></tr>
<tr><td rowspan="3">Stern</td><td>Ice-Belt</td><td>27mm</td><td>18mm</td><td>9mm</td></tr>
<tr><td>Lower</td><td>24mm</td><td>11mm</td><td>13mm</td></tr>
<tr><td>Bottom</td><td>11mm</td><td>11mm</td><td>0mm</td></tr>
</table>

Table 6.2: Summary of plate thicknesses.

For the polar classification one can see that the highest thicknesses occur in the bow and fore ship ice-belt area. As discussed in Section 2.1, the crushing and bending of ice will primary occur at the waterline in the bow part. Hence, extra steel was needed to be able to handle the ice load. As the ice floats against the ship, the load will decrease, and so will the plate thickness required.

As Ice(C) classification was not that strict as PC(6), the rules were only including the ice belt area in the calculation of plate thicknesses. For other areas, these were calculated regarding rules for classification of regular vessels.

6.3 Stiffeners

Following on to the next section, the stiffeners are introduced. The results illustrated in the summary report can be viewed in Table 6.3.

			Class Notation	
			PC(6)	Ice(C)
Sections	Bow		HP160x7	HP160x7
	Forship	Ice-Belt	HP160x7	HP160x7
		Lower	HP220x11.5	HP180x11
		Bottom	HP180x8	HP180x11
	Midship	Ice-Belt	HP160x7	HP160x7
		Lower	HP160x8	HP180x11
		Bottom	HP180x11	HP180x11
	Stern	Ice-Belt	HP160x7	HP160x7
		Lower	HP180x11	HP180x11
		Bottom	HP180x11	HP180x11

Table 6.3: Summary of stiffener dimensions.

As seen in Table 6.3, the dimensions are lower in the ice belt, than in the other areas. In the application, the stiffener direction inside ice-belt was assigned in a transverse direction with a spacing of 300mm. Outside the ice-belt, the stiffeners were assigned in a longitudinal direction, with a spacing of 600mm.

6.4 Primary support members

For the last section, the primary support members get introduced. These can be seen in Table 6.4.

			Class Notation	
			PC(6)	Ice(C)
Sections	Bow		250x10+200x15	200x10+100x10
	Forship	Ice-Belt	250x10+200x15	200x10+100x10
		Lower	250x10+200x15	200x10+100x10
		Bottom	250x10+200x15	200x10+100x10
	Midship	Ice-Belt	250x10+200x15	200x10+100x10
		Lower	250x12+250x25	200x10+100x10
		Bottom	350x10+250x20	200x10+100x10
	Stern	Ice-Belt	250x10+200x15	200x10+100x10
		Lower	250x10+200x15	200x10+100x10
		Bottom	350x10+250x20	200x10+100x10

Table 6.4: Summary of *PSM* dimensions.

For the polar and baltic regions, DNV GL had no special requirements for the primary support members. Due to no extra requirements, the rules for regular vessels were used in these calculations, but the polar-/ice-loads were applied instead of regular loads. As viewed in Figure 6.4, the Ice(C) class support members, is all the same. This was caused because of the C_1-factor, which gave the magnitude of the load expected in the hull area, was equal all over the vessel.

7 | Finite element analysis for midship ice-belt

The following chapter contain analyses using the midship ice-belt panel as basis.

7.1 Ice pressure load applied to the model

The same pressure as calculated in the application was used for the analyses, equalling 2,678 MPa at average for the midship of the vessel. To use this average pressure as a force in Siemens NX, some small new calculation had to be done. The pressure was multiplied with hull area factor and transformed from MPa to kN. By using DNV GL design load patch calculating this, it shows how the force calculated is distributed and how large the pressure area is.

The kN force was found by:

$$Force(F) = \frac{Average\,Pressure * Hull\,area\,factor * Design\,load\,patch\,heigth * Design\,load\,patch\,width}{1000}(kN) \quad (7.1)$$

This was applied in the centre of the model with the spatial distribution. The points used in this distribution are illustrated in Figure 7.1, and in Figure 7.2 the force applied to the model can be viewed.

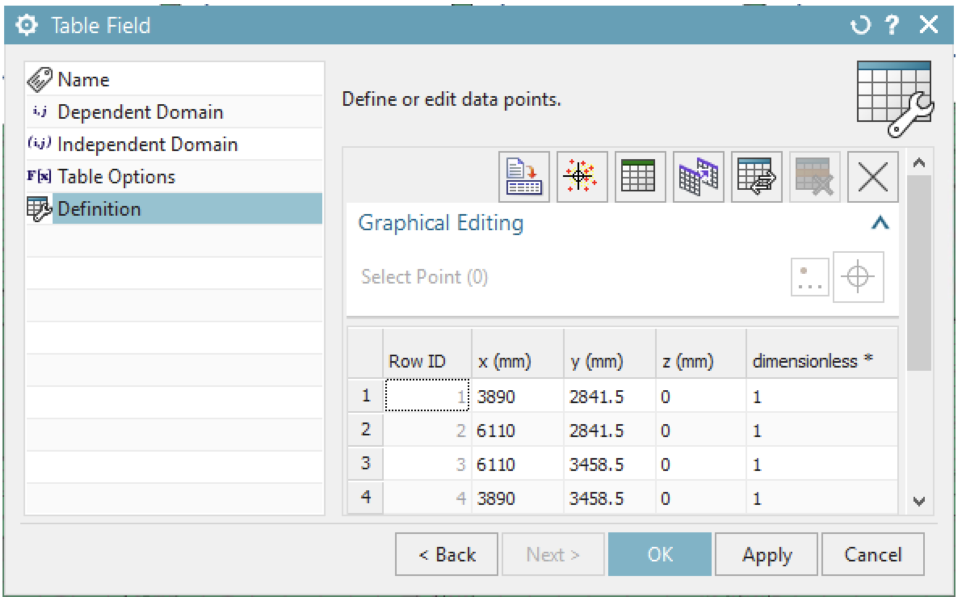


Figure 7.1: Spatial distribution of force.

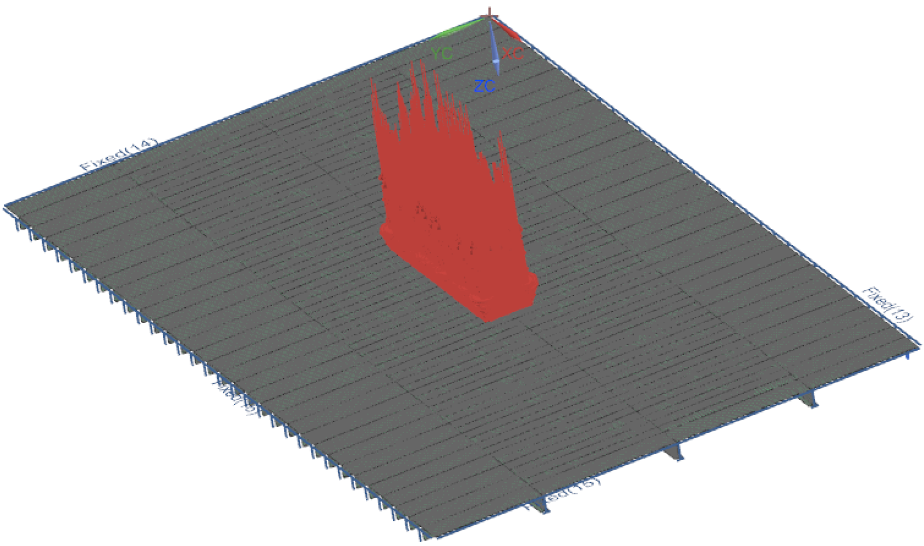


Figure 7.2: Force applied to the panel.

7.2 Panel test based on data from excel

This section covers the first test of the Ice(C), and PC(6) classified midship ice belt panels, and how the elements were reacting when they were subject to ice-/polar load.

The load and dimensions can be viewed in Table 6.1, 6.2, 6.3 and 6.4, and viewed as a panel in Figure 7.3, 7.4 and 7.5.

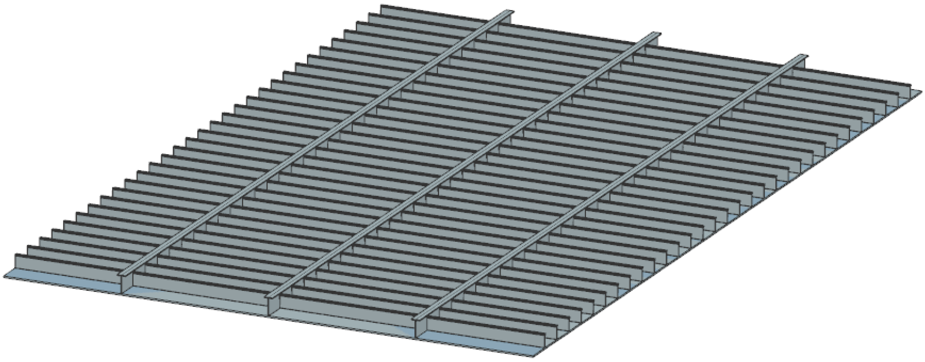


Figure 7.3: Iso view of panel.

Figure 7.4: Girders.

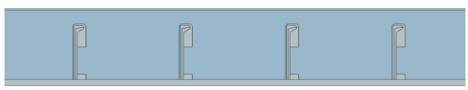


Figure 7.5: Stiffeners.

The main task for this first analysis was to investigate whether the panels calculated with the application satisfied the given pressure, or not. The panel calculated based on Ice(C) class was first analysed, followed by an analysis of the PC(6) panel.

7.2.1 Ice Class C panel with ice load

Thickness	Highest Von Mises stress in girder web	Allowed Von Mises stress	Highest Von Mises stress in girder flange	Allowed Von Mises stress
Original design	986 MPa	470 MPa	414 MPa	470 MPa

Table 7.1: Result of Ice(C) panel test, longitudinal girders.

Thickness	Highest Von Mises stress in stiffener web	Allowed Von Mises stress	Highest Von Mises stress in stiffener flange	Allowed Von Mises stress
Original design	324 MPa	470 MPa	408 MPa	470 MPa

Table 7.2: Result of Ice(C) panel test, stiffeners.

During the ice-panel test, almost all elements were under the allowed stress level, except the girder web. In the connection between the girder web and stiffener, a cut-out was made, which decreased the amount of steel in the girder web. This caused some high stresses in the top of the cut-out and can be viewed in Figure 7.6.

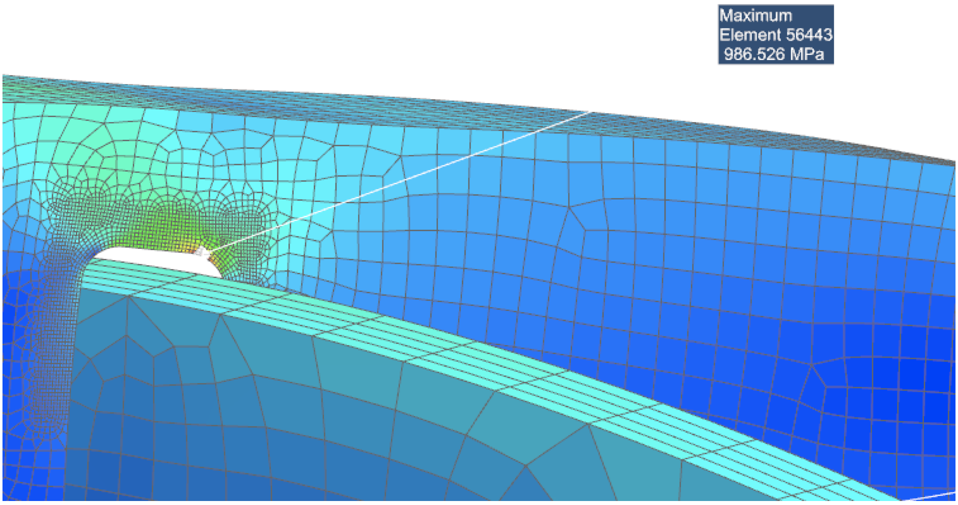


Figure 7.6: High stresses in the cut-out area.

The problem of the high stresses will be solved in Section 7.3.1.

7.2.2 Polar Class 6 panel with polar load

Thickness	Highest Von Mises stress in girder web	Allowed Von Mises stress	Highest Von Mises stress in girder flange	Allowed Von Mises stress
Stresses	2060 MPa	470 MPa	867 MPa	470 MPa

Table 7.3: Result of PC(6) panel test, longitudinal girders.

Thickness	Highest Von Mises stress in stiffener web	Allowed Von Mises stress	Highest Von Mises stress in stiffener flange	Allowed Von Mises stress
Stresses	665 MPa	470 MPa	865 MPa	470 MPa

Table 7.4: Result of PC(6) panel test, stiffeners.

The test results of the polar panel can be viewed in Figure 7.3 and Table 7.4. Like the previous test, the girder web turns out to have the highest stress level, and it still occurs in the cut-out area. A further discussion and solving of this problem will be given in Section 7.3.1, and in Figure 7.7 an illustration of the stress concentration at the cut-out area can be viewed.

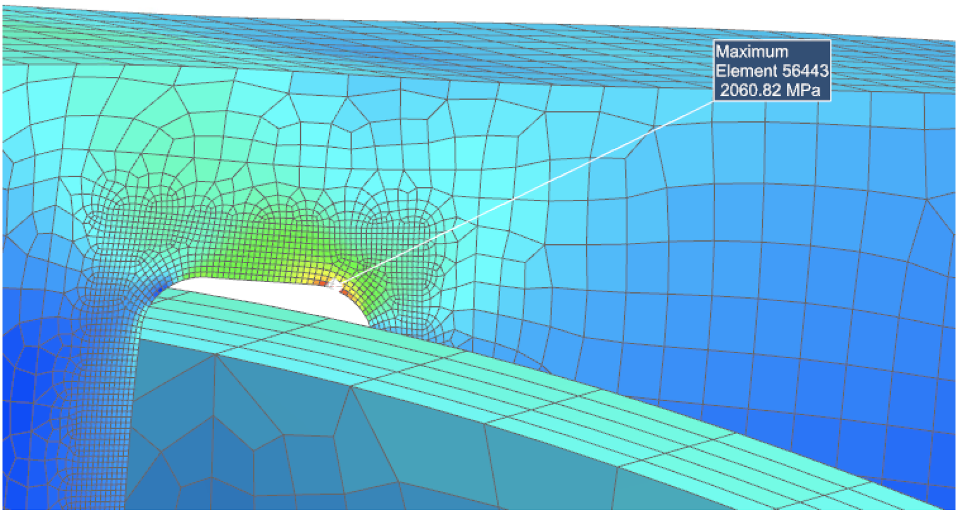


Figure 7.7: High stresses in the cut-out area.

7.3 Practical case

Because of high stresses in the analyses of the panels calculated from the application, a meeting with the project holders were held. During this meeting, a drawing of the original vessel was shown. The sketch showed that for the panel used in this analysis, there was introduced an extra girder to give additional support. Based on this new information, this thesis decided to copy the same transverse girder to the panel. An illustration of the "new" panel design can be viewed in Figure 7.8, 7.9 and 7.10.

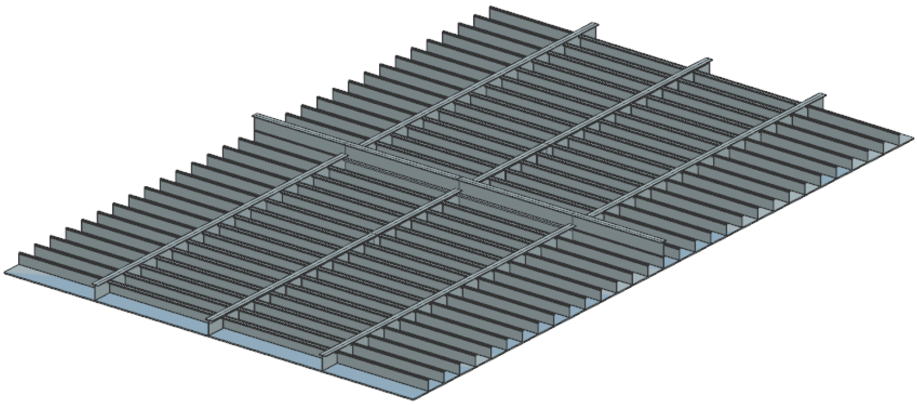


Figure 7.8: Iso view of the design.

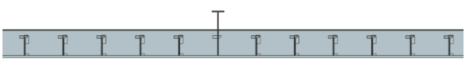


Figure 7.9: Stiffener design.

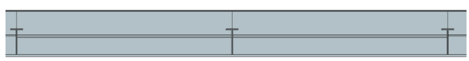


Figure 7.10: Girder design.

7.3.1 Case 0 - Panel test based on data from excel with extra girder

Both Ice(C) panel and PC(6) panel will be analysed in the following section, including the addition of the new transversal girder. This girder was placed in the middle of the plate width and was fixed in both ends, equally as the plate.

Ice classified panel

Thickness	Highest Von Mises stress in girder web	Allowed Von Mises stress	Highest Von Mises stress in girder flange	Allowed Von Mises stress
Original design	986 MPa	470 MPa	414 MPa	470 MPa
With Girder	434 MPa	470 MPa	179 MPa	470 MPa

Table 7.5: Result of Ice(C) panel test, longitudinal girders.

Thickness	Highest Von Mises stress in girder web	Allowed Von Mises stress	Highest Von Mises stress in girder flange	Allowed Von Mises stress
Stresses	284 MPa	470 MPa	300 MPa	470 MPa

Table 7.6: Result of Ice(C) panel test, transverse girder.

Thickness	Highest Von Mises stress in stiffener web	Allowed Von Mises stress	Highest Von Mises stress in stiffener flange	Allowed Von Mises stress
Original design	324 MPa	470 MPa	408 MPa	470 MPa
With Girder	136 MPa	470 MPa	177 MPa	470 MPa

Table 7.7: Result of Ice(C) panel test, stiffeners.

In Tables 7.5, 7.6 and 7.7, the results of panel test with an extra girder added are illustrated. The panel fulfilled all requirements, and no further additions were needed.

Polar classified panel

Thickness	Highest Von Mises stress in girder web	Allowed Von Mises stress	Highest Von Mises stress in girder flange	Allowed Von Mises stress
Original design	2060 MPa	470 MPa	867 MPa	470 MPa
With Girder	958 MPa	470 MPa	281 MPa	470 MPa

Table 7.8: Result of PC(6) panel test, longitudinal girders.

Thickness	Highest Von Mises stress in girder web	Allowed Von Mises stress	Highest Von Mises stress in girder flange	Allowed Von Mises stress
Stresses	656 MPa	470 MPa	691 MPa	470 MPa

Table 7.9: Result of PC(6) panel test, transverse girder.

Thickness	Highest Von Mises stress in stiffener web	Allowed Von Mises stress	Highest Von Mises stress in stiffener flange	Allowed Von Mises stress
Original design	665 MPa	470 MPa	865 MPa	470 MPa
With Girder	328 MPa	470 MPa	408 MPa	470 MPa

Table 7.10: Result of PC(6) panel test, stiffeners.

For the PC(6) panel, the girder addition was not enough to make the panel fulfil all requirements. The reason for this could be that the transverse girder used, was equal to the one used in the Ice(C) classified panel. To find out what needed to fulfil the requirements, a new test was done, increasing the girder to a dimension of 350x20 + 200x15. The results of this test can be viewed in Table 7.11, 7.12 and 7.13.

Thickness	Highest Von Mises stress in girder web	Allowed Von Mises stress	Highest Von Mises stress in girder flange	Allowed Von Mises stress
Original design	2060 MPa	470 MPa	867 MPa	470 MPa
With Girder	922 MPa	470 MPa	293 MPa	470 MPa

Table 7.11: Result of second PC(6) panel test, longitudinal girders.

Thickness	Highest Von Mises stress in girder web	Allowed Von Mises stress	Highest Von Mises stress in girder flange	Allowed Von Mises stress
Stresses	390 MPa	470 MPa	414 MPa	470 MPa

Table 7.12: Result of second PC(6) panel test, transverse girder.

Thickness	Highest Von Mises stress in stiffener web	Allowed Von Mises stress	Highest Von Mises stress in stiffener flange	Allowed Von Mises stress
Original design	665 MPa	470 MPa	865 MPa	470 MPa
With Girder	238 MPa	470 MPa	249 MPa	470 MPa

Table 7.13: Result of second PC(6) panel test, stiffeners.

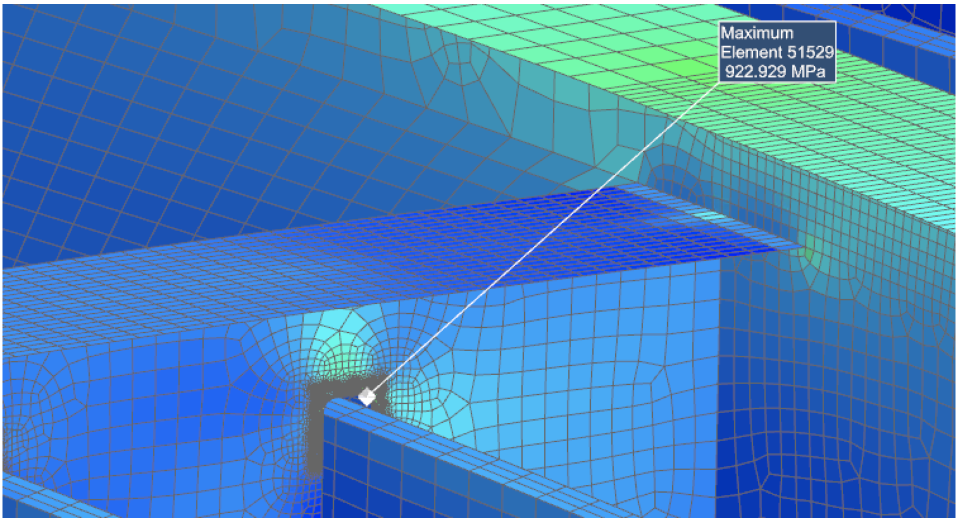


Figure 7.11: High stresses in cut-out area.

Still, the cut-outs close to the transverse girder indicated some high stresses (Illustrated in Figure 7.11). The thesis decided to introduce small plates welded to the top of the cut-out for extra support.The results of this test can be viewed in Table 7.14, 7.15 and 7.16.

Thickness	Highest Von Mises stress in girder web	Allowed Von Mises stress	Highest Von Mises stress in girder flange	Allowed Von Mises stress
Original design	2060 MPa	470 MPa	867 MPa	470 MPa
With Girder	447 MPa	470 MPa	311 MPa	470 MPa

Table 7.14: Result of third PC(6) panel test, longitudinal girders.

Thickness	Highest Von Mises stress in girder web	Allowed Von Mises stress	Highest Von Mises stress in girder flange	Allowed Von Mises stress
Stresses	386 MPa	470 MPa	419 MPa	470 MPa

Table 7.15: Result of third PC(6) panel test, transverse girder.

Thickness	Highest Von Mises stress in stiffener web	Allowed Von Mises stress	Highest Von Mises stress in stiffener flange	Allowed Von Mises stress
Original design	665 MPa	470 MPa	865 MPa	470 MPa
With Girder	208 MPa	470 MPa	232 MPa	470 MPa

Table 7.16: Result of third PC(6) panel test, stiffeners.

As the final test was successful, the polar midship ice-belt panel calculated for polar rules fulfilled the requirements, and the thesis moved on to the next cases. In Figure 7.12, the final design of the cut-outs can be viewed.

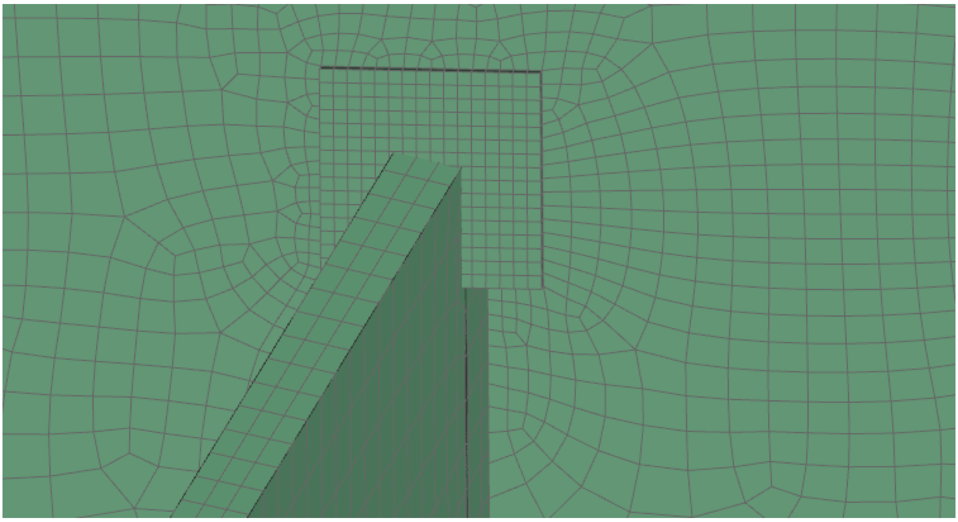


Figure 7.12: Final cut-out plate design.

7.4 Case study

A suggested task of the project holders was to investigate what minimum addition of steel elements could be done for the Ice(C) classified panel, to meet the requirements of a PC(6) classification. Hence, this section introduces a case study of five different cases to find the minimum addition.

7.4.1 Case 1 - With brackets

During the sensitivity study of the panel, one could see that the highest stresses were gathered around the middle of the centre girder. Due to this, the thesis knew that to find the minimum change of the structure, some steel had to be assembled to this part of the panel. The first case was, therefore, the easiest one; assemble brackets to the centre girder. The design of the bracket was based on rules of structural design principles (DNV GL "Pt.3 Ch.3 Sec.6", 2018). It was stated that the arm length of the bracket should not be less than 0.38 times the height of the girder web. The design can be viewed in Figure 7.13.

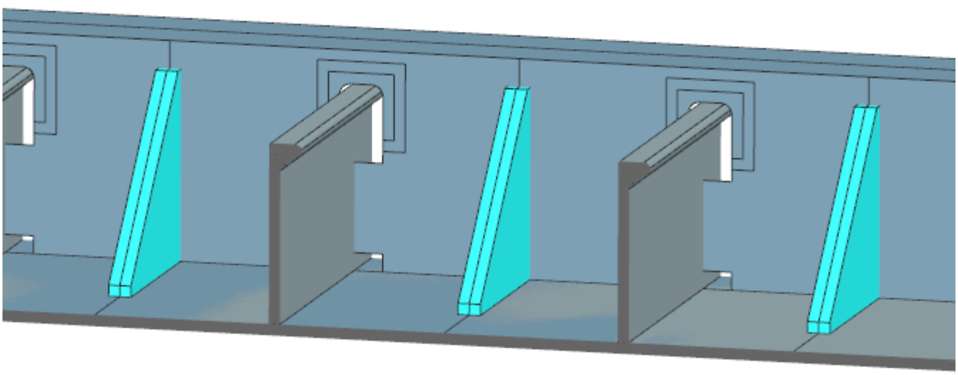


Figure 7.13: Design of bracket.

All the brackets were having a spacing of 300mm between each other and were placed in the middle of two stiffeners. When the brackets and stiffeners were distributed every other, the thesis thought that this would create a higher stress tolerance both for the girder and the stiffener.

Testing of Case 1

To find the most feasible bracket, different thicknesses were tested; 10mm, 20mm, 40mm, 60mm and 100mm. While testing the brackets of different thicknesses, a knowledge of how much the stress would decrease/increase was found.

Thickness	Highest Von Mises stress in stiffener web	Allowed Von Mises stress	Highest Von Mises stress in stiffener flange	Allowed Von Mises stress
Original design	395 MPa	470 MPa	497 MPa	470 MPa
10 mm	473 MPa	470 MPa	456 MPa	470 MPa
20 mm	468 MPa	470 MPa	456 MPa	470 MPa
40 mm	461 MPa	470 MPa	456 MPa	470 MPa
60 mm	458 MPa	470 MPa	455 MPa	470 MPa
100 mm	456 MPa	470 MPa	454 MPa	470 MPa

Table 7.17: Result of Case 1, stiffeners.

Thickness	Highest Von Mises stress in girder web	Allowed Von Mises stress	Highest Von Mises stress in girder flange	Allowed Von Mises stress
Original design	1480 MPa	470 MPa	506 MPa	470 MPa
10 mm	1454 MPa	470 MPa	488 MPa	470 MPa
20 mm	1458 MPa	470 MPa	488 MPa	470 MPa
40 mm	1457 MPa	470 MPa	487 MPa	470 MPa
60 mm	1453 MPa	470 MPa	487 MPa	470 MPa
100 mm	1447 MPa	470 MPa	487 MPa	470 MPa

Table 7.18: Result of Case 1, longitudinal girders.

Thickness	Highest Von Mises stress in girder web	Allowed Von Mises stress	Highest Von Mises stress in girder flange	Allowed Von Mises stress
Original design	803 MPa	470 MPa	848 MPa	470 MPa
10 mm	813 MPa	470 MPa	844 MPa	470 MPa
20 mm	812 MPa	470 MPa	843 MPa	470 MPa
40 mm	811 MPa	470 MPa	842 MPa	470 MPa
60 mm	811 MPa	470 MPa	842 MPa	470 MPa
100 mm	809 MPa	470 MPa	840 MPa	470 MPa

Table 7.19: Result of Case 1, transverse girder.

Table 7.17, 7.18 and 7.19 summarise the test results from Case 1.

As one can see in Table 7.18, the Von Mises stress in girder web increases according to the increase of bracket thickness. This high stress is located in the top of the stiffener cut-out (illustrated in Figure 7.14). An explanation of why the stress was increasing in this area could be that, without the brackets, the deformation would be distributed along the length of the girder, because they are only fixed in the ends. Now, with brackets at each 300 mm, the deformation would be more distributed between each bracket, and the cut-out would be subject to tension load higher than before the brackets were assembled.

Testing the highest thickness, one can see that the stress started to go down. If the bracket thickness further on were increased, maybe the stress would decrease to a more feasible level. To get to this level, the thickness had to be increased a lot, which would, on the other hand, cause troubles with the fitting of brackets.

Due to these challenges, this case is discarded until further cases are undergone.

Critical section

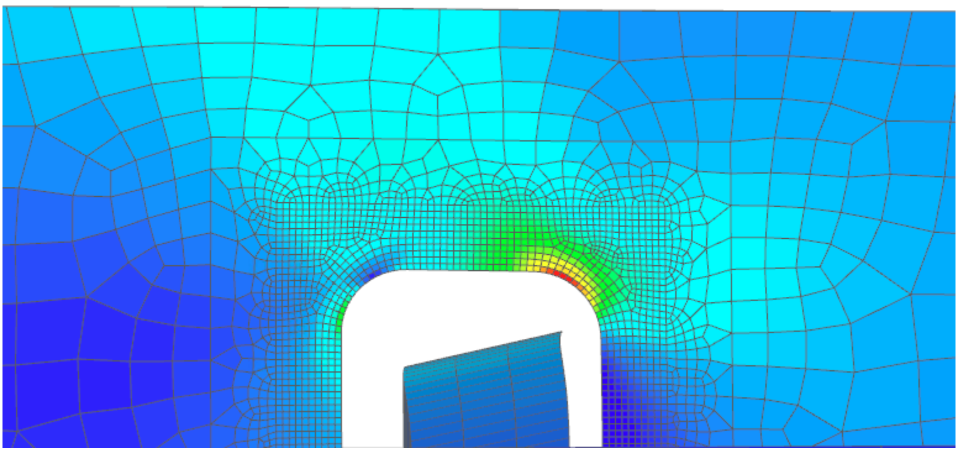


Figure 7.14: Critical section of Case 1.

7.4.2 Case 2 - Flat bar

The next case up was with a flat bar welded on to the backside of the stiffeners. The flat bar was also welded at the ends to the web of the girder. For this test, it was expected that the stress in stiffeners would be decreased. As well as the first case, this case was tested with different thicknesses for the flat bar. In Figure 7.15, the design of the bar and stiffener can be viewed.

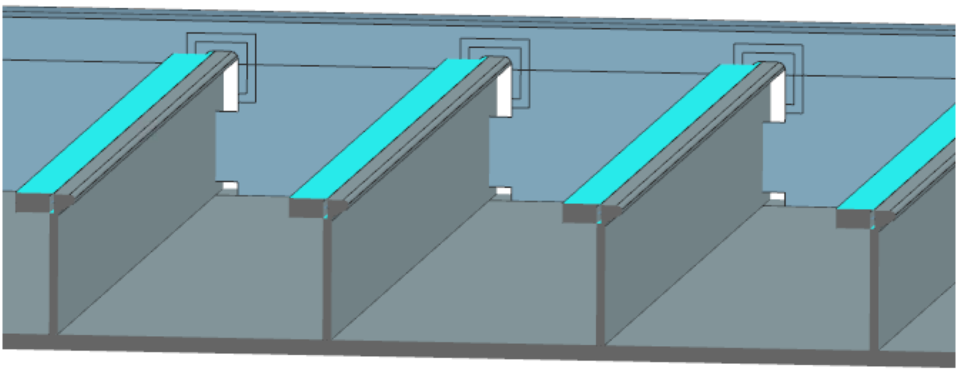


Figure 7.15: Flat bar inserted in panel.

Testing of Case 2

Five different dimensions were tested. The first thickness tested was equal to the stiffener bulb thickness, and further on, the thicknesses were increased to check how the stress level would vary. A summary of the loads is presented in Table 7.20, 7.21, 7.23 and 7.22.

Thickness	Highest Von Mises stress in stiffener web	Allowed Von Mises stress	Highest Von Mises stress in stiffener flange	Allowed Von Mises stress
Original design	395 MPa	470 MPa	497 MPa	470 MPa
22 mm	307 MPa	470 MPa	331 MPa	470 MPa
30 mm	282 MPa	470 MPa	306 MPa	470 MPa
40 mm	261 MPa	470 MPa	282 MPa	470 MPa
60 mm	229 MPa	470 MPa	243 MPa	470 MPa
100 mm	186 MPa	470 MPa	189 MPa	470 MPa

Table 7.20: Result of Case 2, stiffeners.

Thickness	Highest Von Mises stress in girder web	Allowed Von Mises stress	Highest Von Mises stress in girder flange	Allowed Von Mises stress
Original design	1480 MPa	470 MPa	506 MPa	470 MPa
22 mm	1165 MPa	470 MPa	452 MPa	470 MPa
30 mm	1129 MPa	470 MPa	446 MPa	470 MPa
40 mm	1094 MPa	470 MPa	438 MPa	470 MPa
60 mm	1041 MPa	470 MPa	423 MPa	470 MPa
100 mm	960 MPa	470 MPa	394 MPa	470 MPa

Table 7.21: Result of Case 2, longitudinal girders.

Thickness	Highest Von Mises stress in girder web	Allowed Von Mises stress	Highest Von Mises stress in girder flange	Allowed Von Mises stress
Original design	803 MPa	470 MPa	848 MPa	470 MPa
22 mm	683 MPa	470 MPa	717 MPa	470 MPa
30 mm	653 MPa	470 MPa	685 MPa	470 MPa
40 mm	620 MPa	470 MPa	650 MPa	470 MPa
60 mm	568 MPa	470 MPa	596 MPa	470 MPa
100 mm	492 MPa	470 MPa	516 MPa	470 MPa

Table 7.22: Result of case 2, transverse girder.

Thickness	Highest Von Mises stress in flat bar	Allowed Von Mises stress
22 mm	406 MPa	470 MPa
30 mm	367 MPa	470 MPa
40 mm	336 MPa	470 MPa
60 mm	303 MPa	470 MPa
100 mm	280 MPa	470 MPa

Table 7.23: Result of Case 2, flat bar.

Table 7.20, 7.21, 7.22 and 7.23 summarise the test results from Case 2.

With a 22mm thick flat bar applied to the stiffeners, the stiffener web and flange/bulb were automatically below the allowed Von Mises stress. For the girder, the stress was still too high on the web, but the flange got feasible stress (Critical section illustrated in Figure 7.16). Due to high stresses in both girder web and transverse girder, new thicknesses had to be tested.

Thicknesses of 30-, 40-, 60- and 100mm were tested for the panel, but none of them gave a successful analyse result. If the flat bar were increased in size, this would cause space problems and welding problems. The steel weight and cost would also be assumed to be crucially increased. Due to these problems, a new case was established. The flat bar was still applied to the stiffener, and the thickness was set to 30mm.

Critical section

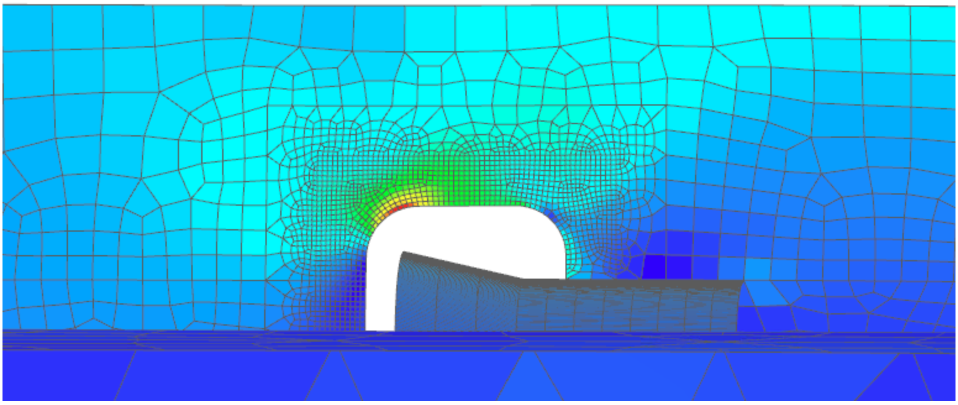


Figure 7.16: Critical section of Case 2.

7.4.3 Case 3 - Flat bar and extra steel in girder flange

In Case 3, the panel was designed with a flat bar of 30 mm and an extra steel plate at the girder flange. During this case, the additional plate thickness was increased from 5-25mm with a step of 5mm. The new panel can be viewed in Figure 7.17.

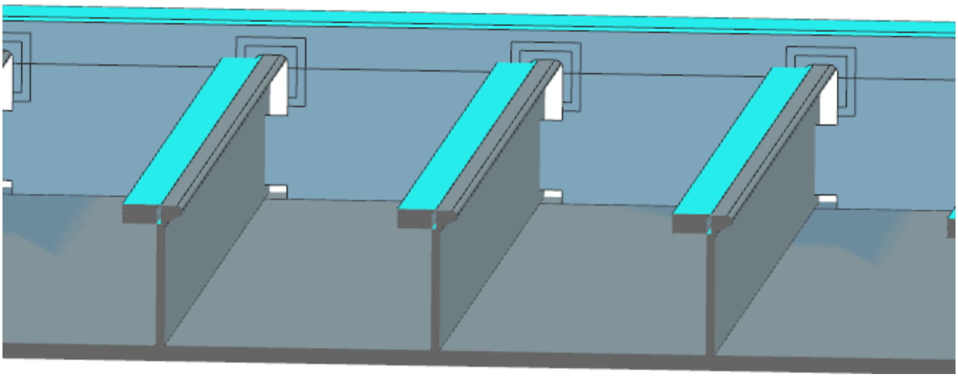


Figure 7.17: Design of flat bar and extra steel.

Testing of Case 3

Thickness	Highest Von Mises stress in stiffener web	Allowed Von Mises stress	Highest Von Mises stress in stiffener flange	Allowed Von Mises stress
Original design	395 MPa	470 MPa	497 MPa	470 MPa
5 mm	262 MPa	470 MPa	298 MPa	470 MPa
10 mm	270 MPa	470 MPa	292 MPa	470 MPa
15 mm	311 MPa	470 MPa	287 MPa	470 MPa
20 mm	246 MPa	470 MPa	283 MPa	470 MPa
25 mm	263 MPa	470 MPa	279 MPa	470 MPa

Table 7.24: Result of Case 3, stiffeners.

Thickness	Highest Von Mises stress in girder web	Allowed Von Mises stress	Highest Von Mises stress in girder flange	Allowed Von Mises stress
Original design	1480 MPa	470 MPa	506 MPa	470 MPa
5 mm	1039 MPa	470 MPa	385 MPa	470 MPa
10 mm	978 MPa	470 MPa	345 MPa	470 MPa
15 mm	933 MPa	470 MPa	317 MPa	470 MPa
20 mm	897 MPa	470 MPa	289 MPa	470 MPa
25 mm	867 MPa	470 MPa	279 MPa	470 MPa

Table 7.25: Result of Case 3, longitudinal girders.

Thickness	Highest Von Mises stress in girder web	Allowed Von Mises stress	Highest Von Mises stress in girder flange	Allowed Von Mises stress
Original design	803 MPa	470 MPa	848 MPa	470 MPa
5 mm	637 MPa	470 MPa	668 MPa	470 MPa
10 mm	624 MPa	470 MPa	655 MPa	470 MPa
15 mm	614 MPa	470 MPa	644 MPa	470 MPa
20 mm	604 MPa	470 MPa	634 MPa	470 MPa
25 mm	596 MPa	470 MPa	625 MPa	470 MPa

Table 7.26: Result of Case 3, transverse girder.

Thickness	Highest Von Mises stress in flat bar	Allowed Von Mises stress
5 mm	351 MPa	470 MPa
10 mm	338 MPa	470 MPa
15 mm	327 MPa	470 MPa
20 mm	318 MPa	470 MPa
25 mm	310 MPa	470 MPa

Table 7.27: Result of Case 3, flat bar.

Table 7.24, 7.25, 7.26 and 7.27 summarise the test results from Case 3.

All elements were influenced by the addition in this case. As the stiffener, girder flange and flat bar were at a feasible stress level during all of the analyses, this indicated that the thesis was on the right track to find the optimum panel design.

The transverse girder web and longitudinal girder web/flange still had some difficulties getting below the allowed stress level (Critical section illustrated in Figure 7.18) and case 4 was decided for further investigations.

Critical section

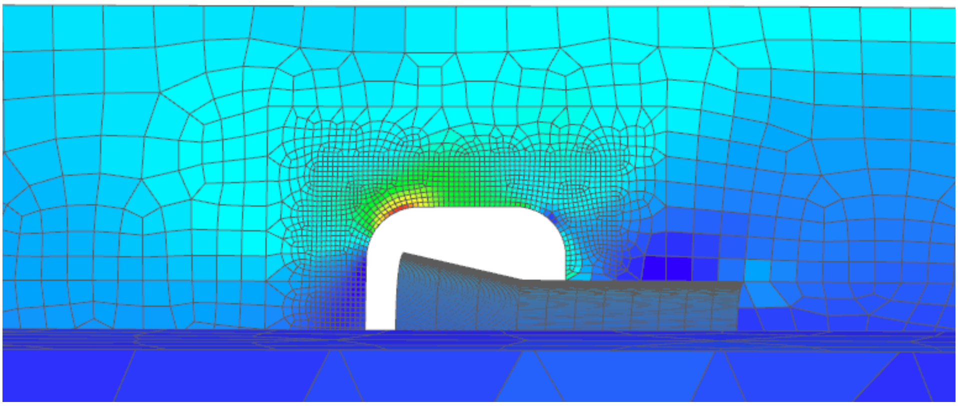


Figure 7.18: Critical section of Case 3.

7.4.4 Case 4 - Flat bar and plate at cut-out

Because most of the girder stress was located in the cut-out area, this case introduced a plate covering the stiffener cut-out. This plate was welded both in the girder web and in the stiffener. Figure 7.19 illustrates how the flat bar and cut-out plate was designed.

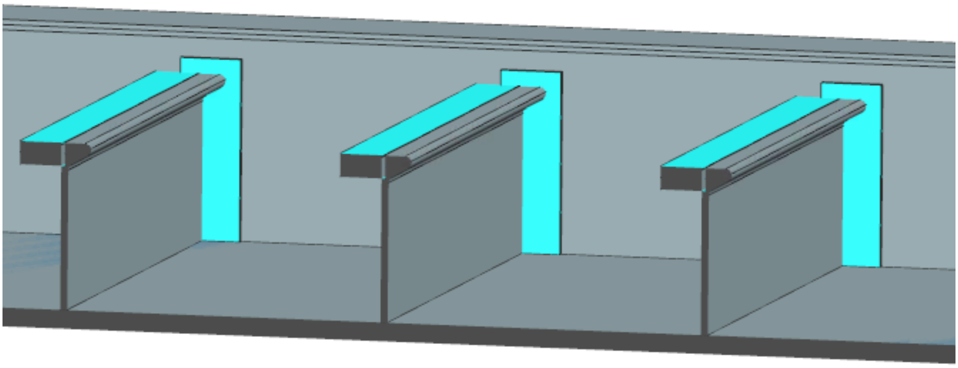


Figure 7.19: Design of flat bar and plate at cutout.

Testing of Case 4

Thickness	Highest Von Mises stress in stiffener web	Allowed Von Mises stress	Highest Von Mises stress in stiffener flange	Allowed Von Mises stress
Original design	395 MPa	470 MPa	497 MPa	470 MPa
5 mm	238 MPa	470 MPa	298 MPa	470 MPa
10 mm	238 MPa	470 MPa	298 MPa	470 MPa
15 mm	238 MPa	470 MPa	298 MPa	470 MPa
20 mm	237 MPa	470 MPa	298 MPa	470 MPa
25 mm	237 MPa	470 MPa	298 MPa	470 MPa

Table 7.28: Result of Case 4, stiffeners.

Thickness	Highest Von Mises stress in girder web	Allowed Von Mises stress	Highest Von Mises stress in girder flange	Allowed Von Mises stress
Original design	1480 MPa	470 MPa	506 MPa	470 MPa
5 mm	355 MPa	470 MPa	390 MPa	470 MPa
10 mm	370 MPa	470 MPa	389 MPa	470 MPa
15 mm	380 MPa	470 MPa	388 MPa	470 MPa
20 mm	388 MPa	470 MPa	387 MPa	470 MPa
25 mm	393 MPa	470 MPa	387 MPa	470 MPa

Table 7.29: Result of Case 4, longitudinal girders.

Thickness	Highest Von Mises stress in girder web	Allowed Von Mises stress	Highest Von Mises stress in girder flange	Allowed Von Mises stress
Original design	803 MPa	470 MPa	848 MPa	470 MPa
5 mm	642 MPa	470 MPa	679 MPa	470 MPa
10 mm	642 MPa	470 MPa	679 MPa	470 MPa
15 mm	642 MPa	470 MPa	678 MPa	470 MPa
20 mm	642 MPa	470 MPa	678 MPa	470 MPa
25 mm	642 MPa	470 MPa	678 MPa	470 MPa

Table 7.30: Result of Case 4, transverse girder.

Thickness	Highest Von Mises stress in flat bar	Allowed Von Mises stress
5 mm	297 MPa	470 MPa
10 mm	296 MPa	470 MPa
15 mm	296 MPa	470 MPa
20 mm	295 MPa	470 MPa
25 mm	295 MPa	470 MPa

Table 7.31: Result of Case 4, flat bar.

Table 7.28, 7.29, 7.30 and 7.31 summarise the test results from Case 4.

Compared with the other completed cases, this case was the closest one to a feasible stress level. For the stiffener, this had already a satisfying stress level when the flat bar was applied in Case 2.

The combination of flat bar and cut-out plate did crucial influence of the girder. Illustrated in Table 7.29, the stress level decrease from 1480 MPa to 355 MPa in the girder web and 506 MPa to 390 MPa in the girder flange during the first test. With the increase of cut-out plate thickness, the stress level increases, which can be caused by larger transitions between the girder web and cut-out plate.

As the cut-out plate influences both the longitudinal girder and the stiffener, the transverse girder is not influenced by this change, compared with the two previous cases. As the stress level still was not satisfied, Case 5 was established, with a combination of earlier tested cases. The critical section can be viewed in Figure 7.20.

Critical section

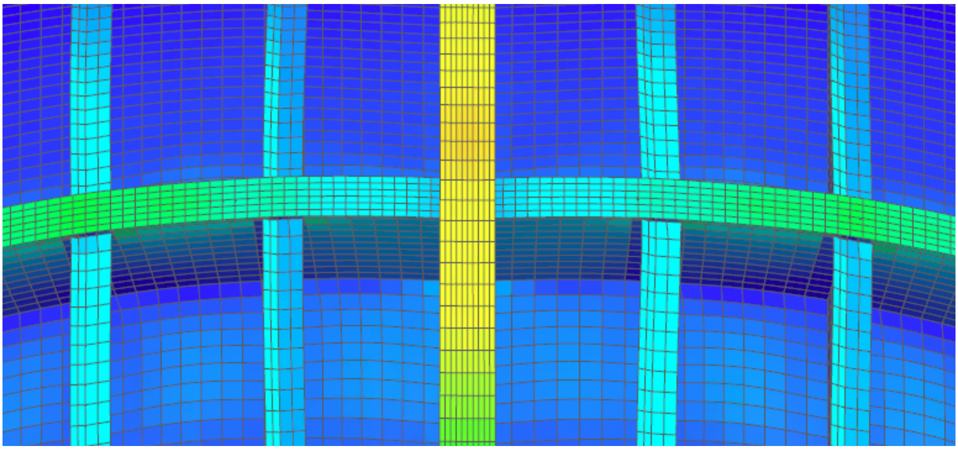


Figure 7.20: Critical section of Case 4.

7.4.5 Case 5 - Flat bar, plate at cut-out and extra steel on girder flange

Case 5 was made by the results of earlier cases, and introduced to a flat bar, a plate at the cut-out area and extra steel plate for both the transverse and longitudinal girder flange. During these tests, the extra steel plate at transverse girder flange varied from 0-30mm with steps of 10mm. The design of Case 5 can be viewed in Figure 7.21.

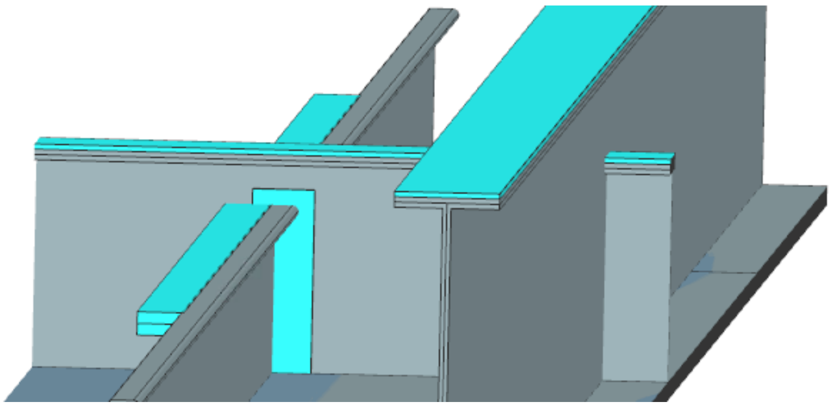


Figure 7.21: Design of flat bar, plate at cutout and extra girder flange steel.

Testing of Case 5

Thickness	Highest Von Mises stress in stiffener web	Allowed Von Mises stress	Highest Von Mises stress in stiffener flange	Allowed Von Mises stress
Original design	395 MPa	470 MPa	497 MPa	470 MPa
Flatbar, 30mm **Cut-out plate, 5mm** **Flange extra plate girders, 5mm** **Flange extra plate transverse girder, 0mm**	232 MPa	470 MPa	292 MPa	470 MPa
Flatbar, 30mm **Cut-out plate, 5mm** **Flange extra plate girders, 5mm** **Flange extra plate transverse girder, 10mm**	190 MPa	470 MPa	242 MPa	470 MPa
Flatbar, 30mm **Cut-out plate, 5mm** **Flange extra plate girders, 5mm** **Flange extra plate transverse girder, 20mm**	174 MPa	470 MPa	222 MPa	470 MPa
Flatbar, 30mm **Cut-out plate, 5mm** **Flange extra plate girders, 5mm** **Flange extra plate transverse girder, 30mm**	164 MPa	470 MPa	209 MPa	470 MPa

Table 7.32: Result of Case 5, stiffeners.

Thickness	Highest Von Mises stress in girder web	Allowed Von Mises stress	Highest Von Mises stress in girder flange	Allowed Von Mises stress
Original design	1480 MPa	470 MPa	506 MPa	470 MPa
Flatbar, 30mm **Cut-out plate, 5mm** **Flange extra plate girders, 5mm** **Flange extra plate transverse girder, 0mm**	323 MPa	470 MPa	350 MPa	470 MPa
Flatbar, 30mm **Cut-out plate, 5mm** **Flange extra plate girders, 5mm** **Flange extra plate transverse girder, 10mm**	267 MPa	470 MPa	309 MPa	470 MPa
Flatbar, 30mm **Cut-out plate, 5mm** **Flange extra plate girders, 5mm** **Flange extra plate transverse girder, 20mm**	260 MPa	470 MPa	293 MPa	470 MPa
Flatbar, 30mm **Cut-out plate, 5mm** **Flange extra plate girders, 5mm** **Flange extra plate transverse girder, 30mm**	252 MPa	470 MPa	283 MPa	470 MPa

Table 7.33: Result of Case 5, longitudinal girders.

Thickness	Highest Von Mises stress in girder web	Allowed Von Mises stress	Highest Von Mises stress in girder flange	Allowed Von Mises stress
Original design	803 MPa	470 MPa	848 MPa	470 MPa
Flatbar, 30mm **Cut-out plate, 5mm** **Flange extra plate girders, 5mm** **Flange extra plate transverse girder, 0mm**	627 MPa	470 MPa	663 MPa	470 MPa
Flatbar, 30mm **Cut-out plate, 5mm** **Flange extra plate girders, 5mm** **Flange extra plate transverse girder, 10mm**	478 MPa	470 MPa	523 MPa	470 MPa
Flatbar, 30mm **Cut-out plate, 5mm** **Flange extra plate girders, 5mm** **Flange extra plate transverse girder, 20mm**	397 MPa	470 MPa	451 MPa	470 MPa
Flatbar, 30mm **Cut-out plate, 5mm** **Flange extra plate girders, 5mm** **Flange extra plate transverse girder, 30mm**	341 MPa	470 MPa	403 MPa	470 MPa

Table 7.34: Result of Case 5, transverse girder.

Thickness	Highest Von Mises stress in flat bar	Allowed Von Mises stress
Flatbar, 30mm **Cut-out plate, 5mm** **Flange extra plate girders, 5mm** **Flange extra plate transverse girder, 0mm**	290 MPa	470 MPa
Flatbar, 30mm **Cut-out plate, 5mm** **Flange extra plate girders, 5mm** **Flange extra plate transverse girder, 10mm**	239 MPa	470 MPa
Flatbar, 30mm **Cut-out plate, 5mm** **Flange extra plate girders, 5mm** **Flange extra plate transverse girder, 20mm**	216 MPa	470 MPa
Flatbar, 30mm **Cut-out plate, 5mm** **Flange extra plate girders, 5mm** **Flange extra plate transverse girder, 30mm**	201 MPa	470 MPa

Table 7.35: Result of Case 5, flat bar.

Table 7.32, 7.33, 7.34 and 7.35 summarise the test results from Case 5.

The analyse completed with a panel approved for all stresses in the elements. The thesis was now successful in finding a panel design using only additional elements, and non of the original elements were changed from the original design.

The final additional elements used:

Flat bar 30mm.

Cut-out plate 5mm.

Long. girder flange plate 5mm.

Trans. girder flange plate 20mm.

8 | Discussion

As a basis of this thesis, a problem was described and given by Marin Teknikk AS. As they had a customer asking of which structural causes a change of class notation from Ice(C) to PC(6) would have for the structural elements in the ship hull, they needed a quick method for investigation of this change. Due to this problem, this thesis decided to perform two different methods for structural optimisation of a vessel which is changing class notation from Ice(C) to PC(6); rule-based method and finite element method.

8.1 Rule-based method

In the first method, a calculation application was created to investigate which new dimensions the ship hull elements would have as a cause of this change. The goal of this method was, as an interest of the firm, to create an application that, in a small amount of time, would give an estimate of new dimensions as a cause of change in class notation.

For the first research question, the thesis asked which class notations are essential. For Baltic and Polar regions, rules and regulations are made by different societies. As DNV GL is a class society from Norway, and this is the rules used in all classes during the master degree, the choice felt naturally on DNV GL' rules and regulations for this thesis. As the firm would like a comparison between structural elements as a cause of the class change from Ice(C) to PC(6), the student had to investigate which regulations were relevant for this thesis. In the rules and regulations of DNV GL, cold climate is an own chapter. This chapter is divided into several sections, but this thesis used only two of these; Northern Baltic for Ice(C), and POLAR Class for PC(6).

8.1.1 Using calculation application for structural changes

In Chapter 6, the results of the rule-based method is presented. According to the method given in Section 4.1, the application satisfied all points given. The application had a small amount of input, automatically gave an estimate of new dimensions, and at the end, the user was able to export a summary report with all estimated values.

As the calculation application was implemented in the software application Microsoft Excel, the graphical user interface in the final application has its limitations. If the project had lasted for an extended period of time, more equations and functionality could have been implemented in a scripting program. The tradeoff between functionality and usability in the resulting application can be said to be good enough.

Regarding the calculation results of the application, they can be seen as early estimates for the complete dimensions. As Section 7.2 indicates, the panel estimated by Excel does not satisfy all allowed Von Mises stress levels, but with an addition of a transverse girder, and some other small adjustments for the PC(6) panel, both the panels got under the allowed stress level.

8.2 Finite element method

In the second method, the Ice(C) midship panel was further investigated. In this part, the goal was to find out if a small amount of steel was enough to make the Ice(C) panel feasible with PC(6) loads. The part started by testing if the calculation application estimated panels which satisfied the given load for its classification. Both for the Ice(C) and PC(6) panel, the analyse indicated some high stresses in the elements, and as a result of this, a discussion between the student and the company was held. In this discussion, it was told that the real built ship, in this region, had a transverse girder for extra support. As a cause of this, the thesis decided to apply this girder to the model for further investigation.

The next chapter of this method started a case study, which contained six different cases. The first case, Case 0, had the same goal as the analyse in Section 7.2, but the transverse girder was implemented. With the new girder applied, the analyse of the Ice(C) panel ended successfully with a feasible stress level. Still, the PC(6) panel needed further investigation because of high stresses in the girders. As the transverse girder applied to the model had the same dimensions as the one used in the built ship, the thesis concluded that this girder was of too small dimension to handle the PC(6) load. A new, larger girder, was therefor implemented and gave better results for the analyse. With this larger girder, all elements except the longitudinal girder web, in the cut-out area, were at a feasible stress level. It can be different reasons why the long. girder web did not get a feasible stress level; bad design of cut-out, still under dimensioned girder or wrong dimensions calculated by the application. To deal with the problem, the thesis decided to add some small plates at the cut-out where the stresses were too large. This resulted in a successful analyse, and the thesis moved further in the case study.

8.2.1 Case study

The next five cases had the same goal; complete a panel test of the Ice(C) panel with a minimum added steel to satisfy the polar load. In the first case, brackets were added for extra support at the girder flange. Instead of supporting the girder web, the brackets ended up giving the girder web higher stresses in the cut-out area. It was also tried with higher thicknesses, but nothing provided a satisfying solution. Hence, the case was discarded.

The second case did much more influence on the panel. In this case, a flat bar was welded on the backside of the bulb profiles and in the girder web at the ends. This caused a significant decrease in the stress of both stiffener and girder flange. Because the girder web and the transverse girder still had some high stresses, the thesis decided to investigate a new case.

For the third case, the thesis tried to increase the thickness of long. girder flange, by welding a plate onto it. Still, the flat bar was in the same place, but with a thickness of 30mm. In this case, also the girder web decreased, but still not under an allowed stress level. Same for the trans. girder as the longitudinal.

As the high stresses in the transverse girder were located around the cut-out area, the thesis decided to introduce a plate covering the cut-out. This plate was welded both to the stiffener and the girder web. For this case, the girder web also got below an allowed stress level, but the trans. girder was still above.

For the last case, the student increased the thickness of trans. girder flange by welding a plate onto it. As seen in Table 7.34, the perfect combination of the last case was with a plate thickness of 20mm. The thesis had than answered to the second research question, and stated that for this vessel, it is possible to add a small amount of structure to meet the requirements of a higher class notation.

8.3 Comparison

In the first method of research question number three, using the midship ice-belt panel, the new dimensions were estimated in the application, giving an estimate of which new dimension the engineer could expect regarding the change of class notation. In the calculation application, the Ice(C) panel has an estimated weight of 929 kg, and the PC(6) panel an estimated weight of 1850 kg. As Table 8.1 indicates, the change of class notation cause an increase of 922 kg for the midship panel.

The same Ice(C) panel was used in the second method as in the first, indicating which minimum change an engineer could do to satisfy the requirements of PC(6) regulations. As Case 5 indicates in Section 7.4.5, the optimum additions of Ice(C) panel were;

- Adding Flat bar of 30mm
- Adding cut-out plate of 5mm
- Adding extra plate at long. girder flange of 5mm
- Adding extra plate at trans. girder flange of 20mm

These additions caused a dramatic change in weight. The additional structure had a weight of 1375, which gave a total weight of 2303 kg. Compared to method 1, which had a total weight of 1850, this makes a difference between the two of them of 453 kg. ***All data from this weight comparison can be viewed in appendix 2***.

Weight increase	
Rule based method	922 kg
Finite element method	1375 kg
Difference	453 kg

Table 8.1: Comparison of weight, Rule based method vs Finite element method.

As the difference of weight in the two methods is approx 500 kg, one can discuss which one to choose based on the vessels best. For the first method, all elements have to be switched out, which could cause a crucial economic consequence. For method number two, the ship would stay as it is and extra steel would be added on to the panel elements. Added steel would lead to a higher increase of structural weight, and higher structural weight will then again cause other problems on board the vessel. This spiral is why weight estimation of a vessel is one of the hardest problems in the design period; a small change in one part can cause a bigger problem in another part.

9 | Conclusion

During this Master thesis, the student has completed two different methods for structural optimisation of a yacht vessel changing class notation. The different parts of the project seem to be a good solution to the problem stated in the startup phase of the project.

As there are both benefits and difficulties in both methods used, it is hard to conclude whether to choose one or the other. The first method is using a short amount of time to give an estimation of the structural components. This could be a beneficial application for the company in an early phase of the design period. With early estimates of structural elements, a lot of time spending on calculations could be saved, and with saved time equals saved money.

The second method is more time demanding, as the method needs more thorough construction with elements, mesh, constraints and loads. Hence, with the right amount of time, this method would give the designer a better conclusion about whether to use one dimension or the other. The second method will also be more feasible in the later phases of the design process or if a redesign is preferred. The method can be used for structural optimisation of a ship which will meet higher requirements than the class notation it has.

Compared with the scope, objective and RQ's, the student is satisfied with the results. Both the application and the finite elements gave results which could be used for further investigations. The student is also pleased by the fact that Marin Teknikk would like to use this application in their project phases for estimates of structural elements.

During the project phase, the student has gained useful experience in the subject. To get this experience, an essential factor has been to have regular meetings with both the supervisor at NTNU, but also at Marin Teknikk.

10 | Future Work

For the calculation application, there are several things to create a basis for future work. As the application is installed with a calculation of the frame lengths along with the ship, it is possible to add weight estimation for the hull weight. This would, in addition to element dimensions, give an estimate of the total hull weight for the designer in an early phase. As the application mainly focuses on calculating dimensions from baseline to the main deck, an implementation for the ship could be to include the dimensions above the main deck.

Ice-loads are loads which a lot of engineers are struggling with. As the loads are very unstable and will vary from voyage to voyage, this is a subject that should be further investigated. For the finite element analysis completed in this thesis, the same assumption as done by classification societies, with a rectangular ice load patch, is included. It is hard to know whether this is a rough estimate or an estimate which should be done lighter. This would be a topic of interest to gain more expertise in this subject.

As the thesis found a minimum change of the ice-C panel, it is not for sure that this change is the absolute best. Further case studies could be done for both the midship ice belt panel, but also for other panels of the vessel. It would also be interesting to check other panels calculated by the applications and compare the results of these panels as well.

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Appendices

CD

Appendix 1	Summary report
Appendix 2	Weight comparison
Appendix 3	Assumptions for calculation application
Appendix 4	Factors used in Chapter 3 "Classifications of ships"
Appendix 5	Input pages calculation application

Appendix 1

Summary Report

Structural Optimisation of an Ice-Strengthened Yacht Vessel

A calculation application by Sondre Gjerset Rødseth

Results

Inputs

Ship's Length Over All	L	116,50	m
Ship's Breadth	B	18,00	m
Frame Spacing	s	600,00	mm
Frame Spacing in Ice Belt	s_{IB}	300,00	mm
Depth	D	8,60	m
Draft	T	5,00	m
L_{PP}	L_{PP}	104,11	m

ICE Class:	ICE C
Choose Polar Class:	PC6
Flat Side:	No
Orientation of Plating	Longitudinal
Ship with thrusters or podded propulsion	Yes
Direction of framing	Longitudinal
Material Class	235

Ship length at UIWL	L_i	105,25
UIWL angle	α_i	17
UIWL normal frame angle	β'_i	25
Ship Displacement at UIWL	Δ_{tk}	9,571
Smallest angle between the chord of the waterline and the line of the first level framing	Ω	10
Frame Spacing	s	600,00
Distance between frame supports	l	1800
Distance between frame supports in ice belt	l_{IB}	1800
Block Coefficient	C_B	0,8

Ice Loads

PC6

Bow		
Average Pressure	2,50	MPa
Design Load Patch Width	2,01	m
Design Load Patch Height	0,64	m

Forship		
Average Pressure	2,68	MPa
Design Load Patch Width	2,22	m
Design Load Patch Height	0,62	m

Midship		
Average Pressure	2,68	MPa
Design Load Patch Width	2,22	m
Design Load Patch Height	0,62	m

Stern		
Average Pressure	2,68	MPa
Design Load Patch Width	2,22	m
Design Load Patch Height	0,62	m

ICE C

Pressures in Bow		
Shell Transverse	0,91	MPa
Shell Longitudinal	0,69	MPa
Frames Transverse	0,91	MPa
Frames Longitudinal	0,52	MPa

Pressures in Midship		
Shell Transverse	0,57	MPa
Shell Longitudinal	0,44	MPa
Frames Transverse	0,57	MPa
Frames Longitudinal	0,33	MPa

Pressures in Stern		
Shell Transverse	0,57	MPa
Shell Longitudinal	0,44	MPa
Frames Transverse	0,57	MPa
Frames Longitudinal	0,33	MPa

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Plating

PC6

Plating Thicknesses Stern		
Ice Belt	27,00	mm
Lower	24,00	mm
Bottom	11,00	mm

Plating Thicknesses Midship		
Ice Belt	25,00	mm
Lower	19,00	mm
Bottom	11,00	mm

Plating Thicknesses Forship		
Ice Belt	36,00	mm
Lower	27,00	mm
Bottom	21,00	mm

Plating Thicknesses Bow		
Whole bow	36,00	mm

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Plating

ICE C

Plating Thicknesses Stern

Ice Belt	18,00	mm
Lower	11,00	mm
Bottom	11,00	mm

Plating Thicknesses Midship

Ice Belt	18,00	mm
Lower	11,00	mm
Bottom	11,00	mm

Plating Thicknesses Forship

Ice Belt	21,00	mm
Lower	11,00	mm
Bottom	11,00	mm

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Plating Comparison

Plating Thicknesses Stern		
Ice Belt	9,00	mm
Lower	13,00	mm
Bottom	0,00	mm

Plating Thicknesses Midship		
Ice Belt	7,00	mm
Lower	8,00	mm
Bottom	0,00	mm

Plating Thicknesses Forship		
Ice Belt	15,00	mm
Lower	16,00	mm
Bottom	10,00	mm

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Framing

PC6

Framing Profile Stern

	Profile	Cross Section Area cm2
Ice Belt	HP160x7	14,58
Lower	HP180x11	24,2
Bottom	HP180x11	24,2

Framing Profile Midship

	Profile	Cross Section Area cm2
Ice Belt	HP160x7	14,58
Lower	HP160x8	16,18
Bottom	HP180x11	24,2

Framing Profile Forship

	Profile	Cross Section Area cm2
Ice Belt	HP160x7	14,58
Lower	HP220x11,5	32,24
Bottom	HP180x8	18,83

Framing Profile Bow

	Profile	Cross Section Area cm2
Whole bow	HP160x7	14,58

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Framing

ICE C

Framing Profile Stern

	Profile	Cross Section Area cm2
Ice Belt	HP160x7	14,58
Lower	HP180x11	24,2
Bottom	HP180x11	24,2

Framing Profile Midship

	Profile	Cross Section Area cm2
Ice Belt	HP160x7	14,58
Lower	HP180x11	24,2
Bottom	HP180x11	24,2

Framing Profile Forship

	Profile	Cross Section Area cm2
Ice Belt	HP160x7	14,58
Lower	HP180x11	24,2
Bottom	HP180x11	24,2

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Primary Support Members

PC6

PSM Profile Stern

	Profile	Cross Section Area cm2
Ice Belt	250x10+200x15	5500
Lower	250x10+200x15	5500
Bottom	350x10+250x20	8500

PSM Profile Midship

	Profile	Cross Section Area cm2
Ice Belt	250x10+200x15	5500
Lower	250x12+250x25	9250
Bottom	350x10+250x20	8500

PSM Profile Forship

	Profile	Cross Section Area cm2
Ice Belt	250x10+200x15	5500
Lower	250x10+200x15	5500
Bottom	250x10+200x15	5500

PSM Profile Bow

	Profile	Cross Section Area cm2
Whole bow	250x10+200x15	5500

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Primary Support Members

ICE C

PSM Profile Stern

	Profile	Cross Section Area cm2
Ice Belt	200x10+100x10	3000
Lower	200x10+100x10	3000
Bottom	200x10+100x10	3000

PSM Profile Midship

	Profile	Cross Section Area cm2
Ice Belt	200x10+100x10	3000
Lower	200x10+100x10	3000
Bottom	200x10+100x10	3000

PSM Profile Forship

	Profile	Cross Section Area cm2
Ice Belt	200x10+100x10	3000
Lower	200x10+100x10	3000
Bottom	200x10+100x10	3000

PSM Profile Bow

	Profile	Cross Section Area cm2
Whole bow	200x10+100x10	3000

Data Used For

Finite Element Model

Data Used in an eventually parametric model

Midship Icebelt

Polar Load

Pressure	1650	MPa
Design load patch height	2,220	m
Design load patch width	0,617	m

Ice Load

Pressure	603	MPa
Design load patch height	2,220	m
Design load patch width	0,617	m

Plate Dimension

Length		**10000**	mm
Height		**6300**	mm
Thickness to use	**PC6**	**25,00**	mm
	ICE C	**18,00**	mm

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Data Used in an eventually parametric model

Midship Icebelt

Stiffener Profile

Spacing	**300,00**	mm			
Profile to use		**PC6**	**HP160x7**		
		b		**160**	mm
		t		**7**	mm
		c		**22**	mm
		d		**22,2**	mm
		r		**6**	mm
		ICE C	**HP160x7**		
		b		**160**	mm
		t		**7**	mm
		c		**22**	mm
		d		**22,2**	mm
		r		**6**	mm

Primary Support Members

Spacing	**1800**	mm			
Profile to use		**PC6**	**250x10+200x15**		
		Web heigth		**250**	mm
		Web Thickness		**10**	mm
		Flange Width		**200**	mm
Girders		Flange Thickness		**15**	mm
		ICE C	**200x10+100x10**		
		Web heigth		**200**	mm
		Web Thickness		**10**	mm
		Flange Width		**100**	mm
		Flange Thickness		**10**	mm

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Appendix 2

Weight Comparison

Method 1

Ice C	Plate	Breadth	10	m	**Polar 6**	Plate	Breadth	10	m
		Height	6,3	m			Height	6,3	m
		Thickness	0,018	m			Thickness	0,025	m
		Volume	1,134	m^3			Volume	1,575	m^3
	Stiffener	Cross section area	0,001458	m^2		Stiffener	Cross section area	0,001458	m^2
		Length	6,3	m			Length	6,3	m
		Number of	31				Number of	31	
		Volume	0,2847474	m^3			Volume	0,2847474	m^3
	PSM	Cross section area	3	m^2		PSM	Cross section area	5,5	m^2
		Length	10	m			Length	10	m
		Number of	3				Number of	3	
		Volume	90	m^3			Volume	165	m^3
	Transvers G	Cross section area	3,8	m^2		Transvers G	Cross section area	10	m^2
		Length	6,3	m			Length	6,3	m
		Number of	1				Number of	1	
		Volume	23,94	m^3			Volume	63	m^3
		Total Volume	115	m^3			**Total Volume**	230	m^3
		Density	8,05	kg/m^3			**Density**	8,05	kg/m^3
		Total Weight	**929**	kg			**Total Weight**	**1850**	kg

Method 2

Ice C	Plate	Breadth	10	m	**Addition**	Flat bar	Cross section area	1,32	m^2
		Height	6,3	m			Length	3,5	m
		Thickness	0,018	m			Number of	31	
		Volume	1,134	m^3			Volume	143,22	m^3
	Stiffener	Cross section area	0,001458	m^2					
		Length	6,3	m		Extra steel girder flange	Cross section area	0,5	m^2
		Number of	31				Length	10	m
		Volume	0,2847474	m^3			Number of	3	
	PSM	Cross section area	3	m^2			Volume	15	m^3
		Length	10	m					
		Number of	3			Cut-out plate	Heigth	0,175	m
		Volume	90	m^3			Breadth	0,061	m
	Transvers G	Cross section area	3,8	m^2			Thickness	0,005	m
		Length	6,3	m			Number of	62	
		Number of	1				Volume	0,00330925	m^3
		Volume	23,94	m^3					
						Extra steel T-girder flange	Cross section area	2	m^2
							Length	6,3	m
							Number of	1	
							Volume	12,6	m^3
		Total Volume	115	m^3			**Total Volume**	171	m^3
		Density	8,05	kg/m^3			**Density**	8,05	kg/m^3
		Total Weight	**929**	kg			**Total Weight**	**1375**	kg

Appendix 3

Assumptions for calculation application

Assumptions		
IceLoads	Polar 6	[x] The distance from the forward perpendicular (FE) to station under consideration used in bow section will be assumed as the middle point of bow section.
	Ice C	Ice loads determined according to Northern Baltic - Ice rules. $C_1 = 0,55$ Vertical extension of ice belt plating; 0.4 m above UIWL, 0.5 m below LIWL. Vertical extension of ice belt framing; 0.62 m above UIWL, 1.0 m below LIWL.
SkjulteVariabler	Both	Assuming that the bow is without any bulb; This can be added by the user for own weight estimation.
ShellPlating	Polar 6	All plates are whole millimetres and rounded upwards to nearest mm. Plate length is three times frame spacing.
	ICE C	For calculation of plate thickness, other areas than ice belt, an acceptance criteria AC-1 is used. The maximum permissible bending stress coefficient will be given as 0,8
StiffenerProfiles	Polar 6	For stiffeners at the bottom structure in stern- and midship section a bending moment factor is assumed to be 12.
	ICE C	Assuming that vertical extension of ice framing will be equal along the length of the ship. 1.0m above UIWL and 1.3m below LIWL. Assuming s_1 is equal to stiffener spacing (s) Assuming frames without brackets; $m_1 = 11$ For values of m0; continuous frames between several deck or stringers is assumed gives value 5,7.
Girders	Both	Assumed dimensions to be able to give a profile.
DNV GL	Both	Other assumptions made by DNV GL based on empirical data can be viewed in the rules listed in

		Bibliography.

Table 10.1: Assumptions made in the application

Appendix 4

Factors used in section 3.5

Hull area		*Area*	*Polar class*						
			PC(1)	***PC(2)***	***PC(3)***	***PC(4)***	***PC(5)***	***PC(6)***	***PC(7)***
Bow (B)	All	B	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Bow intermediate (BI)	Ice belt	BI_i	0.90	0.85	0.85	0.80	0.80	1.00*	1.00*
	Lower	BI_l	0.70	0.65	0.65	0.60	0.55	0.55	0.50
	Bottom	BI_b	0.55	0.50	0.45	0.40	0.35	0.30	0.25
Midbody (M)	Ice belt	M_i	0.70	0.65	0.55	0.55	0.50	0.45	0.45
	Lower	M_l	0.55	0.45	0.40	0.35	0.30	0.25	0.25
	Bottom	M_b	0.30	0.30	0.25	**	**	**	**
Stern (S)	Ice belt	S_i	0.90	0.85	0.80	0.75	0.65	0.55	0.50
	Lower	S_l	0.60	0.55	0.50	0.45	0.40	0.40	0.40
	Bottom	S_b	0.35	0.30	0.30	0.25	0.15	**	**

Notes:

* = See [4.1.3].

** = Indicates that strengthening for ice loads is not necessary.

Figure 10.1: Hull area factors.

Hull area		*Area*	*Polar class*						
			PC(1)	***PC(2)***	***PC(3)***	***PC(4)***	***PC(5)***	***PC(6)***	***PC(7)***
Bow (B)	All	B	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Bow intermediate (BI)	Ice belt	BI_i	0.90	0.85	0.85	0.80	0.80	1.00*	1.00*
	Lower	BI_l	0.70	0.65	0.65	0.60	0.55	0.55	0.50
	Bottom	BI_b	0.55	0.50	0.45	0.40	0.35	0.30	0.25
Midbody (M)	Ice belt	M_i	0.70	0.65	0.55	0.55	0.50	0.45	0.45
	Lower	M_l	0.50	0.45	0.40	0.35	0.30	0.25	0.25
	Bottom	M_b	0.30	0.30	0.25	**	**	**	**
Stern (S)	Ice belt	S_i	0.75	0.70	0.65	0.60	0.50	0.40	0.35
	Lower	S_l	0.45	0.40	0.35	0.30	0.25	0.25	0.25
	Bottom	S_b	0.35	0.30	0.30	0.25	0.15	**	**

Figure 10.2: Hull area factors.

Structural member		Peak pressure factor (PPF_i)
Plating	Transversely-framed	$PPF_p = (1.8 - s) \geq 1.2$
	Longitudinally-framed	$PPF_p = (2.2 - 1.2 \cdot s) \geq 1.5$
Frames in transverse Framing systems	With load distributing stringers[1)]	$PPF_t = (1.6 - s) \geq 1.0$
	With no load distributing stringers[1)]	$PPF_t = (1.8 - s) \geq 1.2$
Frames in bottom structures		$PPF_s = 1.0$
Load carrying stringers Side longitudinals Web frames		$PPF_s = 1$, if $S_w \geq 0.5 \cdot w$ $PPF_s = 2.0 - 2.0 \cdot S_w / w$, if $S_w < (0.5 \cdot w)$
where	s = frame or longitudinal spacing [m] S_w = web frame spacing [m] w = ice load patch width [m]	
1) In order that the reduced PPF_t value may be used, the load distributing stringer shall be located at or close to the middle of span of the transverse frames, to have web height not less than the 80% of the transverse frames, and to have net web thickness not less than the net web thickness of the transverse frames.		

Figure 10.3: Peak pressure factors.

Appendix 5

Input pages calculation application

INPUT, Main Particulars

Ship's Length Over All	LOA	116,50	m
Ship's Breadth	B	18,00	m
Frame Spacing	s	600,00	mm
Frame Spacing in Ice Belt	s_{IB}	300,00	mm
Depth	D	8,60	m
Draft	T	5,00	m
L_{PP}	L_{PP}	104,11	m

Estimate

Print Summary

Waterlines

	Height of WL above BL	
Waterline	4492	mm

	Heigth From BL to bottom deck		
Highest Waterline	5100	mm	5100
Lowest Waterline	4492	mm	4492

Add Highest Waterline

Add Lowest Waterline

Clear Waterlines

Decks

Name of Deck	Boat Deck	Deck height above BL	14650 mm

	Name of Deck	Deck height above BL		
1	Tanktop	2300 mm	Add Deck 1	2300
2	Tween Deck	5700 mm	Add Deck 2	5700
3	Main Deck	8600 mm	Add Deck 3	8600
4	Pool Deck	11625 mm	Add Deck 4	11625
5	Boat Deck	14650 mm	Add Deck 5	14650
			ClearDecks	

Other Important Input

ICE Class:	ICE C
Polar Class:	PC6
Flat Side:	No
Orientation of Plating	Longitudinal
Ship with thrusters or podded propulsion	Yes
Direction of framing	Longitudinal
Direction of framing in icebelt	Transversal
Material Class	235
Acceptance Criteria	AC-I

Ship length at UIWL	L_i	105,25	m
UIWL angle	α_i	17	degrees
UIWL normal frame angle	β'_i	25	degrees
Ship Displacement at UIWL [Not to be less than 5 ktonnes]	Δ_{tk}	9,571	ktonnes
Smallest angle between the chord of the waterline and the line of the first level framing	Ω	10	degrees
Distance between frame supports	l	1800	mm
Distance between frame supports in ice belt	l_{IB}	1800	mm
Block Coefficient	C_B	0,8	
Breadth of plates		2400	mm
Machinery Output		4000	kW
Chosen Section for Parametric Modelling (FEM, NX)		Midship Icebelt	

Master's thesis

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