Structural Design and Optimization of an Ice Breaking Platform Supply Vessel

Juncheng Wang

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Supervisor: Prof. Patrick Kaeding, University of Rostock, Germany
Dipl.-Ing. Michael Bohm, P+S Werften, Germany
Dr. Michael Zimmermann, Nordic Yards, Germany

Reviewer: Prof. Zbigniew Sekulski, West Pomeranian University of Technology, Szczecin

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Declaration of Authorship

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ABSTRACT

In this thesis, the main objective is to do scantling, weight optimization and possible cost optimization for a platform supply vessel (PSV) for different polar classes with respect to the rules of Llyod's Register.

Taking polar class 2 as an example, scantling of hull structure was calculated based on equations in the rules (rules for PSV, for general cargo ships, for polar class vessel). According to the calculation and data first processed in Excel, all parameters affecting the scantling can be pointed out, which is critical for the later weight optimization.

Regarding to the limitation of the rules, the structural optimization methodology has to be limited in the relationship of a variety of parameters in the equations. The main weight optimization operation was performed by MALAB according to all equations and constrains needed. The optimized result including dimension of plate, deck, framing and other elements was obtained in the final comparison. In optimization process, panel based optimization was programmed and the combination of serial and parallel algorithm was selected to optimize CPU time. After finding the relationship of variables by using Excel, quantitative relationship and trend between variables was analyzed by using MATLAB. The top appropriate solution corresponding with the criteria was founded based on the database created by MATLAB. As for some detailed design, this research will specially consider about. In this research, several important trends were concluded which could significantly influence the design process.

Cost optimization is a complicated topic for any kind of ship involving variety of aspects. In this research, several main parameters including weight, welding length and part number were identified and taken into account for multi-objective optimization, which was made with the same optimization method. According to Pareto Frontier chart, suitable solution could be found with respect to specific weight of parameters. To check the optimized design, Rules Calc was selected to prove that the design satisfies the requirement of rules. According to plastic design theory, FEM was performed to prove the design is acceptable in strength.

Keywords: Ice breaking, Platform Supply Vessel, Structural design and optimization, cost optimization, part number, welding length, Rule based design

1. INTRODUCTION

1.1 Treasure in ice

The Arctic Ocean is the least travelled of all the world's major oceans. Ice, winter darkness, great distances, environmental challenges are all danger and challenge for any ship. With the development of despite all these issues, the arctic shipping situation is changing. The climate is warming, the ice is retreating, the business demands are increasing and ship traffic is likely to increase. There is increasing public and professional awareness of the sensitivities associated with the arctic. The environmental, social, political and security issues are numerous and interrelated.

There are several factors which are driving the likelihood of increased shipping. The primary issue is the wealth of the resources in the region. The Arctic is said to comprise approximately 25% of the Earth's undeveloped resources [1]. This includes non-renewable mineral and petroleum resources as well as renewable resources such as the fishery. Tourism is another significant driver, growing steadily in recent years. Other key drivers are public sector activities in science, regional management and development, as well as defence and security. While all these aspects are significant, the petroleum resources must be considered the largest factor when considering the future of arctic shipping. Besides, climate change gradually influences the Arctic Ocean. Warming climate enlarge the area and period of navigation [2][3].

With respect to the predicted large offshore oil industry development in the Arctic Ocean, bigger supply vessels with larger range and year round working capacity are expected. In this thesis, the writer will do design and optimization focusing on the structure of Arctic supply vessel regarding different polar classes.

1.2 Project outline

The design Arctic Supply Vessel is base of the investigations. The vessel is in year-round operation in moderate multi-year ice conditions. But work should be the design of structure with respect to different polar classes. The environmental conditions cause challenges for the material and the design. Apart from the environmental conditions there are also challenges caused by heavy cargo and outfitting equipment. In this project, Rules of Llyod's Register is respected [4].

The vessel shall be designed as an Icebreaking Platform Supply Vessel (PSV) for worldwide trade all the year round. It shall be designed for operation in first year ice as well as polar and multi-year ice areas. The vessel should be completely double hull with forecastle and accommodation forward. The basic design parameters are set forth below:

Table 1.1 Design parameters of the Supply Vessel

Items	Value
Length overall (m)	130
Length between Perpendiculars (m)	123
Breadth moulded (m)	24
Depth to main deck (m)	14
Draught, scantling (m)	10.5
Tonnage (GT)	11000
Icebreaker Class	PC2 to PC7
Air temperature (℃)	-40 to 35
Water temperature (℃)	-2 to 30

The work contains the design and optimization of structure and weight assessment. Goal is also the investigation of the influence of the ice-class on the amidship section. Design variation for different ice-classes from ice-free to PC2 has to be investigated and compared.

Considering the threatening navigation environment, weight is crucial for this type of ship. There is a potential to save weight by the optimisation of scantling/plate combination. A catalogue of plate and profile dimensions has to be prepared for each ice-class design. Aside from weight the different designs have to be assessed also regarding the influence of the material catalogue. From this catalogue the influence on the welding effort has to be assessed regarding the welding requirements of the shipyard.

2. Challenge of ice

Ice loads represent the main structural challenge faced by ships in the arctic. And even after years of study, ice loads continue to be poorly understood and difficult to predict.

The difference of normal ice class and polar class especially lower polar class is the composition of the ice. For polar class, multi years ice might exist which is much stiff and harder to break. As well, for polar class, the thickness of ice and the area of ice belt are bigger. In Table 2.1, the ice composition of different polar class (based on WMO Sea Ice Nomenclature) is introduced.

Table 2.1 Descriptions of Polar class [5]

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

2.1 Current research result

Research shows that ice forces arise when breaking a brittle solid. The ice fractures in many ways and creates highly localized and dynamic local pressures. The direct contact pressures are difficult to observe visually or measure electronically. Only recently have technologies been developed to observe the complex reality of the contact, and such observations have only taken place in laboratory. Field tests on ships have given useful data, but have always been difficult to analyze.

Local ice contact with ice will always involve compression of the ice edge. While the experiment shows the wide range of ice strength. The standard test arrangement for measuring the uni-axial compressive strength of ice is done by Timco and Weeks [6]. But the result shows that significant difference exist in the repeated experiments, and the scatter in the data overwhelms the trend of the mean. The same phenomenon happened in Jones' experiment (see Figure 2.1).

The load of ice arising from collision events could mainly result in local structural response and also global response when a head-on ram happens. While comparing with global response, local response could result in more serious issue and potential.

There have been many ship trials to measure local loads in ice, but the research result is still rewarding in argument. The load measurements have been found to be quite non-uniform.

Later, the concept of the pressure-area relationship was developed as a way to quantify and present the spatial variability of ice pressures [8][9].

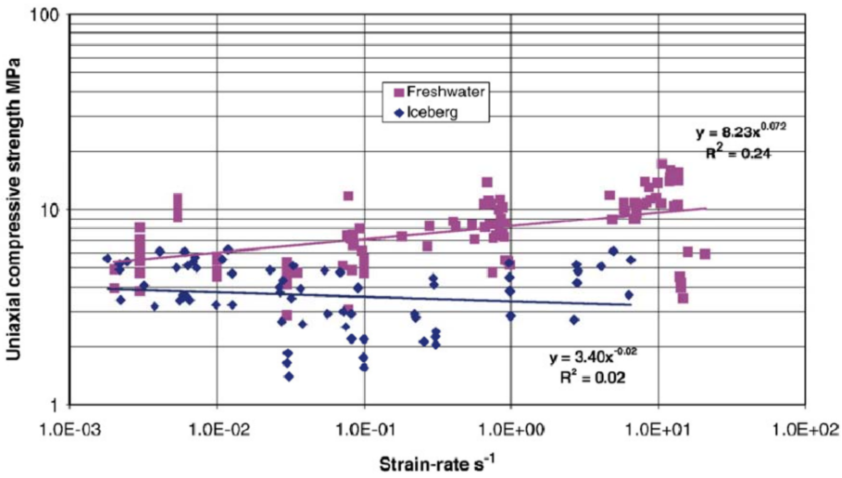


Figure 2.1 Uni-axial Compressive Strength Data for Iceberg and Fresh Water Ice at -10℃ [7]

Afterwards, the scientists propose a design pressure-area curve (see Figure 2.2) that is derived from a statistical assessment of the available pressure data with inclusion of 'exposure'. The proposed pressure-area curve just happens to go through the highest measured values of pressure.

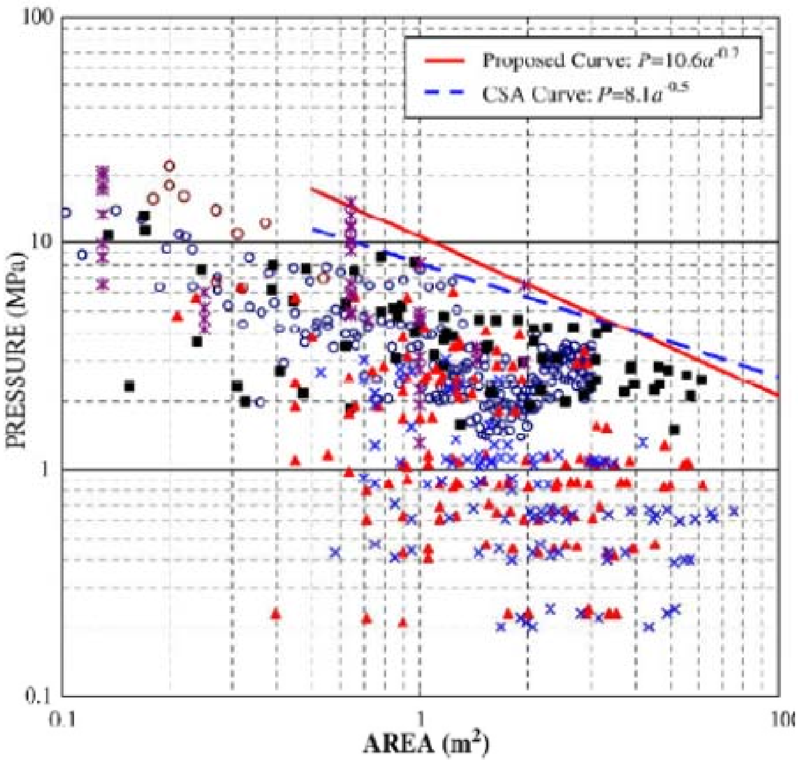


Figure 2.2 Local pressure-area curves [10]

To unify the criteria for structure calculation with respect to different ice load, based on WMO Sea Ice Nomenclature, Polar Class Notations are used throughout the Guidelines to convey differences. The owner should select an appropriate Polar Class and level of propulsion power.

The descriptions in Table 2.1 guide the owners and designers in selecting an appropriate Polar Class. Based on the polar class selection, structure parameters of hull can be calculated by using the equations and requirement concerning of polar class published by the International Association of Classification Societies (IACS).

Besides, Ships operating in the Polar Regions are subjected to not only highly concentrated ice loading but also air temperatures down to -40°C. Consequently, large load carrying capacity and high ductility are required. Additionally, considering reducing structural weight, different materials have to be well considered [11]. Riska and other scientists concluded the factors should be followed when choosing material [12]:

Design minimum temperature

Associated wind speed

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

Stress category of the member, and anticipated strain rate

Steel thickness

Stress relieving and post-welded heat treatment

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

Accessibility to structural components for welding inspection and periodic surveys

Weld acceptance criteria

Provision of artificial means of heating

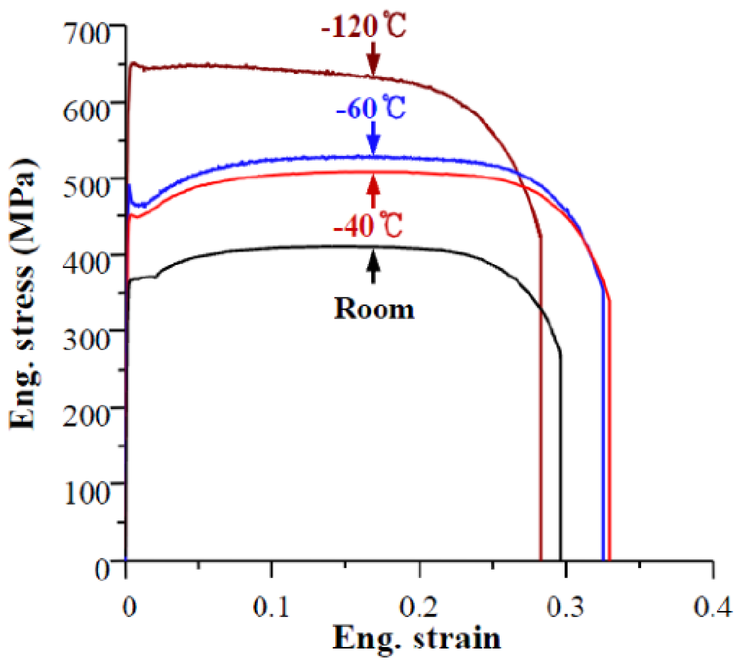


Figure 2.3 Stress-strain Behavior for Tests at Various Temperatures (Liquid Nitrogen cooled system)[14]

Recent research about the effect of cold temperatures has shown that the yield strength can be significantly enhanced at colder temperatures. While, there is argument about the influence on fracture strain [13]. Figure 2.3 shows the experiment made by Kim, which shows strain is not affected obviously by cold temperature.

2.2 Buckling combining ice load

In the calculation of early stage, we found the pressure of ice load is around 10 MPa in a longitudinal rectangular area of, which means almost 1000 m hydro pressure on 0.87m high ice belt shell. This is really big load that could create big plating buckling issue in transversal direction. In longitudinal, the issue of the elastic critical buckling stress and shear of plating due to global load distribution is not significant due to the high global section modulus. The transversal compression due to ice load should be well considered in early design stage.

2.2.1 Buckling of normal structure

This subchapter will introduce the buckling issue of normal structure that suffering compression force of only 1 direction. In this project, the corresponding structure includes longitudinal structure, transversal load distribution bulkhead and web frame.

Buckling is a kind of mathematical instability, leading to a failure mode of ship structure. In practice, buckling is characterized by a sudden failure of a structural member subjected to high compressive stress. Theoretically, the actual compressive stress at the point of failure is less than the ultimate compressive stresses of the element. In ship design, elastic critical buckling stress of plate and support elements is used.

According to the difference of elements, buckling can be separated into 2 kinds, buckling of plate panels and buckling of longitudinals. For the buckling stress check, compression of plating with longitudinal or transversal stiffeners has specific methods to calculate. For instance, in LR's rules, the compression of plating with longitudinal stiffeners can be calculated by using the following equations:

$$\sigma_E = 3.6E(\frac{t_p}{s})^2 \tag{2-1}$$

The equation for calculation of compression of plating with transversal stiffeners is:

$$\sigma_E = 0.9c[1 + (\frac{s}{1000S})^2]^2 E(\frac{t_p}{s})^2 \tag{2-2}$$

where

E is modulus of elasticity, in N/mm^2

t_p is built thickness of plating less standard deduction, in mm

s is stiffener spacing, in mm

S is spacing of primary elements, in meters

c is factor depending on profile, which is 1.1 for bulb plates stiffeners

From (2-1) and (2-2), a conclution can be described that the stiffening system that paralled to the compressive force is more effective when other parameters are the same. Based on this, the calculated the scantling of both longitudinal and transversal. The result shows significant difference. Even though longitudinal structure could be more effective to counteract global bending, transversal structure is selected still because the thick plate due to high transversal ice load.

For the buckling of longitudinals, Column buckling (perpendicular to plane of plating) without rotation of cross section, Torsional buckling and web buckling are the main potential issue and should be well considered in design stage.

In ship structure, buckling mainly exist in the region of transversal structure including deck, web frame and transversal bulkhead. The comparison of elastic critical buckling stress and design stress σ_A give the stability of design. In LR rules, the equation of design stress is explained.

2.2.2 Buckling of structure suffering compression in 2 directions

All the transversely effective deck and bulkhead, especially Deck 2, 6.2m high from baseline are undertaking the transversal ice load. In the region of ice belt, the structure might be loaded all ice load. In such big compressive pressure, buckling check is a must. For transversal bulkhead, we consider as follows:

To check the stability of plating between stiffeners, it is usually assumed that the stiffeners are strong enough and fail after the failure of plating, which means that the stiffeners should be designed with proper proportions that help attain such behavior. There are mainly four kinds of load components, namely longitudinal compression/tension, transverse compression/tension, shear force and lateral pressure on the plate between stiffeners, as shown in Figure 2.4, while the in-plane bending effects on plate buckling are also accounted. In normal ship structures, lateral pressure loading comes from water pressure and cargo. In this project, high ice load should be well considered in the plating of transversal bulkhead and web frame in addition.

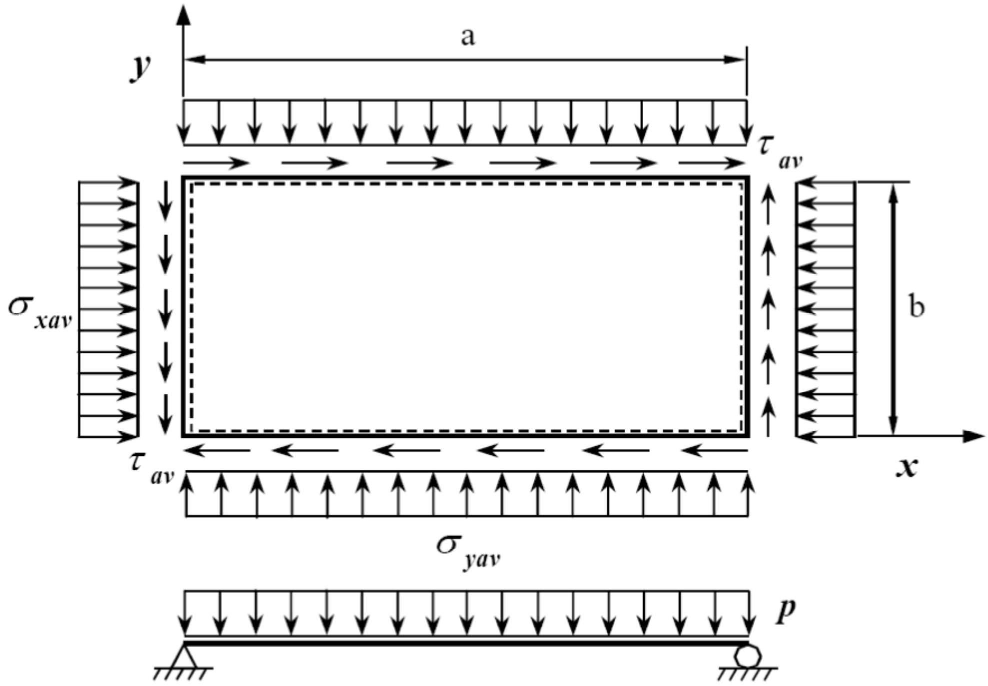


Figure 2.4 Plate Subject to Biaxial Compression/tension, Edge Shear and Lateral Pressure[15]

The lateral pressure mainly comes from still water pressure, wave and ice load. The elastic plate buckling strength components under single types of loads, σ_{xE} for σ_{xav}, σ_{yE} for σ_{yav} and τ_E for τ_{av}. These parameters can be calculated by taking into account the related effects arising from bending, lateral pressure, cut-outs, edge conditions and welding induced residual stresses. The critical (elastic-plastic) buckling strength components under single types of loads include σ_{xB} for σ_{xav}, σ_{yB} for σ_{yav} and τ_B for τ_{av}. By using Johnson-Ostenfeld formula, these parameters can be typically calculated, see equation Eqs. 2-3.

$$\sigma_B = \begin{cases} \sigma_E \, for \sigma_E \le 0.5\sigma_F \\ \sigma_F (1 - \frac{\sigma_F}{4\sigma_E}) for \sigma_E > 0.5\sigma_F \end{cases} \tag{2-3}$$

where

σ_E is elastic plate buckling strength,

σ_B is critical buckling strength, (that is τ_E for shear stress)

σ_F is σ_Y for normal stress, $\frac{\sigma_Y}{\sqrt{3}}, (\tau_Y)$ for shear stress

σ_Y is material yield stress

In LR rules, the same formula and assumption as Eqs. 2-3 is used. Under single types of loads, the critical plate buckling strength must be greater than the corresponding applied stress component with the relevant margin of safety. For combined biaxial compression/tension and edge shear, the following type of critical buckling strength interaction criterion would need to be satisfied, for example:

$$\left(\frac{\sigma_{xav}}{\sigma_{xB}}\right)^c - \alpha \frac{\sigma_{xav}}{\sigma_{xB}} \frac{\sigma_{yav}}{\sigma_{yB}} + \left(\frac{\sigma_{yav}}{\sigma_{yB}}\right)^c + \left(\frac{\tau_{av}}{\tau_B}\right)^c \leq \eta_B \tag{2-4}$$

where

η_B is the usage factor for buckling strength, which is often taken 1.0 for direct strength calculation, but it is taken less than 1.0 in practical design following classification society rules as it is the inverse of safety factor. Compressive stress is taken as negative. In this project, deck structure is bearing compressive stress in transversal direction and tensile or compressive stress in longitudinal direction and should be checked using α=0, and α=1 if either σ_{xav} or σ_{yav} or both are tensile. The constant c is taken as c=2.

Naming x as the longitudinal direction of the ship, the stress in y direction is always compressive and negative due to the ice load. To check the case with ice loading, we assume the ice load average pressure on the panel with the same height of ice load patch.

2.2.3 Empirical approaches

In the solutions of buckling check, the methods are mainly separated into 2 types. One is Direct analysis method, that the theory mentioned above. The second is simplified analysis method, which empirical approaches are included. In this approach, the mechanical collapse test or numerical analysis are processed. Then ultimate strength results are developed by curvature fitting based on the solutions.

The Paik-Thayamballi empirical formula[16] is set forth below:

$$\frac{\sigma_u}{\sigma_Y} = \frac{1}{\sqrt{0.995 + 0.936\lambda^2 + 0.17\beta^2 + 0.188\lambda^2\beta^2 - 0.067\lambda^4}} \tag{2-5}$$

$$\frac{\sigma_u}{\sigma_Y} \leq \frac{1}{\lambda^2} = \frac{\sigma_E}{\sigma_Y} \tag{2-6}$$

with

$$\lambda = \frac{a}{\pi r}\sqrt{\frac{\sigma_Y}{E}} = \frac{a}{\pi}\sqrt{\frac{A\sigma_Y}{IE}} = \sqrt{\frac{\sigma_Y}{\sigma_E}} \tag{2-7}$$

$$\beta = \frac{b}{t}\sqrt{\frac{\sigma_Y}{E}} \tag{2-8}$$

where

I is inertia, in m^4

A is cross section of the plate-stiffener, in m^2

r is radius of gyration, in meter

t is plate thickness, in meter

a is span of the stiffeners, in meter

b is spacing between 2 longitudinals, in meter

When we check the specific value of λ and β, they correspond with the empirical curve in Figure 2.5. If the value is bigger than the correspond position in the diagram, there will be the potential of buckling.

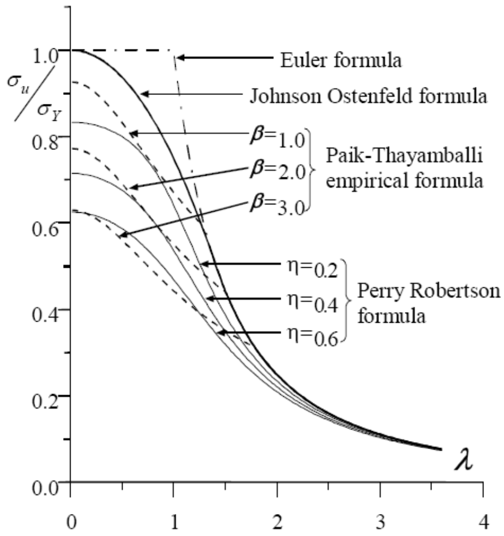


Figure 2.5 Curve fitting of ultimate Strength Formulations for stiffened plate

2.2.4 Additional buckling related rules regarding polar class design

According to the result of scientific research, the ice load undertaken by polar class ship is quite high. In the rules for ship operating in multi-year ice condition, special requirement for structural stability is identified in the rules: Preventing the local buckling in the web, the ratio of web height, h_w, to net web thickness, t_{wn}, of any framing member should follow:

For flat bar section: $\frac{h_w}{t_{wn}} \le \frac{282}{\sqrt{\sigma_y}}$ (2-9)

For bulb, tee and angle section: $\frac{h_w}{t_{wn}} \le \frac{805}{\sqrt{\sigma_y}}$ (2-10)

Besides, the ratio of net web thickness, t_{wn}, in mm, to new thickness of the shell plate in way the framing member , t_{pn}, in mm, of any framing member should follow:

$$\frac{t_{wn}}{t_{pn}} \geq 0.35 \times \sqrt{\frac{\sigma_y}{235}} \qquad (2\text{-}11)$$

To prevent local flange buckling of welded profiles, additional criteria have to be satisfied. As written in the rules, "the flange width, b_f, in mm, is not to be less than five times the next thickness of the web, t_{wn}". At the same time, the flange outstand, b_0, should satisfy:

$$\frac{b_o}{t_{fn}} \leq \frac{155}{\sqrt{\sigma_y}} \qquad (2\text{-}12)$$

where

σ_y is minimum upper yield stress of the material, in N/mm^2.

2.2.5 Utilization of different methodologies

In the design of PSV, several factors would affect the calculation of buckling. First is global bending, which widely exists in all longitudinal elements such as deck plate, shell plate, longitudinal bulkhead and variety of longitudinals. The other influence factor comes from the ice load in transversal direction. The elements such as web frame, deck and transversal bulkhead are undertaking this force. In the calculation process, different methods would be performed at the same time checking the design from diverse point of view.

2.3 Ice load identification by the rules

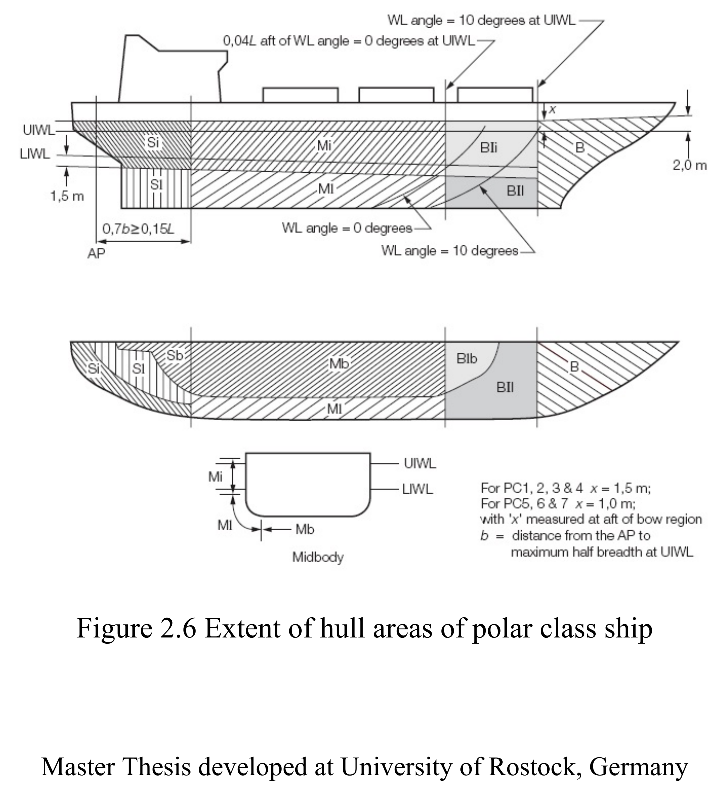


Figure 2.6 Extent of hull areas of polar class ship

In the rules authorized by IACS, the ice load on shell is considered as average pressure in specific rectangular area, which depends on the hull form, panel location (shown in Figure 2.6) and polar class designed.

In this rules, hull is divided into several parts, their names are: bow (*B*), bow intermediate (B_i), midbody (*M*), and stern (*S*). Except bow area, the hull is divided again into ice belt (*i*), lower (*l*) and possible bottom (*b*).

As required, this ship should have ice breaking capacity forwards and backwards. Hence, in the calculation, Bow and Stern area use the same calculation method. Based on the rules, the result of ice load patch in PC2 case is shown in Table 2.2.

Table 2.2 Ice load patch data

Area			Ice load patch breadth (m)	Ice load patch height (m)	Design pressure (MPa)
Bow(B)	All	B	4.06	0.67	11.14
Bow intermediate (BI)	Icebelt	BIi	3.13	0.87	9.12
	Lower	BIl	3.13	0.87	9.12
	Bottom	Bib	3.13	0.87	9.12
Midbody (M)	Icebelt	Mi	3.13	0.87	9.12
	Lower	Ml	3.13	0.87	9.12
	Bottom	Mb	3.13	0.87	9.12
Stern Intermediate (SI)	Icebelt	Sii	3.13	0.87	9.12
	Lower	SIl	3.13	0.87	9.12
	Bottom	SIb	3.13	0.87	9.12
Stern (S)		S	2.36	1.63	10.74

The calculation result following the rules corresponds with the experimental result of Jones and Jardaan (see Figure 2.1 and Figure 2.2).

3. DESIGN BASED ON RULES

This project targets at structural optimization of icebreaking PSV. At the beginning of this project, some of the data are ready as the base stone, including general arrangement and ship hull form. This is the first ship designed following polar class rules, without any similar reference, the design step is considered like open a black box that no one knows what will happen.

In the rules, the relationship between some critical parameters of ship scantling such as member spacing and profile is identified by variety of formulas. Step by step, the numerical relationship based on equations can be built thanks to Microsoft Office Excel. All the variables for the calculation can be measured from the hull form or identified based on judgment and analysis.

3.1 Hull scantling

Shell is the steel structure directly exposed in river or ocean environment, suffering the water pressure and ice load. It is critical for the safety of ship, especially considering big local loads such as ice impact. So, as a polar class PSV, not only rules of normal cargo ship and offshore supply ship, but also the rules for polar class ship should be obeyed.

Considering high ice load requires more strengthened structure, to increase the working efficiency, the calculation starts from the additional rules of polar class.

Based on the result of the ice load calculation, and taking peak pressure factors and hull area factors into account, shell plate thickness for different polar class can be calculated according to the rules. In the following part of the report, without specification, all data and analysis is based on ship of polar class 2.

An easy method to find the relationship between different variables and parameters is checking the equations in the rules. For instance, in transversal framed plating, the net plate thickness is written as Eqs. 2-13.

$$t_{net} = \frac{500s\sqrt{\dfrac{AF \cdot K_p \cdot P_a}{\sigma_y}}}{1+\dfrac{s}{2b}} \tag{3-1}$$

where

s is transverse frame spacing

AF is hull area factor identified in the rules

K_p is peak pressure factor, which is equal to 1.8-s but not less than 1.2 (see Table 2.3)

P_a is average patch pressure

σ_y is minimum upper yield stress of the material

b is the height of design load patch, while in the case of transversely framed plating, b is not more than l=s/4

l is the distance between frame supports

Here the tendency relationship can be easily explained from the equation that 2 way of increasing the plate thickness is to reduce the frame spacing and to use material with higher tensile stress.

Detailed instruction for the whole structure is specified in the rules for General Cargo Ships and OSV.

In some dimension range, smaller stiffener spacing increases the profile of stiffeners, because the identification of peak pressure, which is related to the stiffener spacing. The peak pressure factors identified by Lloyd's Register are shown in Table 2.3.

Table 2.3 The peak pressure factors

Structural member		Peak pressure factor
Plating	Transversely framed	$K_p = (1.8 - s) \geq 1.2$
	Longitudinally framed	$K_p = (2.2 - 1.2s) \geq 1.5$
Frames in transverse framing systems	With load distributing stringers	$K_t = (1.6 - s) \geq 1.0$
	With no load distributing stringers	$K_t = (1.8 - s) \geq 1.2$
Load carrying stringers Side and bottom longitudinals Web frames	If $S_W \geq 0.5w$	$K_S = 1$
	If $S_W < 0.5w$	$K_S = 2 - \frac{S_W}{w}$
s = frame or longitudinal spacing, in meters SW = web frame spacing, in meters w = ice load patch width, in meters		

After acquiring the value of plate thickness, the calculation of stiffener profile can be processed based on the equations. Two primary parameters should be calculated first, that is actual net effective shear area (A_w). Here we take the equation for transversely framed panel as an example to deduce the process and regular pattern.

$$A_w = h t_{wn} n \sin(\frac{\varphi_w}{100}) \geq A_t = 5000 l_L s \frac{AFK_t P_a}{0.577\sigma_y} \tag{3-2}$$

where

h is height of stiffener, in mm

t_{wn} is net web thickness, in mm

φ_w is smallest angle between shell plate and stiffener web, measured at the midspan of the stiffener

l_L is length of loaded portion of span, in meter, which need not exceed the lesser of frame span and height of design ice load patch calculated

K_t is peak pressure factor (see Table 2.3)

The length of portion used for calculation is strictly limited in the height of ice load patch, which means stringer can't assign the ice load until the stringer spacing is smaller than the height of ice load patch. Nevertheless, stringer spacing is normally more than 1m. In other words, less stringer should be more weight efficient according to the formulation in the rules.

In the calculation of the second main parameter, actual net effective plastic section modulus (Z_p), more variables are engaged. Except for the parameter mentioned in the calculation of actual net effective shear area (A_w), frame support type, plate thickness and other variables are related as well.

Moreover, due to the high ice load, local buckling should be checked to assure structural stability. So the method mentioned in chapter 2.2.4 could be used for scantling calculation.

Regarding primary structure suffering ice load, as explained in the rules, the combined effects of shear and bending should be taken into account, and proper peak factor need to be well selected. In fact, the rules didn't identify clearly the calculation equations for such kind of high ice load. For the structure calculation of lower ice class, the range of ice pressure identified in LR rules is much lower than in polar class case. So in this part, we use the rules in DNV for the calculation of web frame and stringer.

The section modulus of a main or intermediate transverse frame shall be calculated by the formula:

$$Z = \frac{0.9 l^2 b P_a}{m_1 \sigma_y} 10^3 \tag{3-3}$$

where

l is the frame span, in meter

m_1 is factor of boundary condition. Considering the general arrangement of the ship, the stringer is continuous longitudinally and is supported by web frames. So in this case, m_1=11.

The minimum shear area (cm^2) should follow

$$A = \frac{7.8 l_s b P_a}{\sigma_y} \tag{3-4}$$

where

l_s is span of stringer, in meter

With respect to the scantling of web frame, the load transferred to a web frame from stringer is calculated in this formula:

$$F = P_a b S \tag{3-5}$$

where

$P_a b$ is not allowed less than 0.3

S is web frame spacing, in meter

For the wen frame simply supported at the upper end and fixed at the lower end, the shear area of a web frame should satisfy:

$$A = \frac{17.3\alpha F}{\sigma_y} \tag{3-6}$$

where

α is a factor relating with the cross sectional area of free flange and web plate (Aa)

The section modulus requirement is given by:

$$Z = \frac{M}{\sigma_y}\sqrt{\frac{1}{1-(\gamma\frac{A}{A_a})^2}}10^3 \tag{3-7}$$

where

M is the maximum calculated bending moment under the load F as given before

γ is a factor relating with the cross sectional area of free flange and web plate (A_a)

For other web frame configurations and boundary conditions, direct stress calculation method should be performed for allowed stress calculation.

$$\sigma = \sqrt{\sigma^2 + 3\tau^2} \leq \sigma_y \tag{3-8}$$

For the calculation of other hull structure excluding the area of ice belt, normal structure rules and the requirement special for offshore supply ships have to be followed.

As explained in Part 8, Part 4, Chapter 4 of LR rules, for offshore supply ships, the modulus of stiffeners should be 1.25 times of the result calculated by rules for general cargo ship. In the rules for general cargo ships, side shell plating is related with parameter such as stiffener spacing, primary element spacing, position of the panel, material yield strength, ship length and so on.

For shell framing, the variable is similar with the ones of plating. While different from primary element spacing, effective length of stiffener is replaced for the calculation.

Furthermore, for ice class ship, especially polar class ship, transversal compressive stress can't be underestimated or serious structure failure would happen. Excluding the rules mentioned above, as the supporting element of stiffener and web frame, ultimate strength and buckling of deck should be well calculated (including plating buckling and transversal element).

Web frame welding with stringer should be well operated as the shear area requirement is high. The calculation of web frame should obey 3 rules, first is the limitation due to the liquid pressure, second is comes from buckling for the sake of the high ice load, and the third is the support of the stringer.

3.2 Scantling of deck

As the platform holding or covering cargo, liquid and equipment, deck is relative stable comparing with the side shell directly composed the ice load. As well, as the structure transversally continuous, water pressure and ice load is added on deck as well.

For weather deck, considering the platform has combine function of weather deck and cargo deck, minimum plate thickness requirement especially for offshore supply vessel is the greater of the following:

$$\begin{cases} t = 0.025L + 4.5 + t_a \\ t = 0.1 f_m s \sqrt{\dfrac{PF_D}{f_y \sigma_y}} + t_a \end{cases} \tag{3-9}$$

where

P is specified design load for weather deck, in t/m^2. As define in project outline, the main deck should undertake 10 t/m^2 cargo load in the cargo deck area and 15 t/m^2 after 24 m forward aft perpendicular.

f_m is factor equal to 0.75

F_D is factor of global strength, equal to 0.67

f_y is factor equal to 0.67

t_a is additional thickness, which is 2.5 mm in general and 1.0 mm for ships with dedicated class notation standby ship

For the deck plating of other lower decks, specific formulas are introduced. In general, the deck plating thickness is reducing with the height of the deck. The deck panel configuration depends on stiffener spacing, material, primary element spacing, pressure added, position and function of the panel. In addition, for the stiffener of deck panel, the calculation method is generally separated into 3 kinds referring to different function of deck, which is weather deck, cargo and accommodation deck. Regarding to the general arrangement, the calculation is performed panel by panel.

No matter longitudinal or transversal structure selected for amidship, deck girder and main frame use the same height considering the limitation of height.

As the deck is the final horizontal structure supporting the structure, compressive ultimate stress and buckling should be checked according to the rules. So thick deck plating is predicted, especially for the deck panel near shell. Here, considering the deck is also longitudinal effective, Von Mises stress should be calculated as well. For the connection of deck plating with longitudinal bulkhead and shell, bracket should be widely used in case of stress concentration.

3.3 Scantling of bulkheads

The function of offshore supply vessel is to support the engineering and the life of engineers on offshore. So these ships need enough reservation capacity of both solid and liquid cargo.
In general, the bulkhead should satisfy the following requirement:
Minimum water tight bulkhead plating thickness of panel should be the greater of the following:

$$\begin{cases} t = 0.004s(1.1 - \dfrac{s}{2500S})\sqrt{h_4 k} \\ t = 5.5 \end{cases} \tag{3-10}$$

Minimum deep tank bulkhead plating thickness of panel should be the greater of the following:

$$\begin{cases} t = 0.004s(1.1 - \dfrac{s}{2500S})\sqrt{\dfrac{\rho h_4 k}{1.025}} + K_1 \\ t = 6.5 \ \ (if \ \ L < 90m) \\ t = 7.5 \ \ (if \ \ L \geq 90m) \end{cases} \tag{3-11}$$

where
h_4 is load head, in meter
k is higher tensile steel factor, which is shown in Table 3.1.
ρ is density of liquid, in t/m^3
K_1 is equal to 3.5 within 3 m below top of bulkhead, 2.5 for position elsewhere
Besides, modulus of rolled and built stiffeners, stringers and web supporting stiffening need to follow different requirements with respect to variables such as stiffening style, stiffener spacing, effective length of stiffening element, liquid density, stiffener profile and so on.
For normal, offshore supply vessel, as transversal bulkhead is rarely connected with shell, the load normally comes from the load of cargo. While for ice class ship, especially polar class

ship, transversal compressive stress should be well considered. Excluding the rules mentioned above, as the supporting element of some of the web frame, ultimate strength and buckling of panel should be well calculated (including buckling of plating and transversal element).

Table 3.1 Higher tensile steel factor

Specified minimum yield stress in N/mm2	K
235	1
265	0.92
315	0.78
355	0.72
390	0.68

Without considering transversal compressive stress, longitudinal bulkhead has to take global bending and shear into account. If the stiffener is longitudinally effective, buckling of profile should be calculated in addition.

3.4 Global strength

As to ice class ship, global strength is not a critical issue for the hull structure, especially for shell. While for the structure of longitudinally effective out of shell in ice belt region, such as the super structure, longitudinal bulkhead and inner bottom, we still need the data of section modulus, bending moment and shear stress for strength calculation.

As mentioned in former part, the global data such as bending moment, section modulus is needed in the calculation. While on the other hand, without section data, global section modulus calculation cannot be performed. So here a closed loop affecting is founded. So in this case, an initial neutral axis and section modulus have to be identified. Then, based on the detailed calculation, neutral axis and section modulus can be corrected gradually until the convergence.

For general cargo ship, the bending moment and shear force comes from 3 parts. While first of all, a minimum hull section modulus should be obeyed. This parameter involves ship length, breadth, block coefficient, material and so on. The first part is the bending moment and shear of still water. This is the result of different distribution of floating force and ship weight in different segments. The permissible still water bending moments identified in the rules is the lesser of the following:

$$\left|\overline{M_s}\right| = \frac{F_D \sigma Z_D}{1000} - \left|M_w\right|$$
$$\left|\overline{M_s}\right| = \frac{F_B \sigma Z_B}{1000} - \left|M_w\right| \quad (3\text{-}12)$$

The second part comes from the water waves. The permissible hull vertical bending stresses for longitudinal structural members is:

$$\begin{cases} \sigma = \dfrac{175}{k} \quad N/mm^2 (Within \quad 0.4L \quad amidship) \\ \sigma = (75 + 534\dfrac{d}{L} - 699(\dfrac{d}{L})^2)\dfrac{1}{k} \quad N/mm^2 (Outside \quad 0.4L \quad amidship) \end{cases} \quad (3\text{-}13)$$

While considering possible extreme environment or issue of manufacturing, local reduction factors are considered. Regarding appropriate combination of bending moments of sagging and hogging, the requirement of maximum hull vertical bending stresses at deck is:

$$\sigma_D = \frac{\left|\overline{M_s} + M_w\right|}{1000 Z_D} \quad N/mm^2 \quad (3\text{-}14)$$

The requirement of maximum hull vertical bending stresses at keel is:

$$\sigma_B = \frac{\left|\overline{M_s} + M_w\right|}{1000 Z_B} \quad N/mm^2 \quad (3\text{-}15)$$

For elements above the neutral axis,

$$F_D = \frac{\sigma_D}{\sigma} \quad (3\text{-}16)$$

For elements below the neutral axis,

$$F_B = \frac{\sigma_B}{\sigma} \quad (3\text{-}17)$$

At the same time, the maximum hull vertical bending stress at deck or keel should less than the permissible combined stress. In addition, the value of maximum hull vertical bending stress at deck and keel need to use the greater of the sagging and hogging stresses.

Another critical requirement is F_D and F_B are not to be taken less than 0.67 for plating and 0.75 for longitudinal stiffeners. In the formulas mentioned in previous content, we find that greater value of F_B and F_D means bigger plate thickness and stiffening profile, which result in heavier structure. In this case, no matter how strong structure comes from rules for ice class strengthening, minimum requirement for uninvolved elements is mandatory.

The third part of bending moment is the one resulting from ice load. As requirement in project outline, this ship should have ice breaking capacity both forwards and backwards. So when calculating the bending moment and shear force, stern should be considered as bow. Based on this, some small modification and update are made according the rules. The design vertical ice bending moment along the hull is to be taken as:

$$M_I = 0.1 C_m L \sin^{-0.2}(\gamma_s) F_{IB} \quad MNm \tag{3-18}$$

where

C_m is longitudinal distribution factor for design vertical ice bending moment

C_m=0 at the aft and for end of L

C_m=1 between 0.3 L and 0.7 L

C_m=0.3 at 0.05 L and 0.95 L from aft

Other places take the intermediate value.

F_{IB} is design vertical ice force for design vertical ice

From the shipyard, we got the diagram with the curvature of bending moment and shear force of the ship considering buoyancy and weight in segments. Taking all of the data into account, the actual hull section modulus at strength deck and keel could be calculated.

3.5 Corrosion and material selection

For general ship, ship in navigating is designed without consideration of regular collision. In this situation, the rules identify corrosion as Table 3.2 shows.

Table 3.2 Standard deduction for corrosion

Structure		*dt* mm	*dt* range mm min.-max.
(a) Compartments carrying dry bulk cargoes		0.05 t	0.5-1
(b) One side exposure to water ballast and/or liquid cargo.	Vertical surfaces and surfaces sloped at an angle greater than 25° to the horizontal line.	0.10 t	2-3
(c) One side exposure to water ballast and/or liquid cargo.	Horizontal surfaces and surfaces sloped at an angle less than 25° to the horizontal line.		
(d) Two side exposure to water ballast and/or liquid cargo.	Vertical surfaces and surfaces sloped at an angle greater than 25° to the horizontal line.	0.15 t	2-4
(e) Two side exposure to water ballast and/or liquid cargo.	Horizontal surfaces and surfaces sloped at an angle less than 25° to the horizontal line.		

In ice condition, not only the normal corrosion due to sea water and air, but also the possible abrasion because of ice collision should be taken into account. In the rules, special corrosion and abrasion additions for shell plating are defined. From PC1 to PC7, from bow to midbody, from ice belt to bottom, the additions decrease gradually, which corresponding the decreasing of ice load the plate might encounter.

In low temperature, the physical property of steel material will change. Two main change are the increasing of yield stress and higher rigidity. Recent research involving the effect of cold temperatures on ship steels has shown that the yield strength can be significantly enhanced at low temperatures and that fracture strain is not strongly affected. The former one improves the performance of steel, but fragile steel means smaller allowed deformation, which is critical to ice load.

Even though recent research showed the positive result, experience should be respected as experimental result differ from different conditions and methods. In shipyards, instead of increasing the thickness of plate and other elements, material with higher steel grade is selected to neutralize the influence of low temperature to stress-strain curve.

Another issue of the material selection is number of steel which correspond with the yield point of steel. Reviewing equations such as Eqs. 3-1, 3-3, 3-9, we could see the quantitative relationship between steel number and scantling.

It is obvious that material with higher yield point could reduce structural weight. Taking GL36 (yield point: 355MPa) and GL46 (yield point: 470 MPa), the reduction of shell plate weight is about 15%. In case there is limitation to scantling, or need to reduce the thickness considering welding and other issues, higher tensile steel could be considered only when it is in necessary.

3.6 Superstructure and foundation

Superstructure means the structure above the main deck. On this ship, deckhouse and the crane track are the two parts of superstructure. As crane tracks are closely connected with side shell and should be calculated following the rules for shell, here only deckhouse design is discussed.

The design of superstructure is following the common design concept with respect to the truth that there is no special requirement due to ice load to superstructure in scantling aspect.

The calculation of superstructure is performed with the following parameters:

Table 3.3 Main parameters of superstructure

Stiffener spacing (mm)	600/800
Deck height (mm)	3000-3800
Number of decks	6
Breadth (mm)	20000-24000
Longitudinal length (mm)	22000-25000

Corresponding with the rules and general arrangement, the weight of superstructure is 675 t.

This design project targets at the design in early stage, without considering all complicate detail. Hence, only weight assessment is processed with regard to engineering experience.

According to general arrangement, 4 diesel generators are equipped in midbody, 2 azipod propulsion thrusters are fixed near stern. Based on experience, the weight of foundation is estimated as in Table 3.4.

Table 3.4 Weight estimation of foundation

Number of generator	4
Weight of each generator foundation (t)	80
Number of propeller	2
Weight of each propeller foundation (t)	120

In total, the weight of foundation for generators and propellers is 560 t.

4. PARAMETERS ANALYSIS AND OPTIMIZATION

4.1 Analysis methodologies introduction

Based on the rules and restriction with respect to the experience, numerical analyzing method using MATLAB is operated to find the overall optimization analysis. Thinking of the tremendous of combination of variables, huge volume of matrix calculation is predicted. To simplify the optimization procedure, a step by step method was induced and developed.

As Figure 4.1 shows, to get gear, main parameters and variables should be fully targeted. In the initial design stage, information involving parameters and their direct relationship were collected thanks to the rules and Microsoft Excel. For instance, the spacing of deck stiffener will greatly affect the deck plate thickness, on the contrary, in ice belt region, the stiffener spacing doesn't affect the shell thickness when it is bigger than the height of design ice load patch.

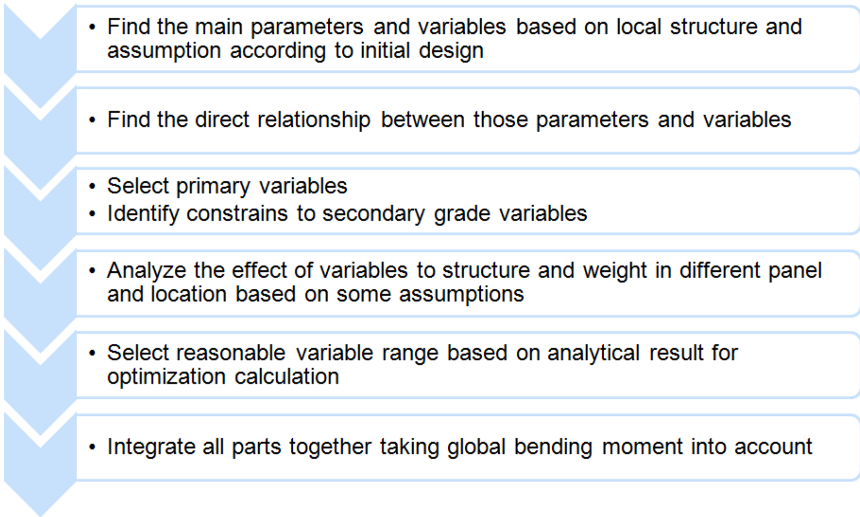


Figure 4.1 The procedure of structure optimization based on MATLAB

As we know, optimization algorithms can be divided in Determinist algorithms and Stochastic algorithms. Determinist method, like Simplexe method, builds based on cost-function evaluations. Basically, their convergence rate is high, but they're not robust which means the results may depend on the starting point of the algorithm. Sometimes, the optimization process might stop at local optimum. Moreover, some cases require the knowledge of the derivatives of the cost function, which make the optimization process complex. Stochastic method is designed based on probabilistic laws and random convergence. They're more robust but the convergence rate is low. The results may also depend on the starting point of the algorithm, but able to find global minimums. Algorithms such as Montecarlo method, Method Tabu and Genetic algorithm are all Stochastic method [17].

Different from other optimization process mentioned, the optimization of ship structure has their own dimensions database, including the catalog of stiffeners profile, the plate thickness that increases by 0.5 mm, etc,. Relatively small variable group and specific dimension catalog shows simple and direct calculation is more applicable for this design task.

It is true that in practice, all elements of the ship are related with each other. Based on the analysis result for initial design, the dimensions of different panel in various locations are not related so closely because of the large reservation required by the rules. For example, with the same stiffened elements and spacing, the plate thickness of longitudinal bulkhead doesn't change with changing the stiffening of shell.

In the initial design stage, the influence of ice load is shown. Due to the heavy ice load, typical cargo ship structure and rules is not mainly acceptable, especially in the design of primary elements, high pressure need the support of inner hull, including inner bottom and longitudinal bulkhead. The thickness might be higher than what required in the rules.

Considering this critical conclusion, in the optimization process, the programming of shell and inner side are programmed together. The global structure optimization is divided into 4 parts in the first step, local optimization and tendency search. These 4 parts are:

1) Shell

2) Deck

3) Longitudinal bulkhead

4) Transversal bulkhead

The local optimization process of panels can be explained as the flow chart shows in Figure 4.2. In this way, the numerical relationship of parameters can be found. Based on the local result, the global optimization calculation will need much less time compare with calculating global structure directly.

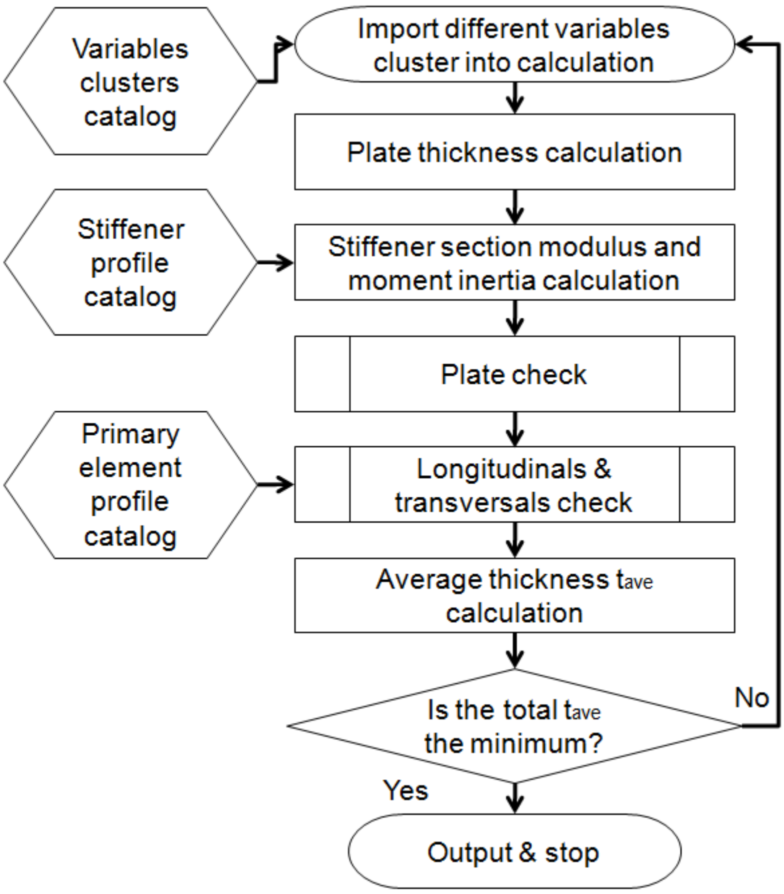


Figure 4.2 Calculation process of local optimization

In the rules of classification society, the relationship of different parameters is shown by equations, which are the tools to calculate the value of parameters. With respect to the calculation loop in initial design, primary variables are selected, such as plate thickness, stiffener spacing, stiffening, web frame thickness and its attached stiffener, loads on the panels, etc. With respect to those primary variables, more secondary variables such as spacing of stringers, number of brackets can be constrained in specific range. In this case, the amount of possible variables combination is greatly reduced.

Understanding the trend of parameter changing with respect to a variety of variable is critical to limit the range of variables and reduce the CPU time. Here, the weight of different panels in different location is calculated regarding to proper assumptions coming from initial design. In the following part, some critical parameters are analyzed to gather this information.

4.2 Variables of shell panel

The challenge of polar class ships is the ice load. To protect the ship from unpredictable ice impact and collision, strong side shell, especially ice belt is must. In the common rules for polar class ships published by International Association of Classification Societies (IACS), the calculation method is set regarding to the pressure and dimension of ice load patch. On the other hand, smaller ice load is possible in bilge and bottom area, which means all side shell panels possibly touching ice is considered using the same calculation theory. Regarding the function and location of panel, we divide and name the panel like Figure 4.3 shows.

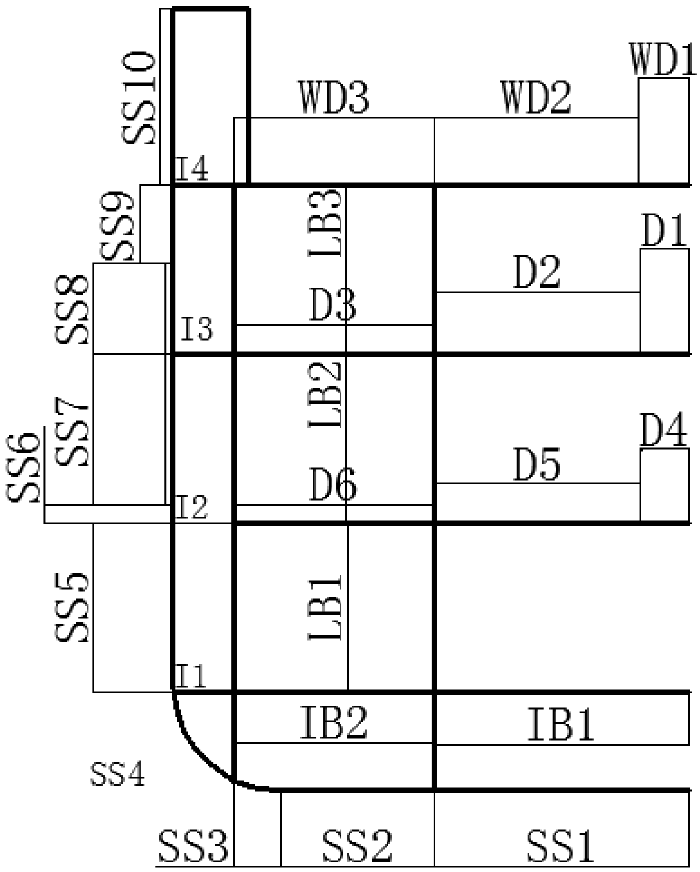


Figure 4.3 Nomenclature of Panels including shell deck and longitudinal bulkhead

In this method, average thickness “t_{ave}” is used to combine the weight of all attached and related elements in one panel including stringer, plate, stiffener and their bracket (some time web frame as well if identified) together and divide the total weight with the area of panel. As the design start from shell, in the calculation of shell panel, plate girder is not taken into account because lacking of information.

The relationship of different variables and structure weight is shown in following sections (All examples come from midbody segment in polar class 2 case.).

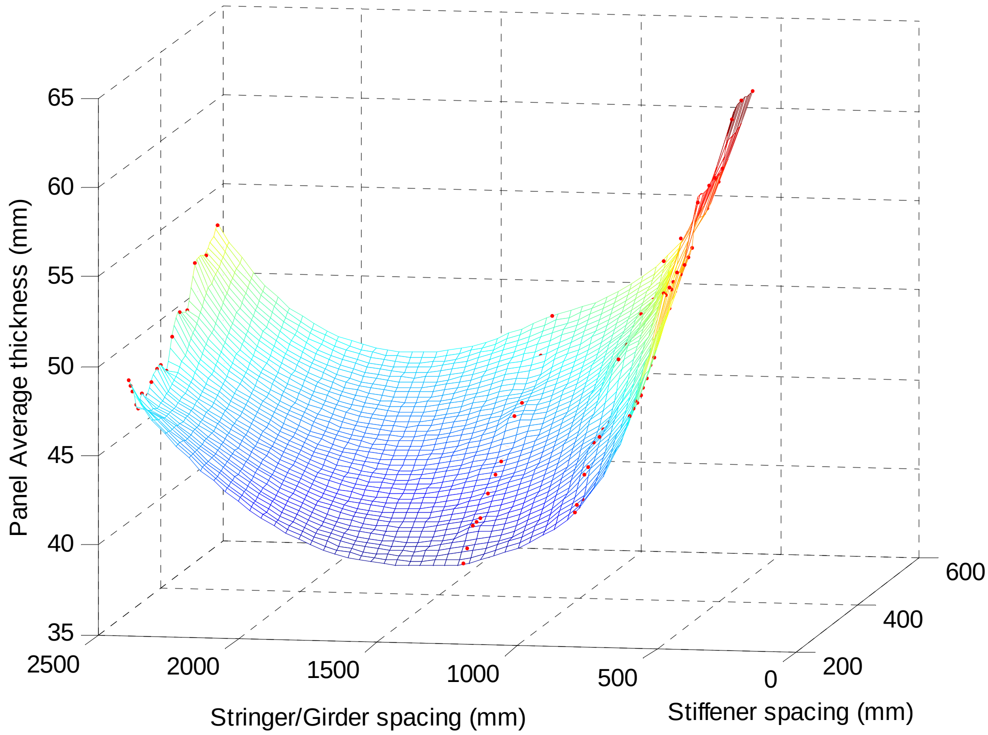
4.2.1 Stiffening

One of the most important global parameters is the type of stiffening. Considering the effect of global bending moment, longitudinal stiffening system is widely used. On the other hand, when ship is small, transversely framed structure which is easy to manufacture is selected.

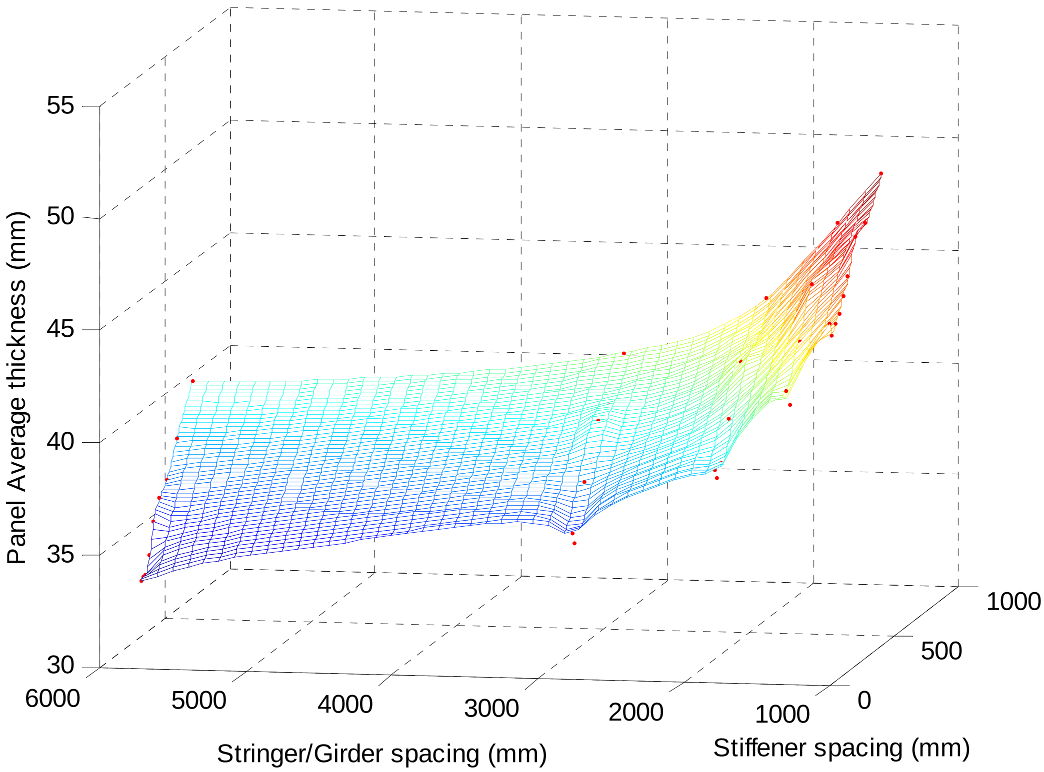
To the ship around 100 m, global bending moment is not big. Besides, being benefited from the huge ice load, thick plate thickness greatly increases the global section modulus out of the area to be discussed. On the other hand, due to the high ice load, hull requires more local strength instead of global strength. Both of these factors push transversal structural as preferred choice. Nevertheless, in weight point view, longitudinal structure is lighter as to ship smaller than 150 m. This seems to be conflicted with the result of general analysis.

Discussing from the calculation of the rules of classification society, judgment can also be made with the same result. For structure design, the main influential factors are section modulus and the reduction factor of maximum hull vertical bending stress (F_D for hull members above the neutral axis and F_B for hull members below the neutral axis). Comparing with the high plate thickness, stiffener longitudinal is minority of the total weight and section area in total. Besides, in the first calculation, with the stiffener spacing 400 mm, F_D is equal to 0.37 and F_B 0.36, which is much lower than the minimum requirement of 0.67 for plate and 0.75 for longitudinal stiffeners. Regarding this, stronger longitudinals should be designed inefficiently. Selecting transversal structure could save significant weight for the whole structure.

To quantitatively solve this problem, in MATLAB, both stiffening system are checked with solutions as many as possible.



(a) Longitudinal framed bottom SS1



(b) Transversal framed bottom SS1

Figure 4.4 Average thickness comparison of different stiffening versus frame spacing and number of stringers

It is obvious to see that the weight of transversal structure is less than longitudinal structure. With the same framing spacing, the weight of transversely framed structure is just around 58% of longitudinal structure.

From the point of view of load transmission, the final support of panel is decks. Transversal stiffener could transfer ice load directly and more averagely to decks. The other persuasive explanation could be the shape of ice load patch. In PC2 case, the calculated ice load patch for mid-ship is 3.13 m in horizontal direction and 0.87 m in vertical direction, which means transversal structure is good at load assignment comparing with longitudinal one which goes with the longer board of ice load patch (see Figure 4.4).

4.2.2 Web frame and floor

As the challenge of this project mainly comes from the ice load, strength of elements bearing possible ice load should be carefully considered. In the calculation of ice load, the load on midbody can be considered an average pressure of about 900 meter high water pressure in a patch area of 3.13×0.87 m. With respect to the high ice load and critical support function of web frame, no matter in longitudinal framed or transversal framed structure, the structure especially the plate thickness of web frame and floor are changed almost linearly with its spacing when it's less than the length of ice load patch. For the sake of the big magnitude of ice pressure and corrosion in water tank, the web frame should keep in enough strength avoiding bending and buckling. On the side adjacent to side shell, thicker plate could be beneficial for the distribution of ice load.

In LR rules, no specific primary elements calculation method for ice load was specified. According to the formula in the rules of DNV, checking by using Von Mises yield theory, the scantling of web frame and girder are calculated. The calculation formula is shown in equation Eqs. 4-1.

$$\begin{cases} F = 1.8phs(kN) \\ M = 0.193Fl \\ A = \dfrac{17.3\alpha f_1 Q}{\sigma} \\ Z = \dfrac{cM}{\sigma} \end{cases} \qquad (4\text{-}1)$$

where

p is the pressure of ice load, which can be calculated by the simplified ice load *h* is the height of the ice load patch

s is the web frame spacing

l is the span of the unsupported distance

A is the shear area

f_l is shear force distribution factor which is 1.1

Q is maximum calculated shear force under the load *F*

σ is the yield stress of material

Following the general arrangement planning, the spacing of web frame should be the multiple of 800 mm. The average thickness of web frame in ice belt being distributed to the side shell is shown in Figure 4.5. Due to the huge ice load, in ice belt region, big web frame spacing like 1600 mm got the thickness in midbody ice belt more than 20 mm for side shell ice belt.

With the extension of web frame spacing, the load transferred to web frame is increasing. Besides, higher web frame spacing means more stress is distributed on each web frame and the web frame on the deck connecting with shell. If web frame spacing increases to more than 2000 mm, much stronger stringer is needed. Regarding the relative requirements written in the rules and the general arrangement made in concept design stage, the spacing of web frame are fixed in optimization process.

From the point view of strength, it is true that T profile web frame could be used to support the structure. While in practice, it is not allowed to have a more than 600 mm high web frame in 1.4 m wide double skin area, but the web frame with 600 mm high is still not enough in strength. So in this case, web frame are taken as non-watertight plate through double skin with manholes and stiffening.

The high ice load is assigned into the paralleled web frame, which means the bigger web frame spacing, the thicker of its plating.

The stiffener spacing affects the result a little bit which we didn't take into account. To control the plate thickness in reasonable range and to save steel, we limit the web frame spacing at 1600 mm.

In case of buckling due to pressure and the stress concentration in the corner and around the man holes, web frame should be stiffened by stiffeners. Here, the stiffener spacing and additional web plate thickness should be calculated by MATLAB and find the best solution with respect to the criteria light weight.

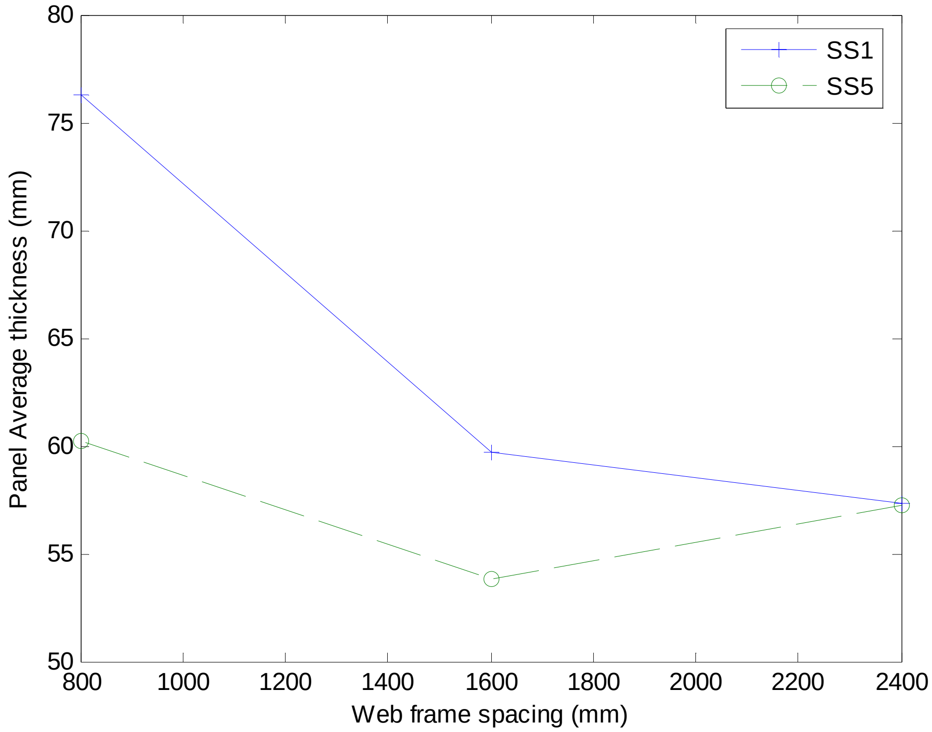


Figure 4.5 Average thickness (include web frame) of web frame with different frame spacing in ice belt as an example versus spacing of web frame

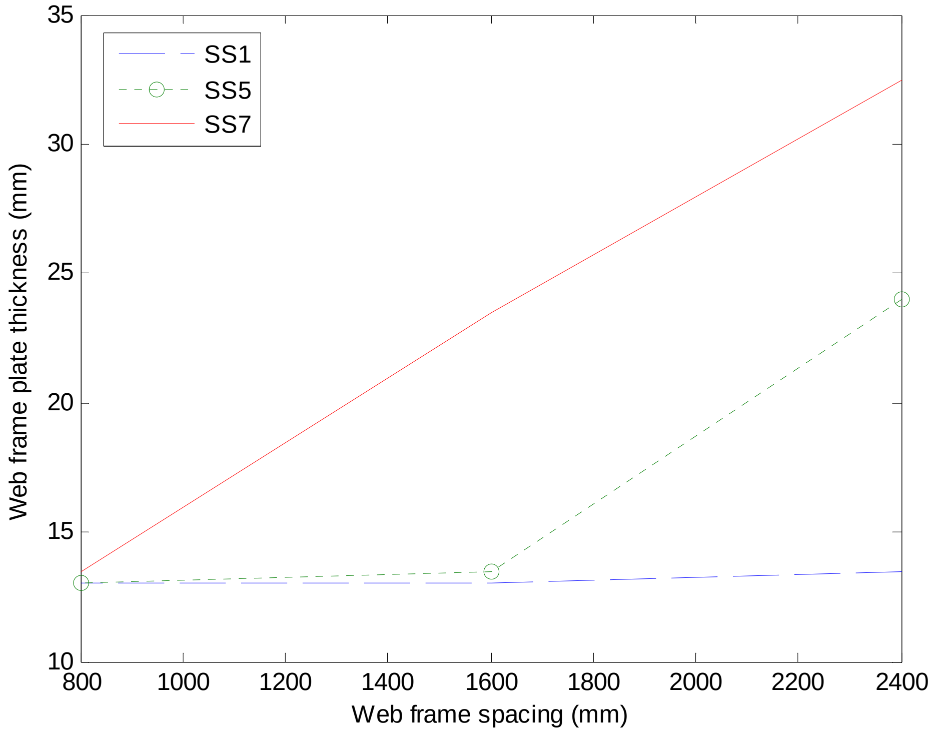


Figure 4.6 Plate thickness of web frame with different web frame spacing as an example versus spacing of web frame

4.2.3 Stiffener spacing

According the equations identified by the rules, the relationship of shell panel and stiffener spacing is shown in Figure 4.7 and Figure 4.8.

The diagrams show that in most cases, reducing stiffener spacing could reduce not only the thickness of plate but also average plate thickness.

From Table 2.3, we found with the decrease of stiffener spacing, the decreasing of stiffener profile area and section didn't reduce proportionally and significantly. This is because the smaller stiffener spacing means possibility of the appearance of higher peak ice load, which is critical for the stability of stiffeners.

In conclusion, reducing stiffener spacing could reduce the total weight of the structure, but not very effective.

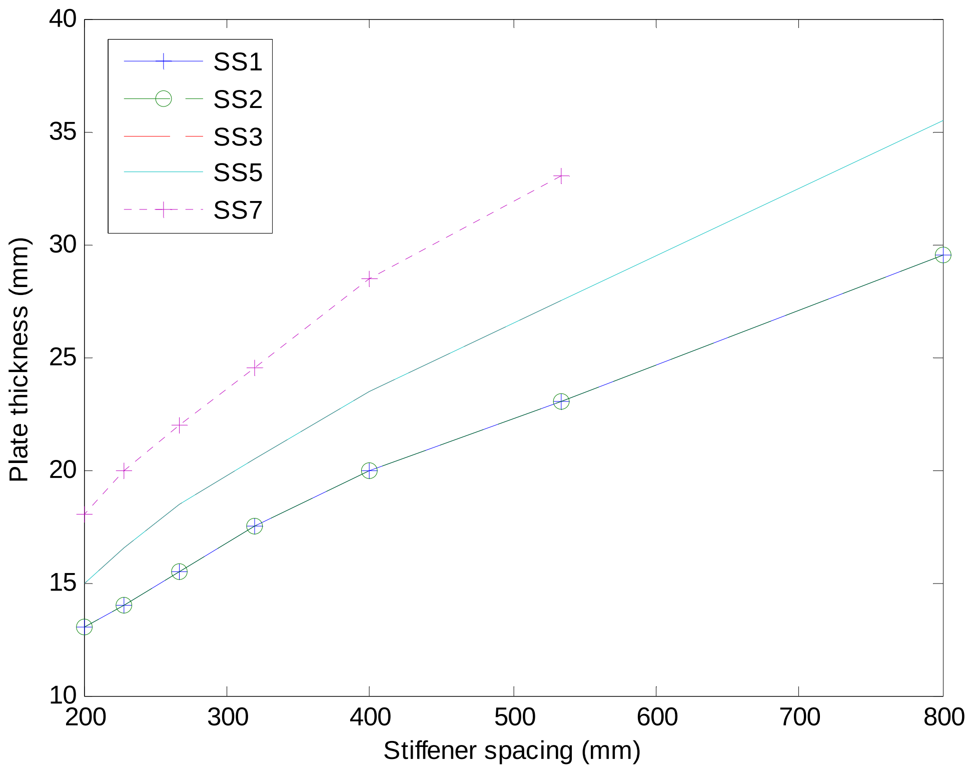


Figure 4.7 Plate thickness of shell panel versus stiffener spacing (transversal framed)

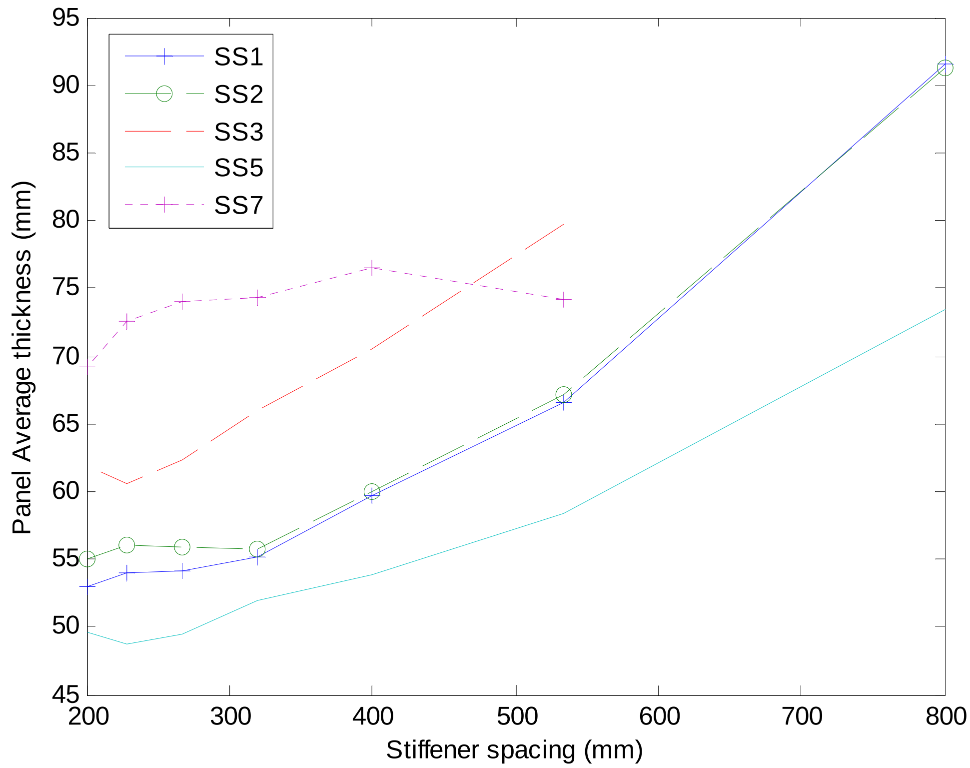


Figure 4.8 Average thickness (include web frame) of ice belt panel versus stiffener spacing (transversal framed)

4.2.5 Stringer

The function of stringer is to assign the load on frame, providing effective support. In this case, the profile of stiffeners can be smaller with the help of stringer. On the other hand, strong stringer and its brackets mean additional mass to the structure and probably more parts to be manufactured. Stronger web frame is required as well to support stringers. To make a good weight balance, the primary criteria, weight, should be calculated and compared. Taking several different shell panels as comparison, the result is shown in Figure 4.9.

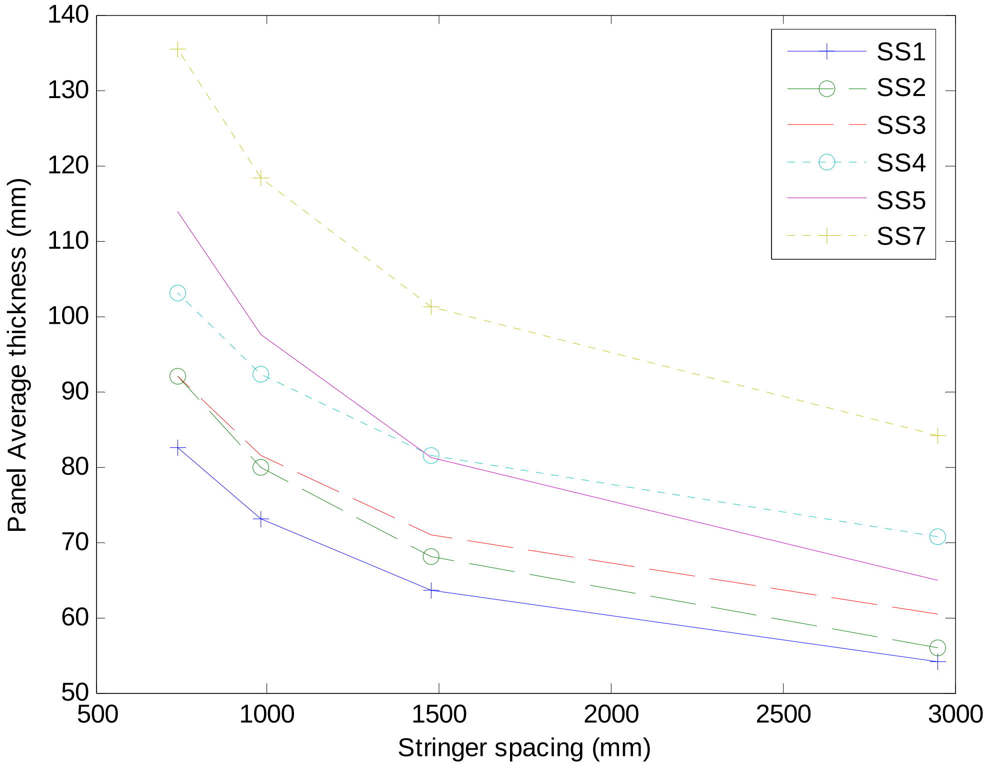


Figure 4.9 Average thickness of panels (inc. web frame) versus various stringer spacing (Stiffener spacing: 229 mm)

The two figures above also prove that the stiffener spacing is more important contributing to the weight of panel. Taking all main parameters into account, the total average thickness of panel including plate thickness, stiffeners, frames and standard stiffener brackets is calculated. The relationship of t_{ave} and stiffener spacing and spacing of stringer is shown in Figure 4.10.

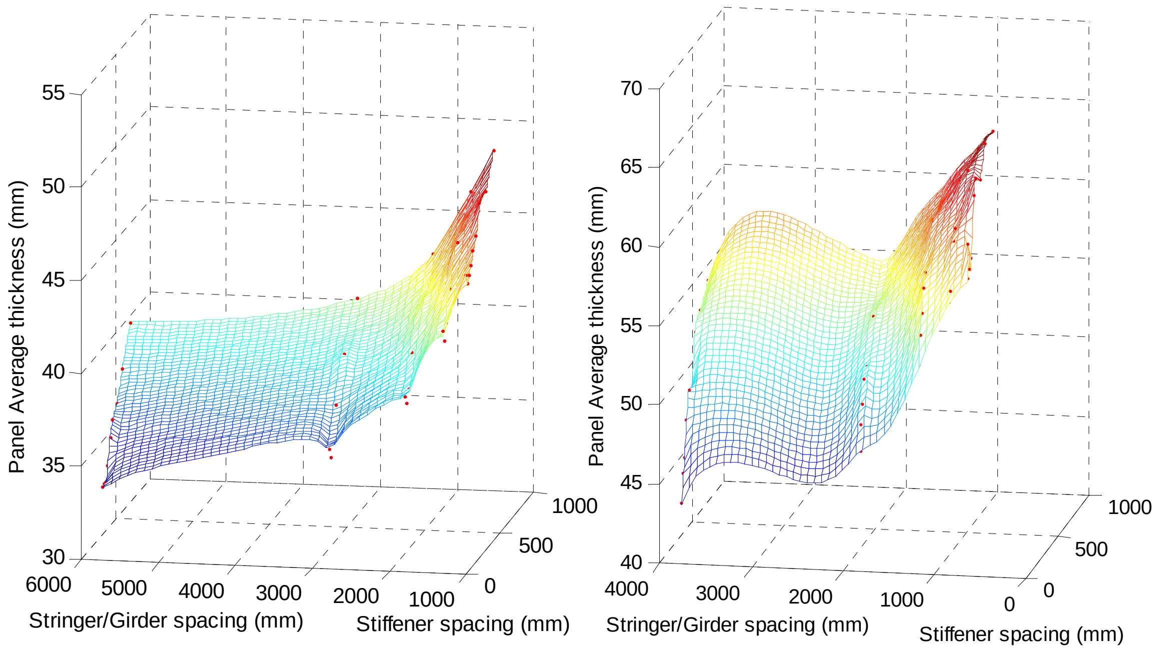


Figure 4.10 Average thickness versus stiffener spacing and spacing of stringer (Left: Panel SS1, Right: panel SS7. Transversely stiffened, web frame spacing: 2400 mm)

From this figure, a critical conclusion is shown that no matter what kind of stiffening selected, smaller stiffener spacing could effectively reduce the weight of the structure. Moreover, in half of the girder distance, a concave rip, which means in practical, adding one stringer in the relative panels could have a local optimized weight. On the other hand, in practical, there are potential limitations for manufacturing, such as minimum stiffener spacing. Besides, it is obvious that smaller stiffener spacing means more parts, more welding in the same area and harder manufacturing process, which is negative in production point view. To make a good balance between weight and production, additional consideration will be analyzed and discussed in the following chapters.

Being analyzed from the rules, the reason of this result comes from the dimension of the patch. Which can be explained as the primary factor is the shear of the load on the elements. When the stringer spacing is bigger than the ice load patch, the shear on the stringer keeps the same, which means the optimized dimension of stringer is constant, resulting in the increasing average weight with respect to the decreasing spacing.

4.3 Deck

As what we analyzed before this section, the dimension of decks changes slightly when shell structure adopt diverse stiffening method and spacing. Yet it doesn't mean structure optimization is not effective for deck panel. For the sake of ice load, For ice class and polar class ship, higher requirement to primary element is demanded and the structure supporting primary element is critical as well. The critical influence factor on deck structure is ice load on side shell. Because of the transversal compression due to the ice load, thick deck plating is required if high compressive force is loaded. So buckling in case of compression in two directions should be checked. When the deck is not transversely effective, like the decks between tanks, the structure only undertakes possible longitudinal compressive force.

In the analysis of MATLAB result, some valuable trends are founded. In deck panel, the load is limited and relatively small, which means the total weight of the panel is not as sensitive to stiffener spacing as shell. In practice, due to the limitation of profile catalog, slight changing of required stiffener section modulus cannot be shown in stiffener profile, which signifies that in some cases, the smaller stiffener spacing make heavy the structure due to dense spacing with the same profile. Taking the panels in different location (weather deck, cargo deck, deep tank bottom, inner bottom) as examples (see Figure 4.11), this issue could be better understood.

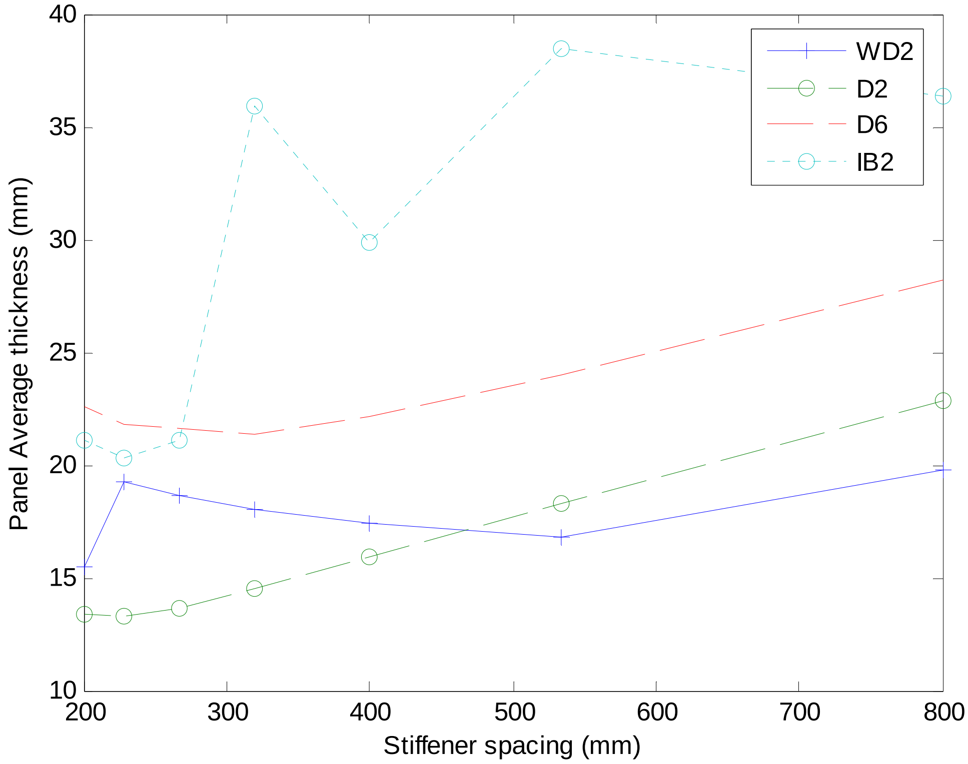


Figure 4.11 Average thickness of panel versus stiffener spacing in several panels

Here we found minimum weight in the range of stiffener spacing. As the vertical pressure and transversal compressive pressure are different panel by panel, precise comparison cannot be processed.

4.4 Longitudinal bulkhead

Inside the ship, the structure construction is relatively mature in design and manufacturing. Moreover, the complex arrangement and structure is not easy to make good weight optimization in early stage. In this section, only main structure is considered.

From the drawing of general arrangement of tank, 4-6 longitudinal bulkheads exist in the block of mid-ship segments that the example of optimization process is operating, are longitudinal effective. As what is talked about before, the global strength of this ship is strong enough and different stiffening affect slightly on minimum section profile of elements.

For the plating of bulkhead, advantages and disadvantages of horizontal and vertical plating are reversed. Generally speaking, horizontal longitudinal bulkhead plating reduces the weight, especially in long bulkhead distance cases. But in this project, due to the high ice load, more strength should be considered in transversal direction, which means stronger and continuous transversal bulkheads and decks. As Figure 4.12 shows, in the general arrangement of tanks, the dimension of tank is limited and horizontal plating means more cutting and welding compare with vertical structure. So in this design, vertical plating is selected.

With respect to the transversely framed shell, vertical framed longitudinal bulkhead could be more useful in strength consideration. Besides, Vertical stiffening system is good at supporting cargo deck. As to the tank bulkhead through tween' decks and watertight bulkheads with diverse length, vertical stiffened structure using unique length is easier for manufacturing and good for block splitting.

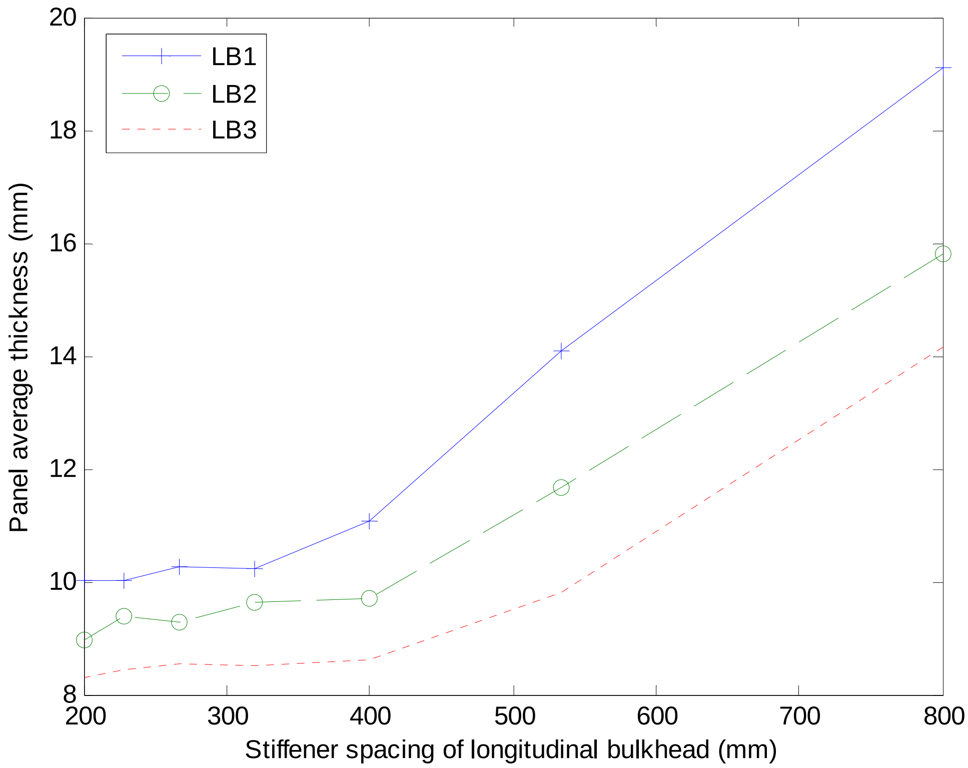


Figure 4.12 Average thickness of panels versus stiffener spacing of longitudinal bulkhead

The result shows that the weight of stiffened panel keeps almost constant when stiffener spacing is smaller than 320 mm. On the other hand, the difference of weight changes significantly following stiffener spacing when it is bigger than 400 mm. Combining the calculation result of panel scantling, the reason can be considered that in the rules, 7.5 mm minimum longitudinal bulkhead plate thickness limited the scantling, which affect the calculation of profile at the same time. The scantling solution is list in Table 4.1.

Table 4.1 Data of optimized longitudinal deep tank longitudinal bulkhead

Panel	t_{ave} (mm)	Plate thick-ness (mm)	Height of tween' deck (m)	Yield strength of plate steel (N/mm2)	Stiffener spacing S (mm)	h_w (mm)	t_w (mm)	Yield strength of profile steel (N/mm2)
LB3	15.551	12.5	3.9	355	800	180	10	355
LB2	18.041	13	3.9	355	800	260	10	355
LB1	22.205	15	3.9	355	800	300	12	355
LB3	12.04	8.5	3.9	355	533.33	160	9	355
LB2	15.685	9	3.9	355	533.33	220	11.5	355
LB1	19.249	10.5	3.9	355	533.33	260	12	355
LB3	11.368	7.5	3.9	355	400	160	7	355
LB2	14.496	7.5	3.9	355	400	200	10	355
LB1	17.153	8	3.9	355	400	240	10	355
LB3	11.596	7.5	3.9	355	320	140	7	355
LB2	15.62	7.5	3.9	355	320	200	9	355
LB1	17.455	7.5	3.9	355	320	220	10	355
LB3	12.415	7.5	3.9	355	266.67	140	7	355
LB2	15.151	7.5	3.9	355	266.67	180	8	355
LB1	19.195	7.5	3.9	355	266.67	200	11.5	355
LB3	12.819	7.5	3.9	355	228.57	120	8	355
LB2	16.426	7.5	3.9	355	228.57	180	8	355
LB1	18.869	7.5	3.9	355	228.57	200	9	355
LB3	12.379	7.5	3.9	355	200	120	6	355
LB2	16.036	7.5	3.9	355	200	160	8	355
LB1	20.493	7.5	3.9	355	200	200	9	355

4.5 Transversal bulkhead

Transversal bulkhead can be identified with two sorts. One is deep tank bulkhead, the other sort is watertight bulkhead. As shown in Chapter 3, different bulkheads are required with different rules. Generally, the function of transversal bulkhead is holding or covering cargo, liquid and equipment, for ice class and polar class ship, high ice load require the transversal effective structure undertake high compressive pressure at the same time to avoid collapse and buckling of the panel.

As to the stiffening type, both horizontal and vertical stiffening methods are widely used the different case. As analyzed in the former part, as for polar class ship, transversal load is dominant. So horizontal stiffening is selected directly considering transversally effective cross section and plate buckling strength, with respect to Eqs. 2-1 and Eqs. 2-2. Taking account of all the mentioned items, the optimization calculation could be processed.

Regarding the parameters, the calculation is processed panel by panel as shown in Figure 4.13.

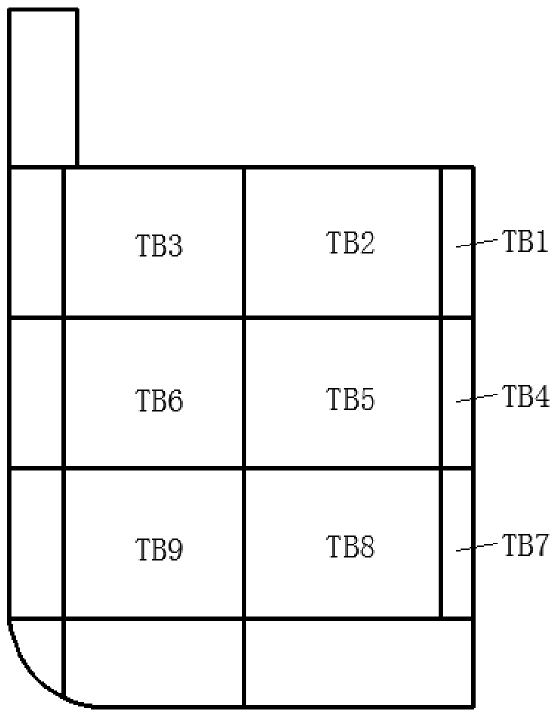
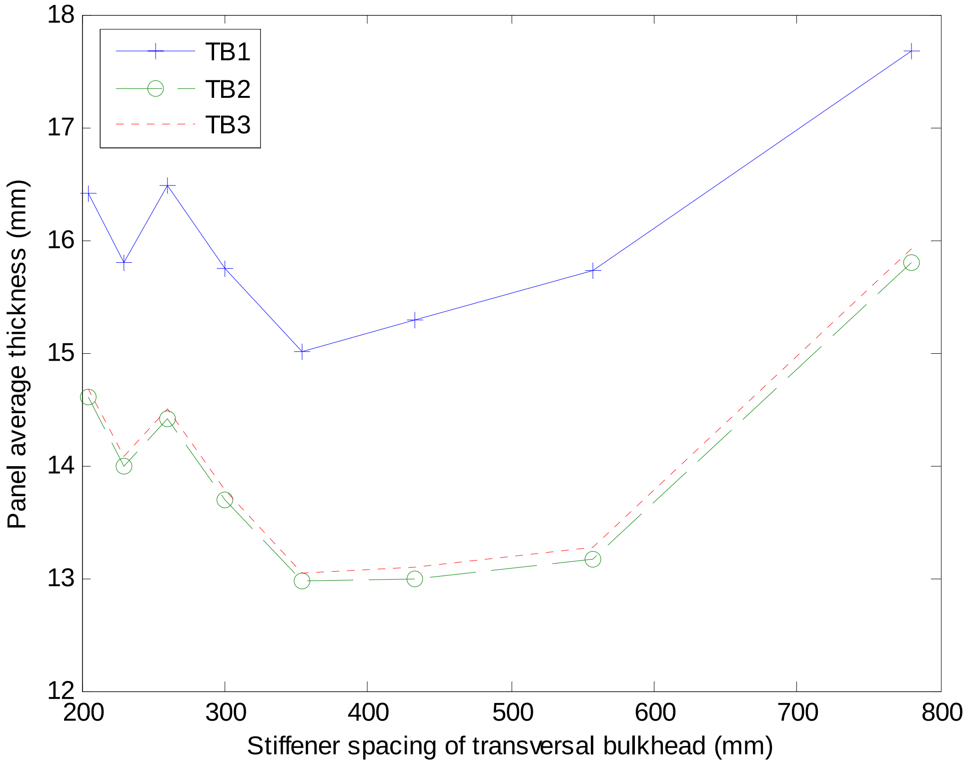
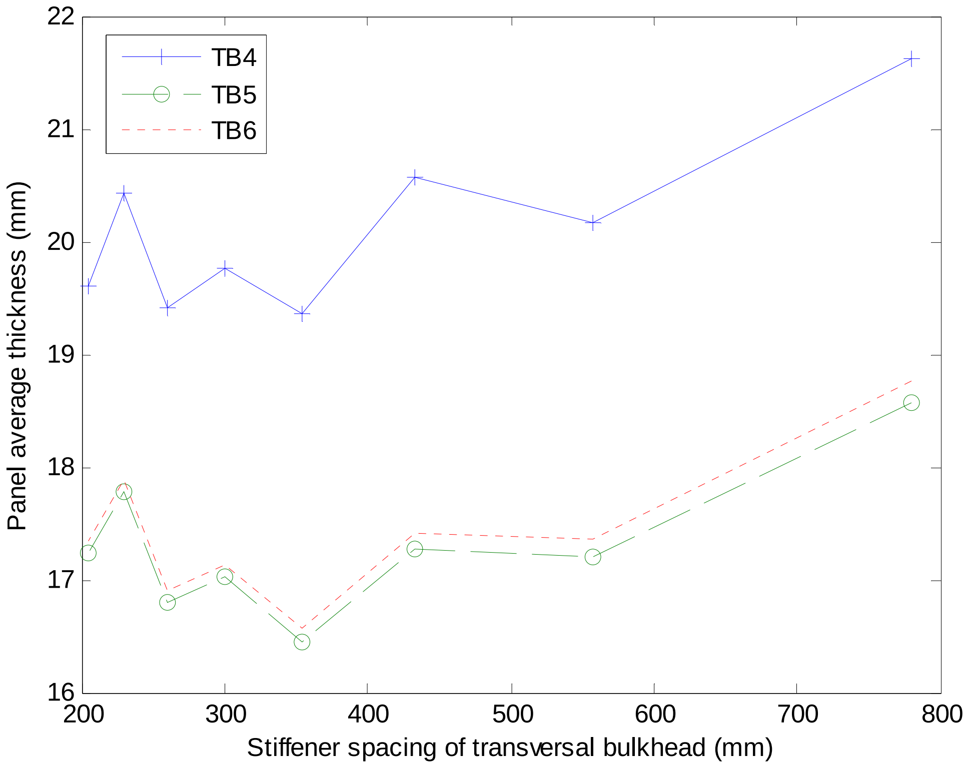


Figure 4.13 Nomenclature of transversal bulkhead panels

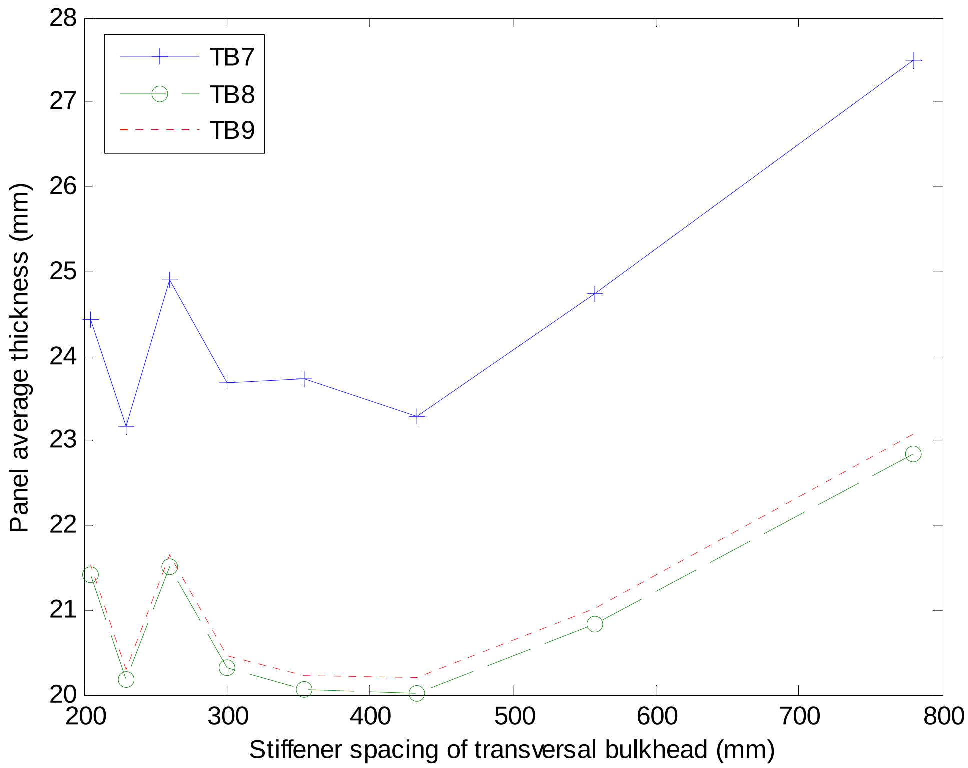
According to the General Arrangement, tanks can be considered as the division of panel (the strengthening of the connection should be well considered). The average thickness versus different stiffener spacing in diverse height shows the curvature of Figure 4.14.


TB1
TB2
TB3
Panel average thickness (mm)
Stiffener spacing of transversal bulkhead (mm)
18
17
16
15
14
13
12
200
300
400
500
600
700
800

(a)


TB4
TB5
TB6
Panel average thickness (mm)
Stiffener spacing of transversal bulkhead (mm)
22
21
20
19
18
17
16
200
300
400
500
600
700
800

(b)



(c)

Figure 4.14 Average thickness of transversal bulkhead panels versus stiffener spacing

As Figure 4.14 shows, in this case, the minimum average thickness value is taken at different stiffener spacing value. As for the panel on the same horizontal direction, stiffener spacing should be the same. As in transversal direction, structure only undertake compressive pressure, hence longitudinal structure is identified to be continuous, which at the same time means plate thickness of each panel adjacent can be not constant. Then run the optimization program, gaining the global average thickness result taking all primary and secondary structure into account.

Another regular pattern can be found that no matter how the stiffener support spacing is, the tendency of weight changing keep the same for the panel on the same depth.

Considering that transversal bulkhead is transversal structure without constant longitudinal spacing. Therefore here, weight of panel is used to replace panel average thickness.

From Figure 4.15 we can find that in different depth, the optimized solution could be with different stiffener spacing. Processing the result with 3D plot, we could find the tendency of weight according to the changing of both stiffener spacing and depth.

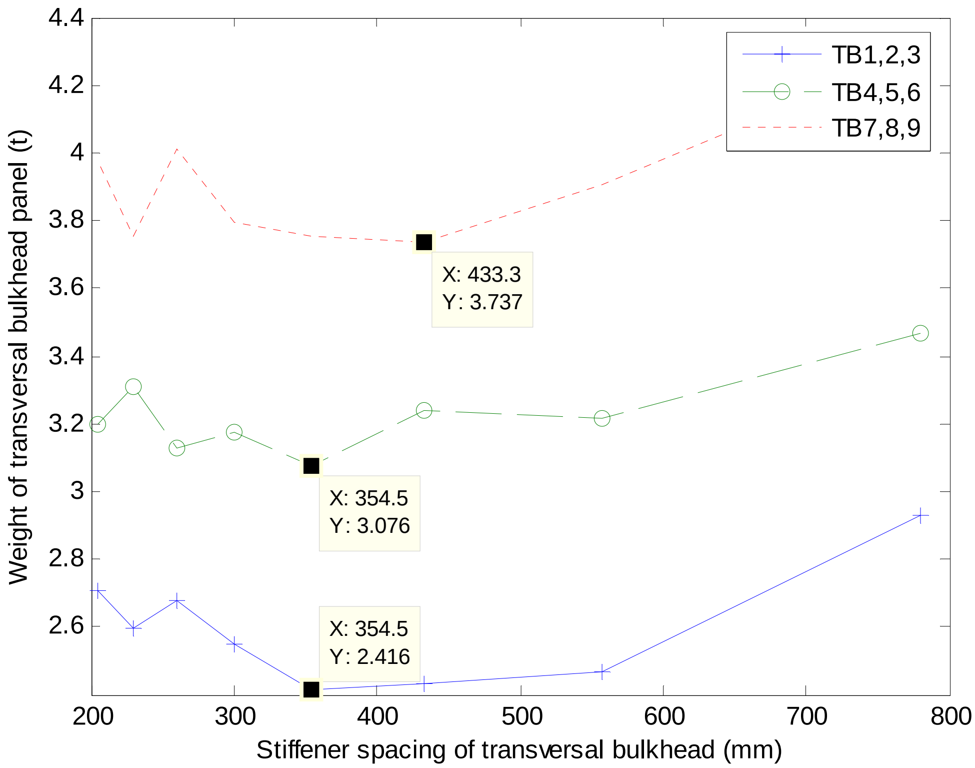


Figure 4.15 Average thickness of panels on horizontal versus stiffener spacing (combination of 3 panels)

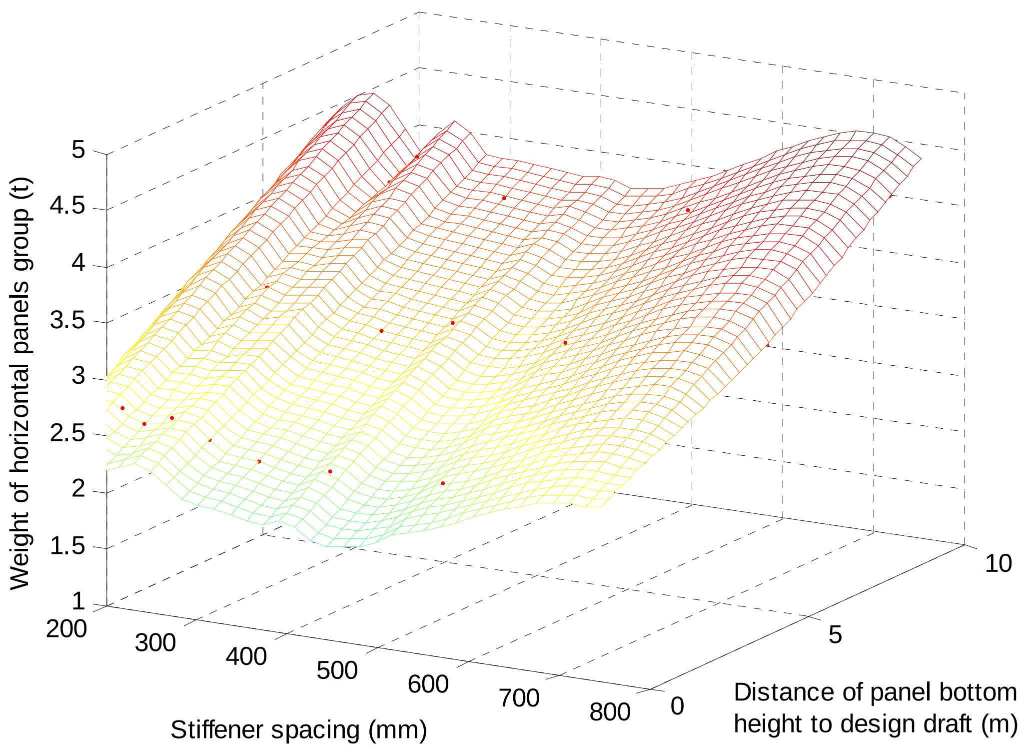


Figure 4.16 Average thickness of panels on horizontal versus stiffener spacing and depth (combination

of 3 panels)

From Figure 4.16 we could obvious find that with the increase of depth, the weight of panel is increasing which corresponds with the fact that bulkhead should hold the water pressure. Besides, the tendency shows stable region catching the optimized result. The minimum weight exists in case the stiffener spacing is in the range of 300-500 mm.

On the other hand, in different segments, the division of panel is diverse. Another common case needs to combine two adjacent panels on the right side together (see Figure 4.17). In this case, the optimized result could be different as shown in Figure 4.18.

Following the same method, the combined optimization is processed. The 2D and 3D result of this case is shown in Figure 4.19 and Figure 4.20.

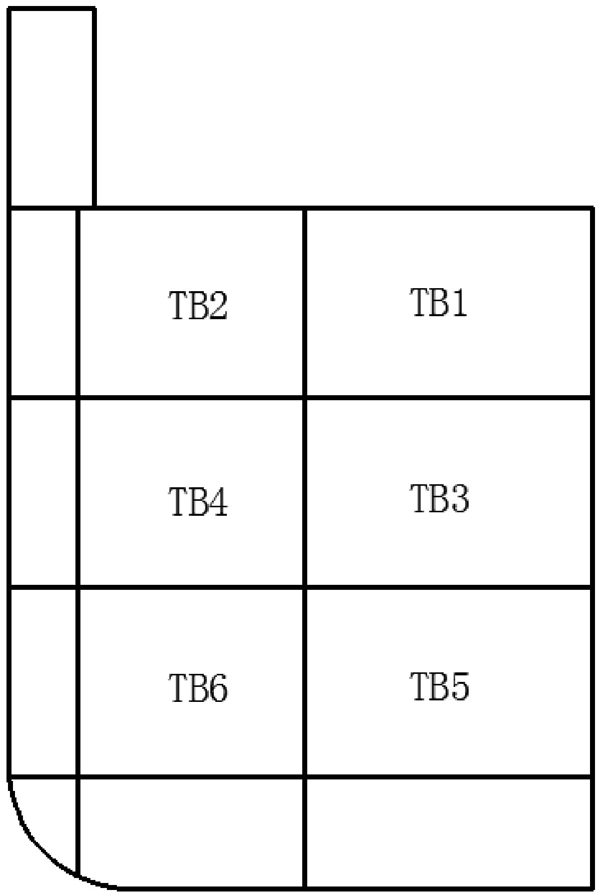
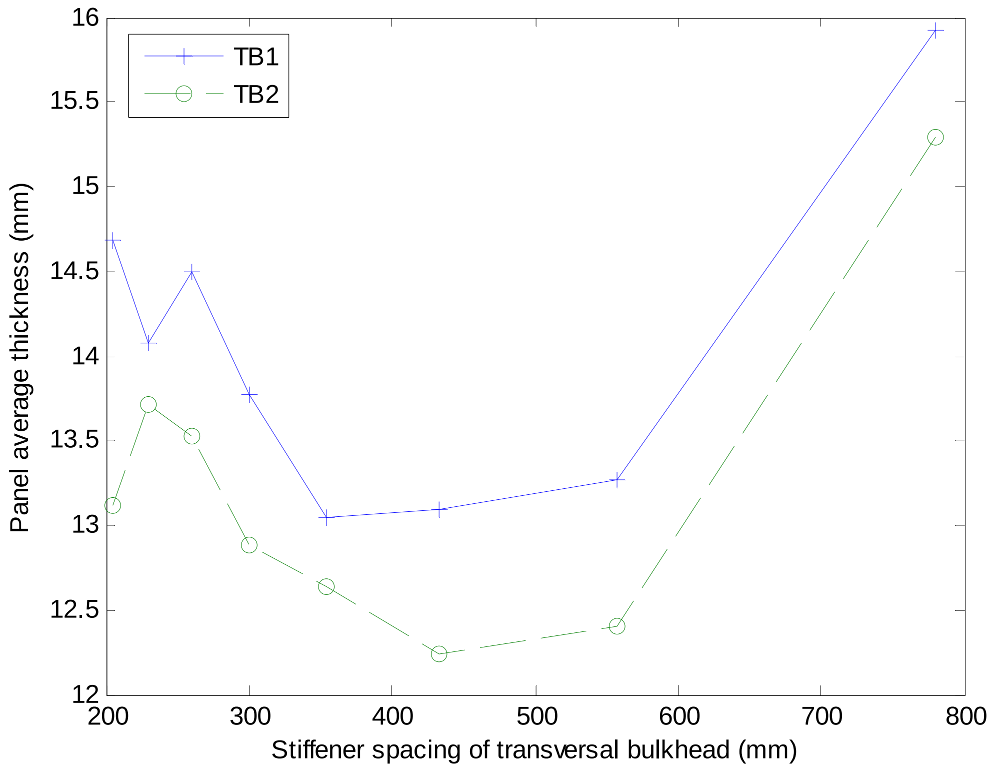
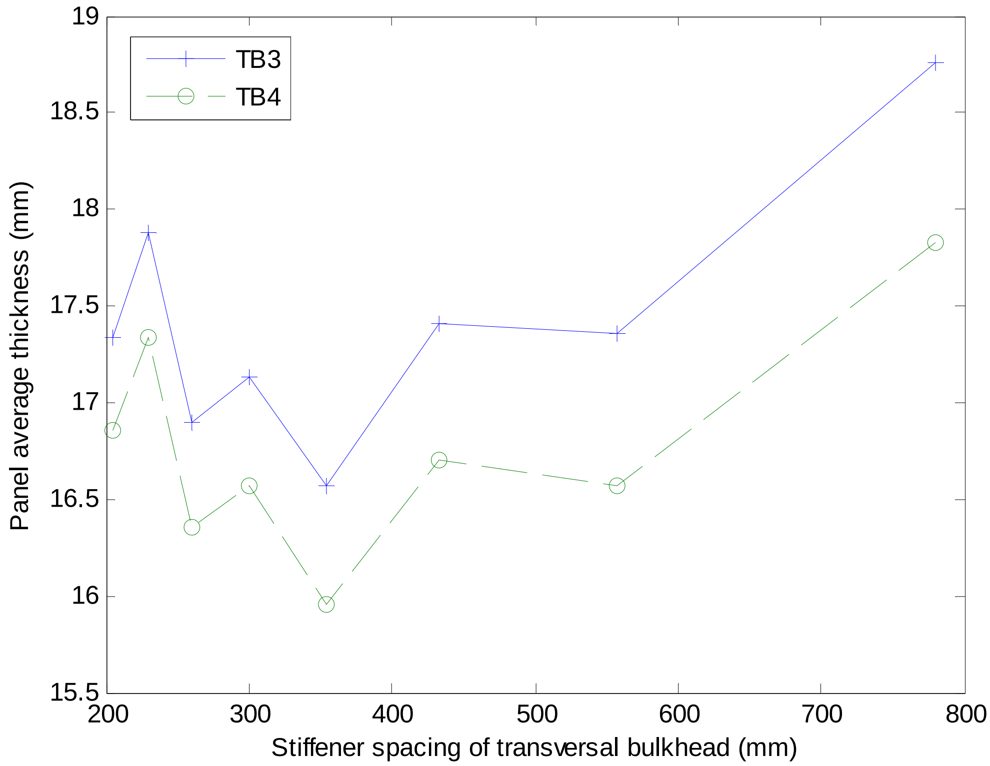


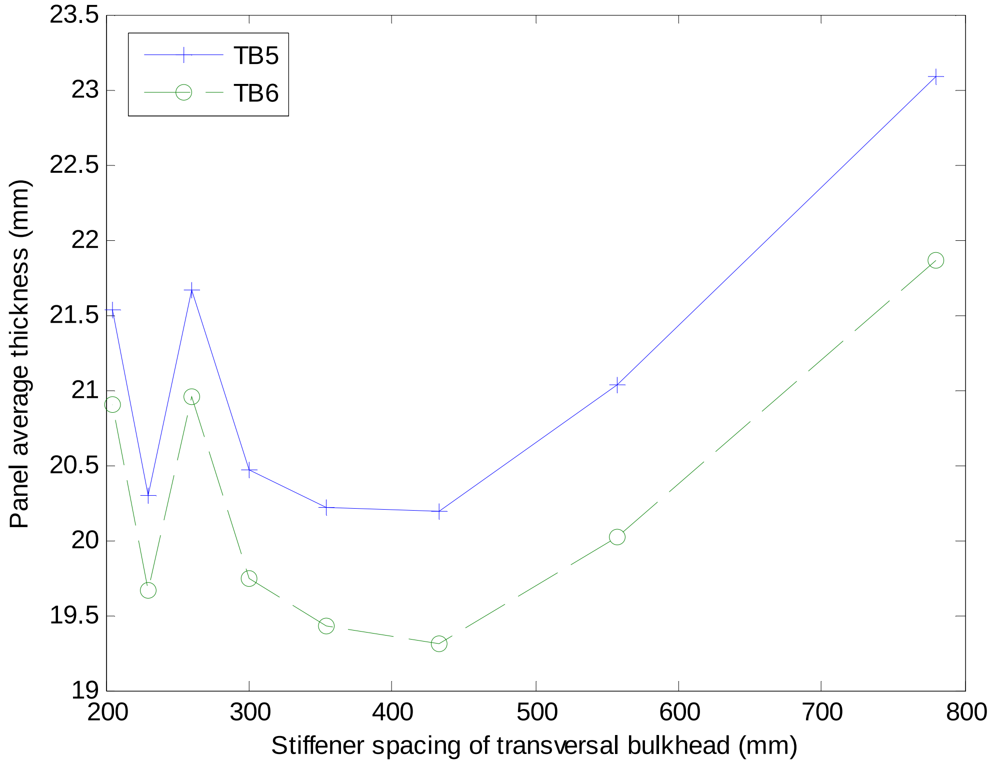
Figure 4.17 Nomenclature of transversal bulkhead panels


16
15.5
15
14.5
14
13.5
13
12.5
12
200
300
400
500
600
700
800
TB1
TB2
Panel average thickness (mm)
Stiffener spacing of transversal bulkhead (mm)

(a)


19
18.5
18
17.5
17
16.5
16
15.5
200
300
400
500
600
700
800
TB3
TB4
Panel average thickness (mm)
Stiffener spacing of transversal bulkhead (mm)

(b)



(c)

Figure 4.18 Average thickness of panels on horizontal versus stiffener spacing (combination of 2 panels)

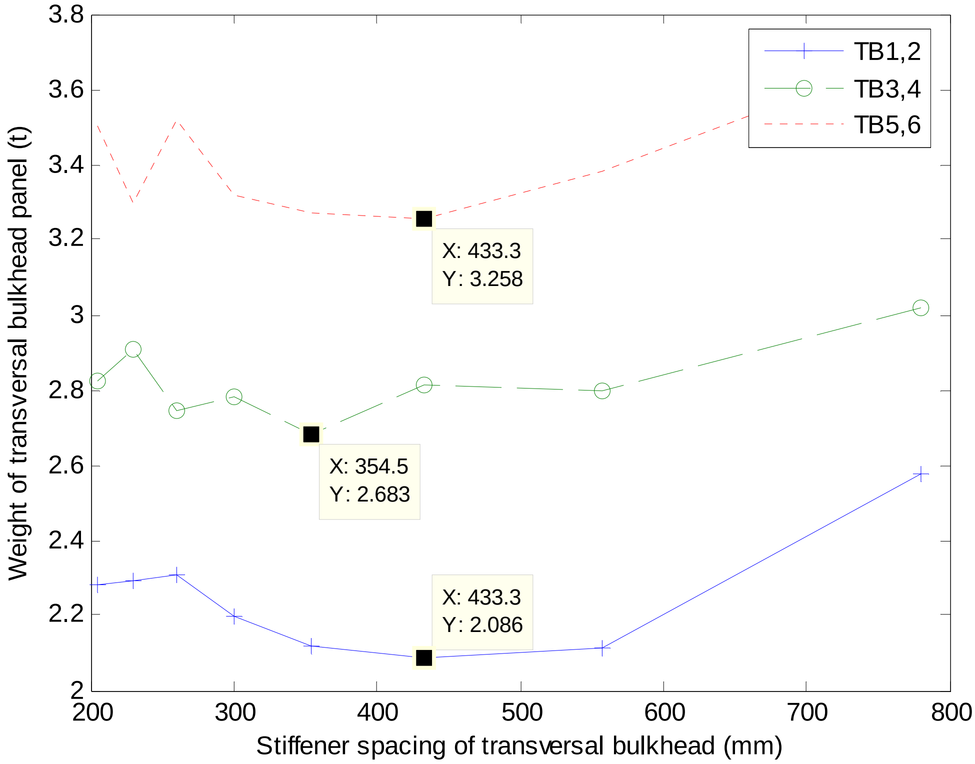


Figure 4.19 Average thickness of panels on horizontal versus stiffener spacing (combination of 2 panels)

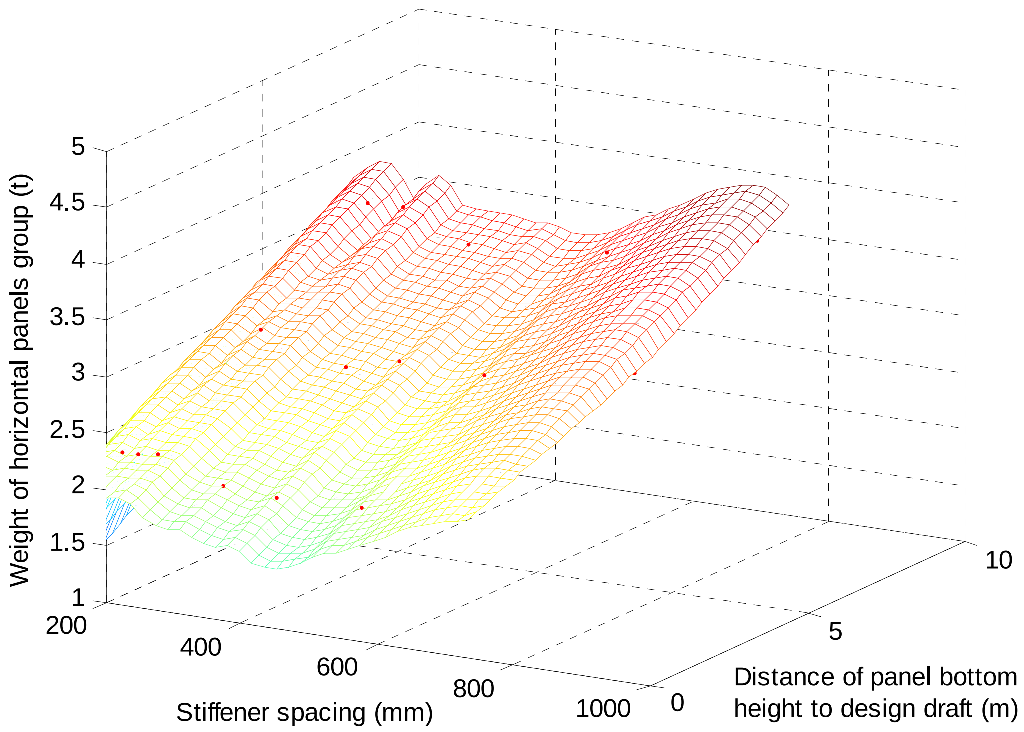


Figure 4.20 Average thickness of panels on horizontal versus stiffener spacing and depth (combination of 2 panels)

4.6 Bow and Stern

Regarding the requirement that ship has ice breaking competent both forwards and backwards, in bow and stern area, for the sake of the high ice load and the small angle between shell plate and stiffener web, there is no bulb profile suitable for the requirements in the rules based on the result of calculation. Thus in bow and stern, elements including web frame, bulkhead and stringer are selected.

The structure inside the shell plate is combined structure with manholes. In this early stage design, since our objective is to give design proposal, the strength calculation is considering the scantling as the grillage structure with full transversal and longitudinal bulkheads. In weight calculation, 60% of full weight will be taken into account considering manholes and cut outs.

In bow and stern, structure is not only suffering compressive in transversal direction, but also longitudinal because of the hull form. Based on the rules, hull plate thickness is calculated regarding various framing spacing.

The result is shown in Table 4.2.

Table 4.2 Shell plate thickness versus angle of hull form

Angle between hull and profile direction (degree)	Framing spacing (mm)				
	400	600	800	1000	1200
15	41	53	66.5	78.5	89
25	42	54.5	68	80	91
35	43	56	69.5	82	93
45	44	58	72	84.5	95.5

The calculation first follows the minimum requirement of the bulkheads, and then buckling due to ice compression is checked. Considering the general arrangement, longitudinal bulkhead spacing is defined as 1.8 m. As well, in the point view of manufacturing, bigger spacing give more spacing for workers and reduce production complexity simultaneously. Based on the result in Table 4.2, transversal bulkhead spacing is identified as 800 mm.

Because of the high compressive load, bulkheads should be strengthened by stiffeners. While in real case, the concomitant of manholes and stiffeners always result in complex manufacturing and issue of stress concentration.

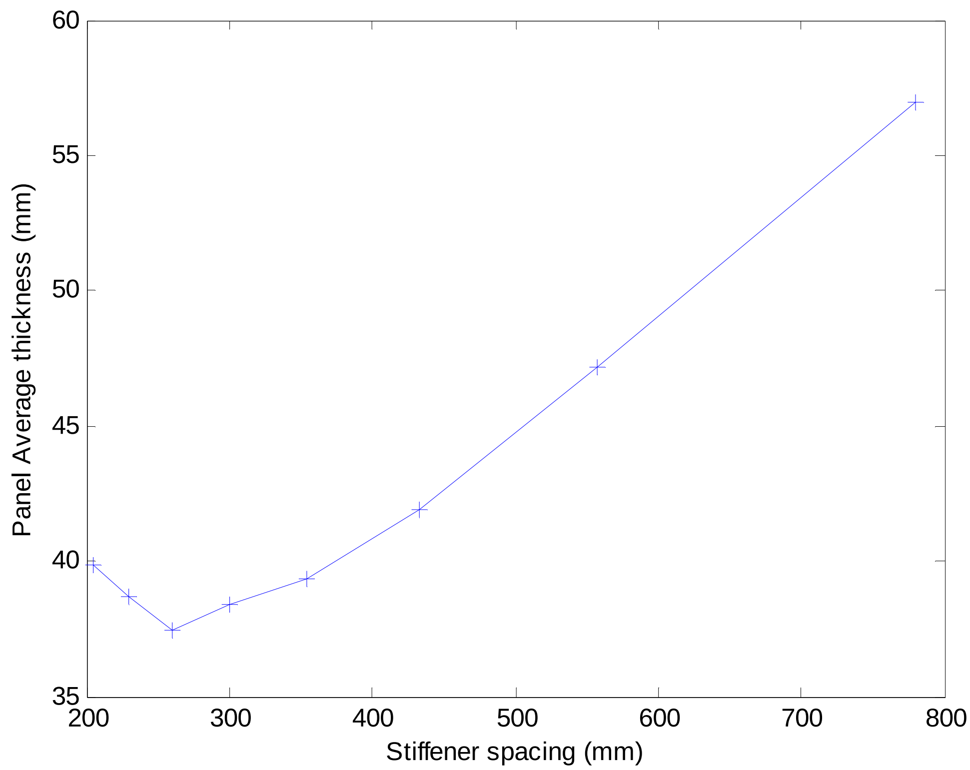


Figure 4.21 Average thickness of longitudinal bulkhead in bow area versus stiffener spacing

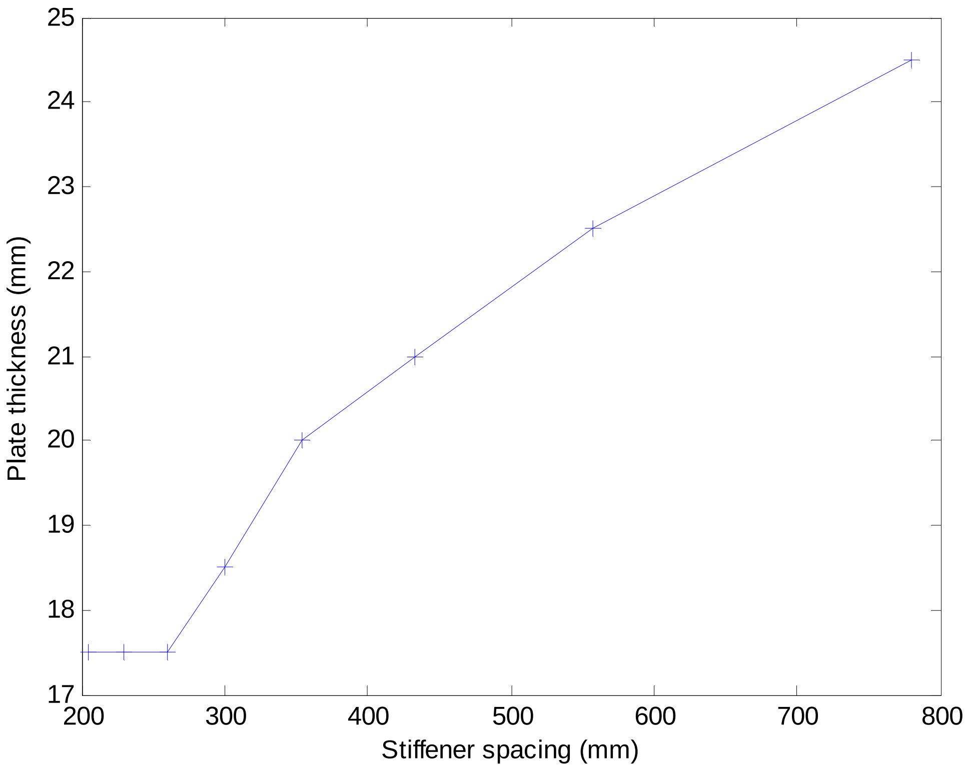


Figure 4.22 Plate thickness of longitudinal bulkhead in bow area versus stiffener spacing

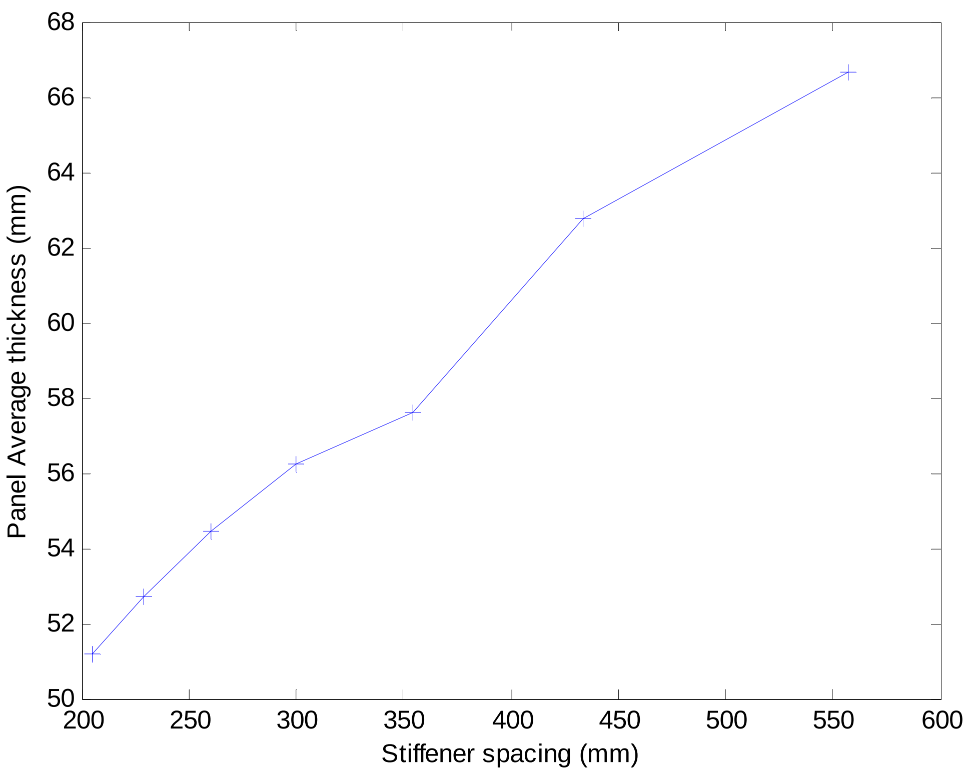


Figure 4.23 Average thickness of transversal bulkhead in bow area versus stiffener spacing

Figure 4.21 and Figure 4.22 show the same relationship between stiffener spacing and weight, plate thickness. For transversal bulkhead, which suffers more compressive stress, the quantitative relationship is shown in Figure 4.23. From the comparison of diagrams, we found the trend that with increasing compressive stress, the relationship of stiffener spacing and panel weight is more unidirectional.

5. WEIGHT ASSESSMENT BASED ON MATLAB

Completing the panel structure optimization, the global optimization can be developed based on the database obtained from the first step. The information needed now is the relationship of the adjacent panels.

Two kind of connection of adjacent panels can be generalized, plate connection and stiffening connection. Theoretically, the connection of panel and be totally independent, which means the connection of panels can be done later. While the point is that the plating spacing of secondary and primary elements should keep the same. For some special cases don't follow this rule, we will discuss about it later.

In detail, this criterion can be explained like this: First, choose the primary panel as the base stone. Here we choose the panel in ice belt. The reason is: First, considering the importance of structure, ice belt is the key part affect the performance of structure. Second, due to the high ice load, continuous stiffening system should be well used in the adjacent panel of ice belt. Third, the high ice pressure means intense grillage system in ice belt. The adjacent stiffeners paralleled should keep the same or be the times of ice belt panel stiffener spacing. When the expansion of panel goes to some panel need higher grillage density, 1/2 or 1/3 or even 1/4 times parallel spacing is possible as well.

Talking about the methodology, mainly three kind of program structure could be selected. Serial structure means the calculation process is panel by panel, solution process looks like the running river. This method has higher global efficiency as the later has more accurate parameter range and more specific constrains.

Parallel structure is the opposite kind method, which divides the serial structure into several independent parts, identifies big variable range for calculation, then combine the result of different parts together with statistical method. With the method, each part works independently without the influence of others, which shorten the programming time and provide higher compatibility of program in different research projects. This method is also good for big programs as it save the time of debugging and CPU time for 1 running.

The methodology selected in this project is the third one, the combination of the mentioned two methods. Regarding the property location and function of different panels, the calculation of global structure are calculated in three different parts, mentioned in last chapter. In each part, the calculation is serial or parallel structure which depends on the relationship of the adjacent panels. For instance, in the connection of ice belt and longitudinal between tween decks, serial structure is selected, while between ice belt and lower area, parallel structure is better.

5.1 Shell

The weight in shell is the main part and easier in calculation due to the regular form. With respect to the dimension of panels between girder and web frame, weight of each panels is calculated and total weight is added.

5.1.1 Midbody

In midbody of the ship, the section keeps constant almost. So the calculation method used for the weight of this segment is repeated the weight in one section panel on the longitudinal direction. The result with respect to different stiffener spacing is shown in Figure 5.1.

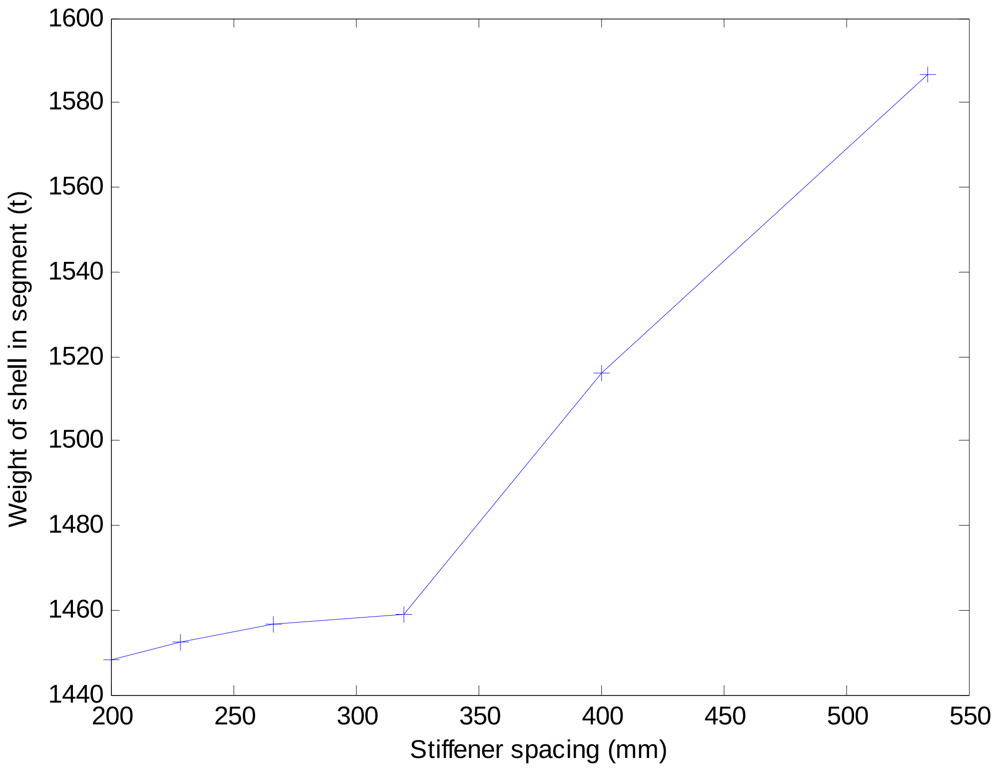


Figure 5.1Weight of shell panel (including web frame) versus stiffener spacing (weight is half of the

vessel)

5.1.2 Bow intermediate and stern intermediate

As the angle change of hull form, each 5 degrees of the maximum angle on the vertical belt is considered as the criteria separating the ship into different segments. Regarding to the identification in polar class rules (see Chapter 2.3), Bow intermediate and stern intermediate regions are divided into 4 parts for calculation. The segment location of these segments is shown in Table 5.1.

Table 5.1 Weight of shell in bow intermediate and stern intermediate region

Seg. No.	Start from Aft. end (m)	End from Aft. end (m)	Angle of hull (degree)	Weight (t) with stiffener spacing (mm)				
				400	320	267	229	200
1	8	22.4	10	0	0	594.42	571.9	560.58
2	22.4	35.2	5	0	420.7	543.16	525.4	512.3
3	94.4	100.8	5	322.18	314.86	312.32	305.32	310.28
4	100.8	105.6	10	0	221.36	220.56	215.82	215.76

From this table, we also can find the tendency that in general, smaller stiffener spacing results smaller weight.

5.1.3 Bow and stern

Table 5.2 Weight of shell at Bow and stern

Segment number	Start from Aft. end (m)	End from Aft. end (m)	Angle from hull form to profile (degree)	Length of shell (m)	Weight (t) with framing spacing 800mm
1	0	2.4	60	24	50.7
2	2.4	5.6	50	27	60.8
3	5.6	9.6	30	29	58.9
4	9.6	13.6	20	29.6	54.4
5	105.6	109.6	20	37.6	69.1
6	109.6	113.6	30	28.2	57.3
7	113.6	117.6	35	25	53.7
8	117.6	121.6	40	17.4	41.1
9	121.6	130	35	12	54.1

Considering the complex hull form in bow and stern area, structure is simplified to be easier for calculation. In this project, the weight estimation for bow and stern is considered as average thickness stiffened plate in each 10 or 20 degrees angle changed segment regarding the shell length of the section at middle point of each segment. Error is common to see using this method, but as weight estimation in early design stage, this method is widely used in shipyards and design office.

The assessment result is shown in Table 5.2. Here we choose framing spacing 800 mm. Besides, as the height of upper ice belt is 12.7 m, near to 14 m which is the height of weather, we design ice belt trough the whole height of vessel. The upper part uses the scantling of midbody for weight assessment. The result calculated in Table 5.2 is following the result of Table 4.2.

5.2 Deck

5.2.1 Midbody

In midbody, the weight calculation method is the same with midbody of shell, adding weight of panels one by one. The result is shown in Figure 5.2.

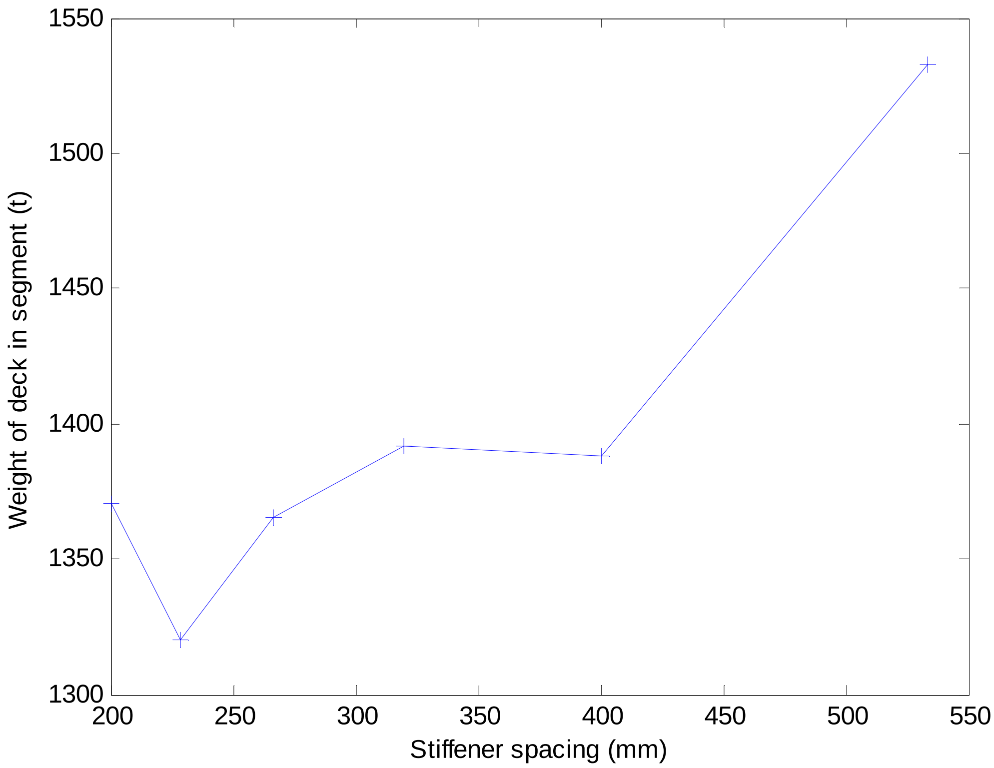


Figure 5.2 Weight of deck panels (including web frame, stringer and girder) versus stiffener spacing (weight is half of the vessel)

5.2.2 Bow intermediate and stern intermediate

The same with shell in intermediate area, the calculation is processed in 4 paralleled parts. The breadth of each deck is estimated and the weight per segment is calculated according to segment length and breadth. The result is shown in Table 5.3.

Table 5.3 Weight of deck at bow intermediate and stern intermediate region

Seg. No.	Start from Aft. end (m)	End from Aft. end (m)	Angle of hull (degree)	Weight (t) with stiffener spacing (mm)				
				400	320	267	229	200
1	8	22.4	10			592.9	573.74	588.44
2	22.4	35.2	5		480.38	474.32	459	470.74
3	94.4	100.8	5	319.78	319.76	315.02	304.6	312.88
4	100.8	105.6	10		240.18	237.16	229.5	235.38

Here, one point critical should be notified that because transversal structure is selected. The frame spacing in paralleled segments is relatively independent, which means frame spacing of midbody is 400 mm, in intermediate and two ends, frame spacing is not limited by this value.

5.2.3 Bow and stern

Regarding the scantling of grillage mentioned in former chapter, deck panel is calculated corresponding with extreme stress and compressive load requirement. Deck at bow and stern is neither cargo deck nor top/bottom of tank. But due to high ice load, the section modulus of stiffened panel is still higher than deck panel at midbody.

Table 5.4 Scantling solution of deck at bow and stern

Framing spacing (mm)	t_{ave} (mm)	Plate thickness (mm)	Height of HP profile (mm)	Web plate thickness of HP profile (mm)
1000	34.15	25	140	7
800	32.417	22	120	8
600	29.693	18.5	120	6
400	27.714	15.5	120	6
Note	Spacing of longitudinal support of deck is 1.8 m			

According to the analysis in Chapter 4.6, the scantling solutions are calculated and shown as below. Considering the hull form is different in all segments, 35 degrees is selected for this calculation to get a simplified model for weight assessment. For the region with higher intersection angle, additional strengthening is needed in real case.

In this weight assessment, the total area of decks is measured. The weight result with respect to different framing spacing is shown in Table 5.5.

Table 5.5 Weight of deck at bow and stern

Framing spacing (mm)	Weight of deck at bow (t)	Weight of deck at stern (t)
1000	147.29	136.43
800	139.82	129.51
600	128.07	118.63
400	119.53	110.72

5.3 Longitudinal bulkhead

In this vessel, most of the deep tank bulkhead exists in midbody and intermediate segments. For longitudinal bulkhead in these segments, the calculation criteria are the same. Hence watertight longitudinal bulkhead with the function of deep tank bulkhead is calculated by:

$$Weight = t_{ave} \times L_{horizontal} \quad (5\text{-}1)$$

5.3.1 Deep tank longitudinal bulkhead

Deep tank longitudinal bulkhead is widely distributed in this vessel. Most of them located at amidship and is longitudinal effective. In this design, there is no stringer between decks. According to General Arrangement and design requirements mentioned in Chapter 3, design solutions are calculated.

In the process of weight assessment, caution should be paid for double skin as there is plate web frame. Based on General Arrangement, the total length of longitudinal bulkhead in horizontal direction is measured and hence weight is calculated as shown in Table 5.6.

In real case, framing spacing of longitudinal bulkhead at double skin in different segments may be different regarding to shell and deck. Hence to have more precise result, weight of longitudinal bulkhead should be calculated by segment. This proposal can be realized combining side shell and double skin bulkhead together.

Table 5.6 Weight of deep tank longitudinal bulkhead

Location	Framing spacing (mm)	Total weight (t)
Double skin	800	259.74
	533.33	219.24
	400	205.04
	320	217.01
	266.67	230.39
	228.57	239.74
	200	245.95
Other location	800	377.77
	533.33	319.62
	400	293.55
	320	304.45
	266.67	318.22
	228.57	327.14
	200	332.37

5.3.2 Non watertight longitudinal bulkhead at bow and stern

The non watertight longitudinal bulkhead located at bow and stern, suffering ice load in longitudinal direction. Here, the form of vessel is simplified for calculation. All longitudinal bulkheads are considered as right angled triangle at bow and right trapezoid at stern (see Figure 5.3 and Figure 5.4).

In weight calculation, 60% of full weight of bulkhead will be taken into account considering manholes, cut outs and other space requirements such as propellers. According to the hull form and bulkhead spacing, we got the area of longitudinal bulkhead at bow and stern region as shown in Table 5.7.

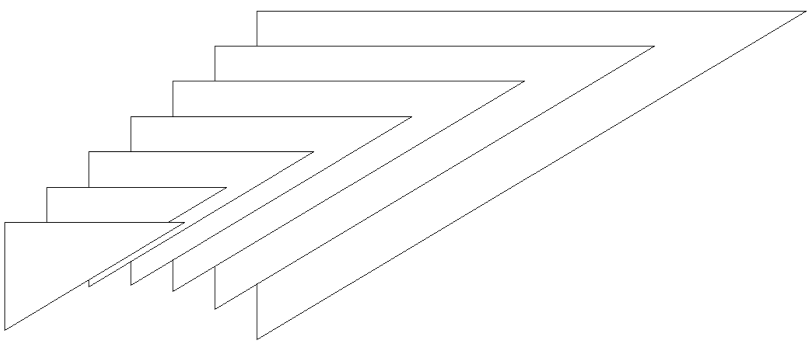


Figure 5.3 Diagram of non-watertight longitudinal bulkhead at bow (starboard half)

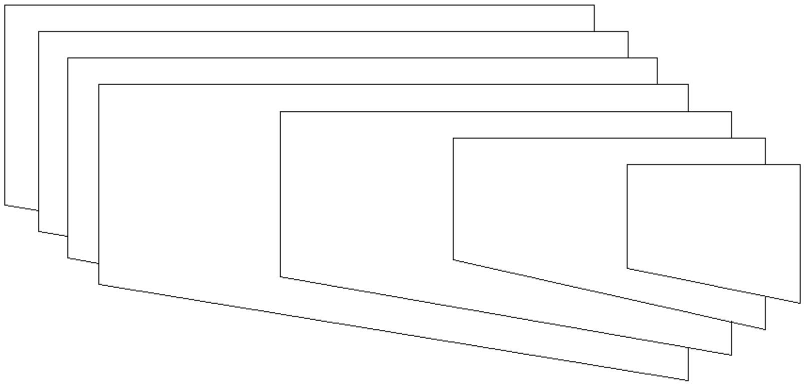


Figure 5.4 Diagram of non-watertight longitudinal bulkhead at stern (starboard half)

Table 5.7 Weight of non-watertight longitudinal bulkhead at bow and stern

Bulkhead framing spacing (mm)	Total weight at bow (t)	Total weight at stern (t)
780	178.96	194.16
557	148.08	160.7
433	131.71	142.9
355	123.71	134.2
300	120.72	131.0
260	117.66	127.7
229	121.47	131.8
205	125.27	135.9

Here we select framing spacing 433 mm for total weight calculation.

5.4 Transversal bulkhead

As to transversal bulkhead, it plays 2 roles, first is deep tank bulkhead, second is structure undertaking compressive ice load. The calculation should be made with respect to location of bulkhead. According to general arrangement, 7 water tight transversal bulkheads are distributed from bow to stern, some of which is deep tank bulkhead at the same time. Besides, some transversal deep tank bulkheads are taken into account as well as they are undertaking the ice load transmitted. Based on the section area of ship, weight of transversal bulkhead can be calculated.

According to the General Arrangement, 7 full deep tank or watertight transversal bulkheads are distributed along longitudinal direction (1 at stern, 1 at bow, 2 at stern intermediate and 3 at midbody). Regarding the analysis in Chapter 4, due to ice load, scantling of deep tank bulkhead and watertight bulkhead obtained the same optimized net result. In this weight assessment, watertight bulkhead is replaced by deep tank bulkhead considering the low percentage and small difference. For bow and stern, the average thickness is used together with section area. The weight of those full transversal bulkheads is shown in Table 5.8.

Table 5.8 Weight of full transversal bulkhead

Position from Aft. end (m)	Weight (t) with stiffener spacing (mm)						
	780	557.14	433.33	354.55	300	260	229.41
4		37.3	35.2	32.3	31.5	30.5	29.5
19.2	41.02	37.746	28.372	34.47	31.52	36.508	34.39
28.8	47.356	42.854	33.076	38.968	35.946	40.862	38.678
48	40.258	37.148	43.914	39.588	44.362	40.116	37.186
67.2	40.258	37.148	43.914	39.588	44.362	40.116	37.186
86.4	40.258	37.148	43.914	39.588	44.362	40.116	37.186
105.6		117.3	110.5	101.4	98.9	95.9	92.8
Total		346.7	338.8	325.8	331.0	324.1	307.0

5.4.1 Other transversal bulkhead at midbody and intermediate

For other non-transversal-effective bulkhead in transverse direction, the function is similar with deep tank bulkhead. But strong transversal bulkhead is good support of shell and double skin. As to the deep tank transversal bulkhead, the scantling can be the same with adjacent longitudinal bulkhead. The weight calculation method is the same with longitudinal bulkhead. The result is shown in Table 5.9.

Table 5.9 Weight of shell supporting transversal bulkhead

Bulkhead framing spacing (mm)	Shell supporting transversal bulkhead (t)	Other deep tank transversal bulkhead (t)	Total (t)
780	122.7	61.3	183.9
557	104.1	51.6	155.7
433	93.7	47.2	140.9
355	85.1	51.4	136.4
300	80.4	52.8	133.2
260	79.6	53.7	133.3
229	77.4	61.3	138.7
205	78.5	51.6	130.1

5.4.2 Non-watertight transversal bulkhead at bow and stern

In weight calculation, 60% of full weight of bulkhead will be taken into account considering manholes and cut outs. The theory is the same with non-watertight longitudinal bulkhead at bow and stern. The section data is shown in Table 5.10. Based on this, the weight can be estimate with good precision. The weight assessment is shown in Table 5.11.

Table 5.10 Data of section at bow and stern

Segment number	Start from Aft. end (m)	End from Aft. end (m)	Average section area (m^2)	Breadth (m)
1	0	5.6	70	24
2	5.6	9.6	103	27
3	9.6	13.6	115	28
4	105.6	109.6	201	24
5	109.6	113.6	133	22.4
6	113.6	117.6	80	18.2
7	117.6	121.6	45	13.6
8	121.6	130	35	12

Table 5.11 Weight of non-watertight transversal non-watertight bulkhead at bow and stern

Bulkhead framing spacing (mm)	Total weight at bow (t)	Total weight at stern (t)
557	383.11	382.57
433	360.77	360.26
355	331.02	330.55
300	323.05	322.59
260	313.03	312.58
229	303.02	302.59
205	294.17	293.75

Here we select framing spacing 433 mm for total weight calculation.

5.5 Other structure

5.5.1 Deckhouse and foundation

The structure excluding in the parts mentioned is considered in this section. The First part is deckhouse and foundation mentioned in Chapter 3.6 which is 675 t and 560 t.

5.5.2 Superstructure at bow and stern

At bow and stern, above main deck, there is structure with different function such as side wall, ice and snow shelter. According to the minimum requirement of shell for offshore supply vessel, weight of structure can be gained with area of panel. For side wall at stern, we assume 40 t taking all structure and bracket into account. For ice and snow shelter, 80 t is evaluated.

5.6 Total weight assessment

Table 5.12 Total structural weight assessment

Structure	Framing spacing (mm)	Weight (t)
Shell of midbody	400	3032.2
Shell of intermediate No.1	267	594.4
Shell of intermediate No.2	320	420.7
Shell of intermediate No.3	400	322.2
Shell of intermediate No.4	320	221.3
Shell at bow and stern	800	500.1
Deck at midbody	400	2776.4
Deck of intermediate No.1	267	592.9
Deck of intermediate No.2	320	480.4
Deck of intermediate No.3	400	319.8
Deck of intermediate No.4	320	240.2
Deck at bow and stern	800	269.3
Longitudinal bulkhead at double skin	400	205
Longitudinal bulkhead at other location	400	293.6
Non-watertight longitudinal bulkhead at bow and stern	433	274.6
Full transversal bulkhead	433	338.8
Other transversal bulkhead at midbody and intermediate	433	140.9
Non-watertight transversal bulkhead at bow and stern	433	721
Deckhouse		675
Foundation		560
Superstructure at bow and stern		120
Total		13098.8

Table 5.12 shows the total weight for PC2 with respect to the design. Using the same method, the data of other polar class can be developed.

6. COST OPTIMIZATION CONSIDERING WELDING PARAMETERS

6.1 Methodology

One of the main objectives of optimization is to decrease the cost in shipbuilding. Excepting weight of material, another two critical indexes of total cost are part number and welding cost. The total number of part is an important parameter affecting the complexity of ship production engineering. Less part number not only means easier BOM and lower management difficulty, but also can reduce manufacturing cost to some extent.

In old time, ships were being constructed by using clinches. Nowadays, welding is the most widely used technology in ship building industry. The connection of metal part commonly uses a variety of welding methods regarding different feature parameters [18].

These features parameters can be separated into two types, technical parameters such as basic metal, thickness, assembling type, welding position, welding process, number of re-starting, welding intensity, type of current, electrode diameter, electrode output, protection gas density, and geometric parameters such as weld section, height of welding [19].

Welding is so complicated that here, only welding length is selected as the consideration of welding cost. With more practical cost information, this welding cost optimization can be calculated with higher accuracy and precision.

As we defined, the calculation is strictly identified in complete panels. Also, considering the complexity of structure, the structure and cost optimization is designed for midbody and intermediate segments. In general, for plate elements, part number and welding length has almost the same result with the same general arrangement. So the optimization is based on the calculation of total part number and total welding length excluding plate and the boundary element of panels.

The optimization is trying to make a good balance between structural weight and production cost. Hence pareto frontier theory is selected to look for the best solutions which are dominant in all the possible results, which means the best solution with different weight of preference. Regarding to different requirement and additional information, right solution could be selected for a good balance.

6.2 The structure optimization considering weight and part number

6.2.1 Shell

As shown in Chapter 4.2, the smaller stiffener spacing means smaller weight. While obviously, part number and welding length in total will increase. The following diagrams in Figure 6.1 and Figure 6.2 quantitatively exhibit the relationship between panel weight and part number. From these figures, we found all solutions with different stiffener spacing get unidirectional curvature which means all solutions are dominant. Hence the scantling should take more information into account before identifying stiffener spacing.

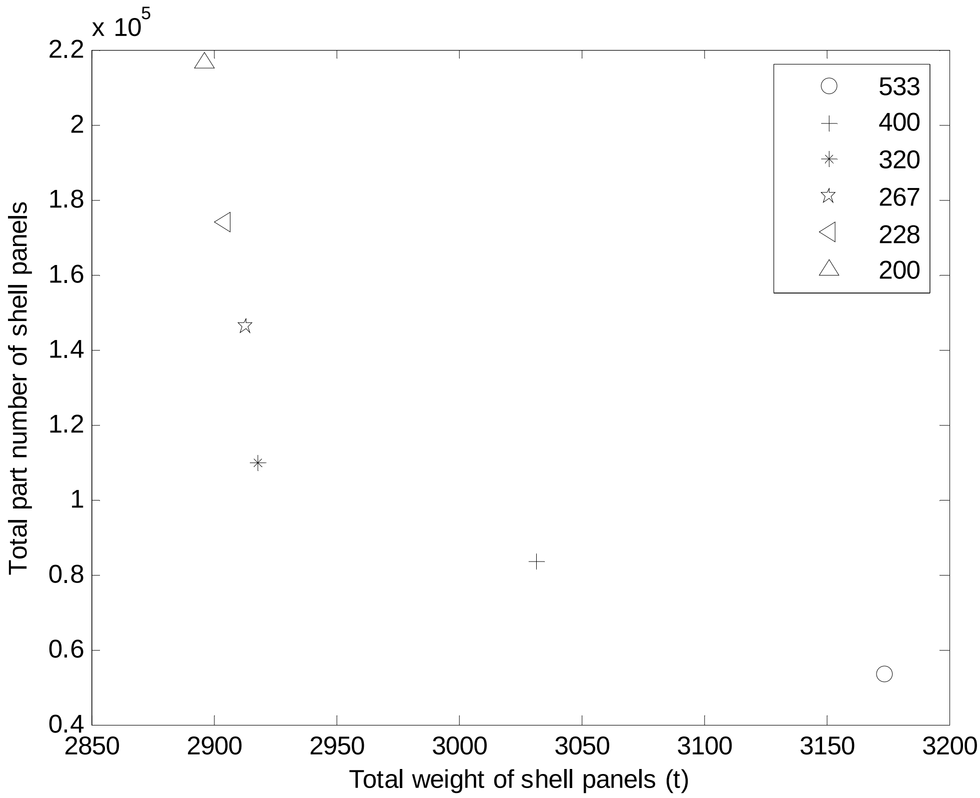


Figure 6.1 Total shell panel part number versus weight of shell structure at midbody

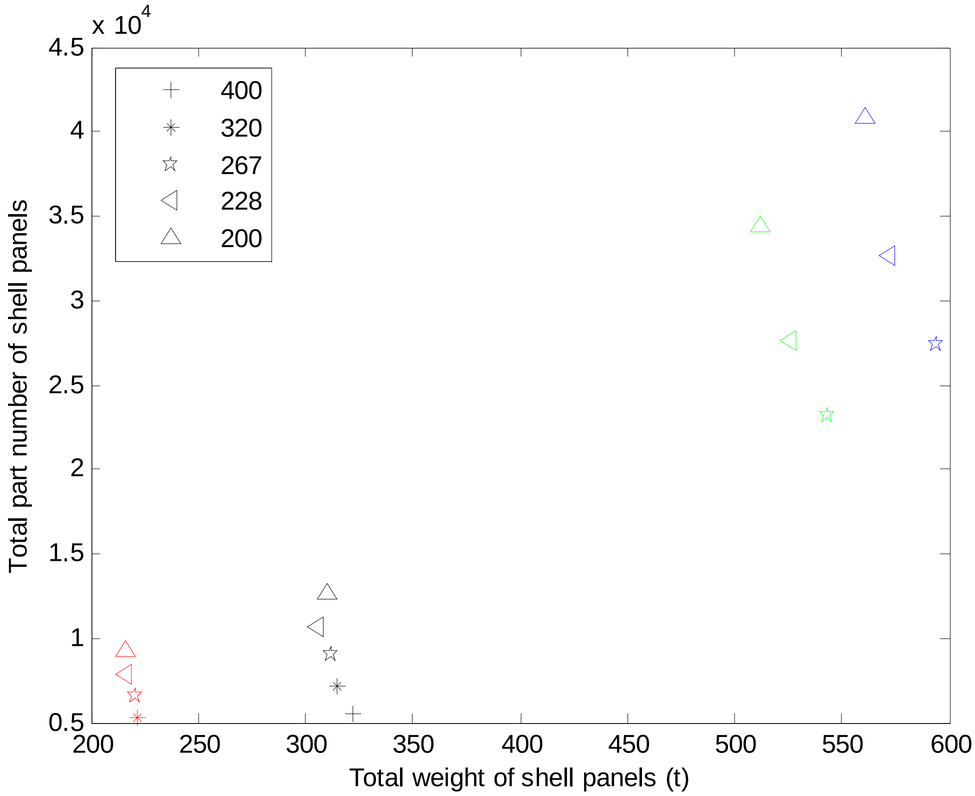


Figure 6.2 Total shell panel part number versus weight of shell structure at intermediate (From right point group to left group: Shell of intermediate No1, 2, 3, 4)

6.2.2 Deck

The cost analysis of deck is the same with shell panels. We divide the analysis into midbody and intermediate segments to ensure a flexible result. Figure 6.3 shows the quantitative relationship of panel weight and part number at midbody, and Figure 6.4 shows the relationship at intermediate segments.

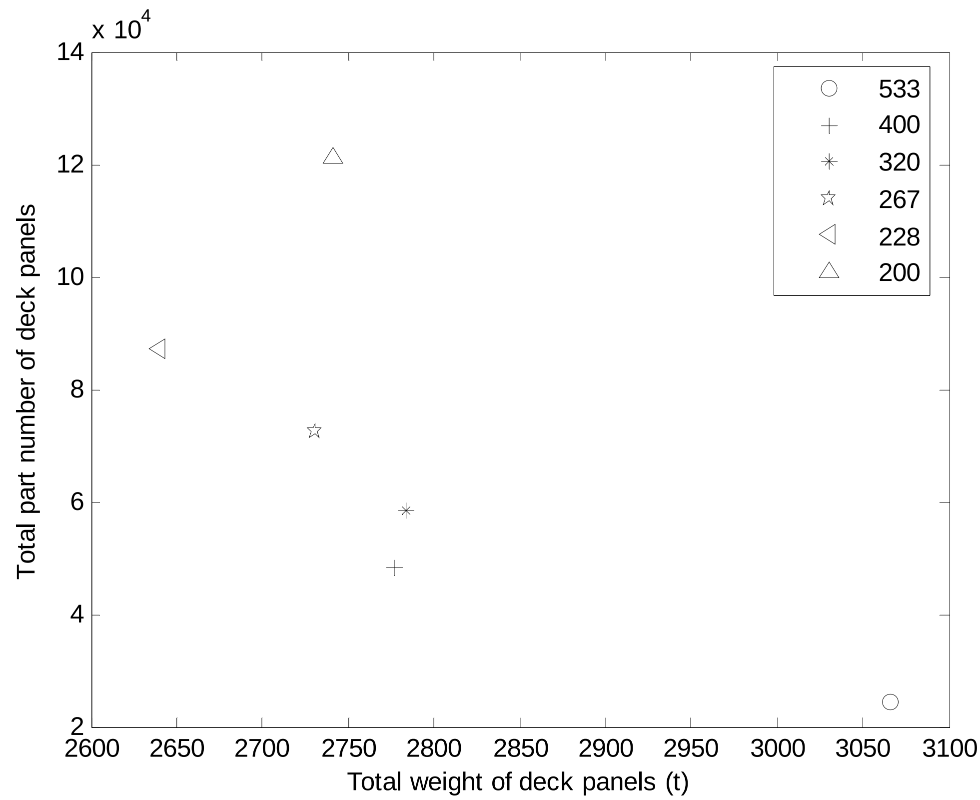


Figure 6.3 Total deck panel part number versus weight of shell structure at midbody

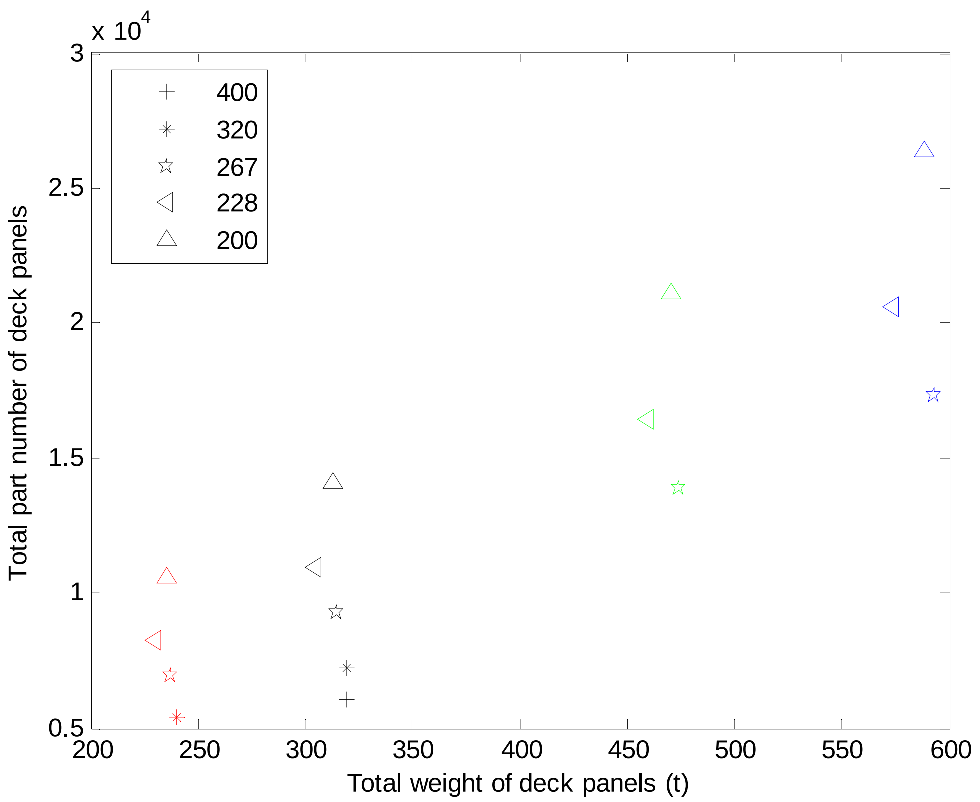


Figure 6.4 Total deck panel part number versus weight of shell structure at intermediate (From right point group to left group: Shell of intermediate No1, 2, 3, 4)

As Figure 6.3 shows, the dominant cases are only when stiffener spacing is 228, 267, 400 and 533 mm. At intermediate segments, similar situation appears.

6.2.3 Longitudinal bulkhead

In Chapter 4.4, the tendency of weight difference versus stiffener spacing is discussed. In general, the smaller stiffener spacing means lower longitudinal bulkhead weight. While obviously, part number and welding length in total will increase. The following diagrams in Figure 6.5 to Figure 6.7 quantitatively exhibit the relationship between panel weight and part number. As the scantling of panels at the same height is the same, average thickness of panel is selected to replace the panel weight.

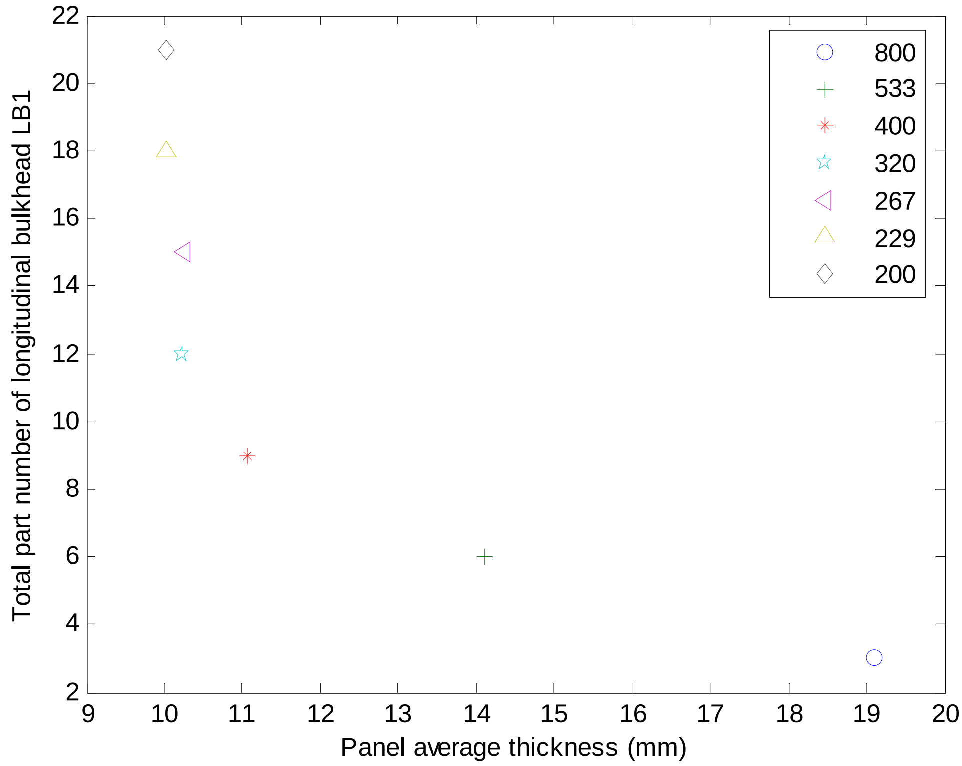


Figure 6.5 Total part number versus panel average thickness (LB1)

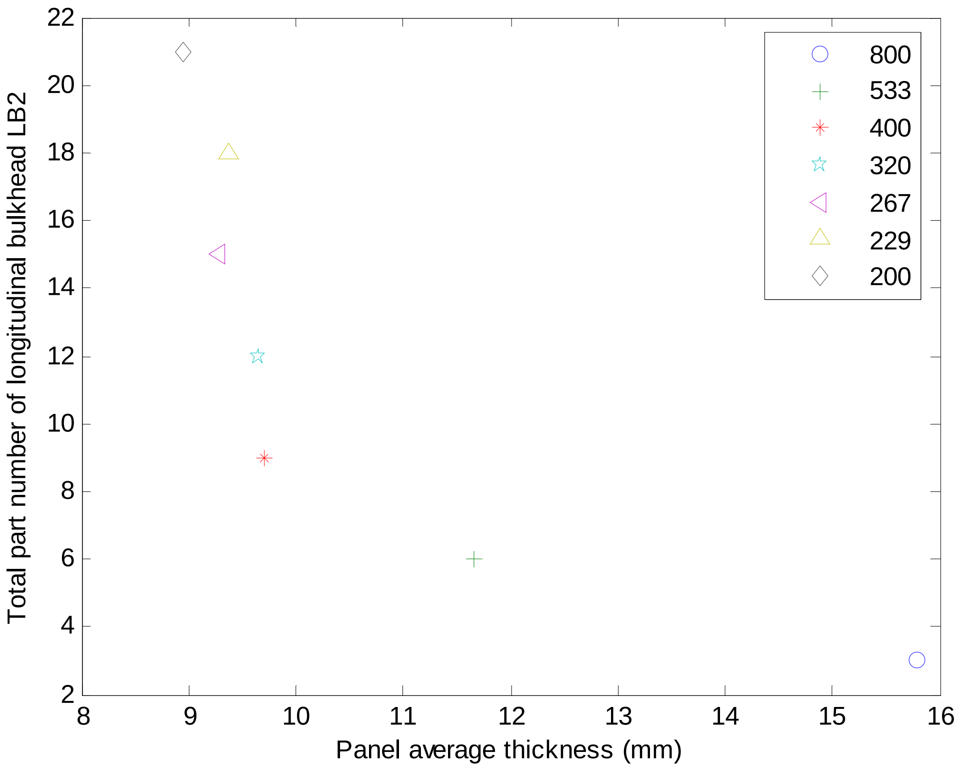


Figure 6.6 Total part number versus panel average thickness (LB2)

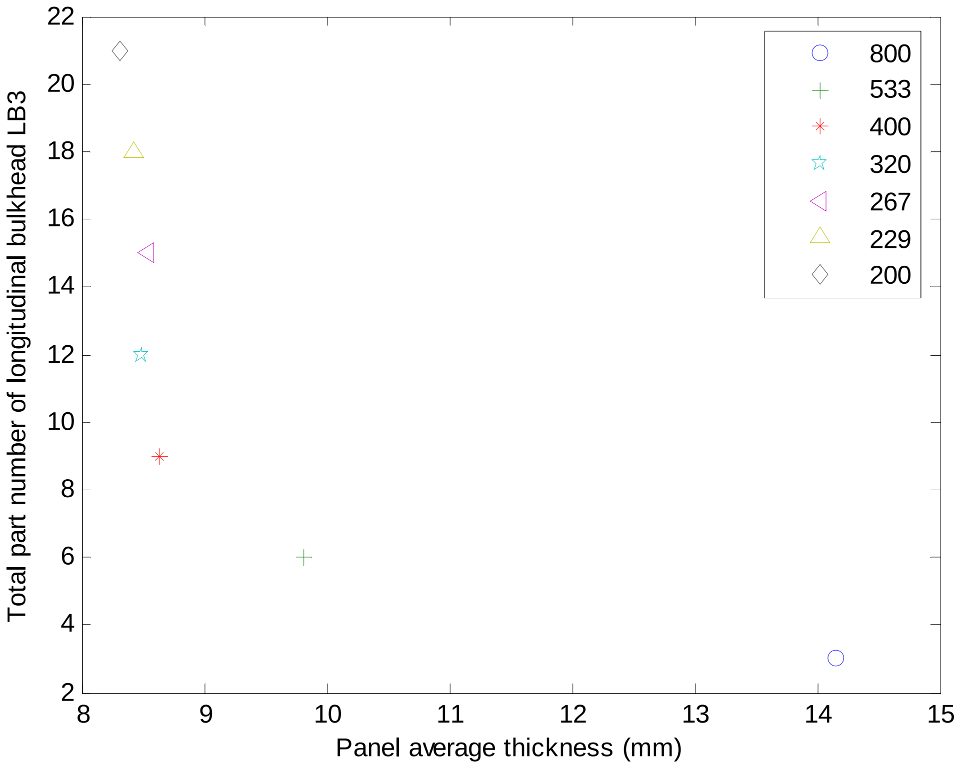


Figure 6.7 Total part number versus panel average thickness (LB3)

Using Pareto Frontier diagram, regarding different weight of factors, we can choose the most applicable scantling for structure.

6.2.4 Transversal bulkhead

As it shows in Chapter 4.5, the minimum weight is calculated when the stiffener spacing is in the range of 300-600 mm, which means the tendency will be different from the Pareto Frontier line. In this chapter, we only take 3-horizontally-adjacent panel case as example (see Figure 4.13).

As the result in Figure 6.8 shows, the case of stiffener spacing 780 mm, 557 mm, 433 mm and 355 mm occupy the dominant position. Regarding the gradient shown in the diagram, stiffener spacing of 577 mm is more appropriate as its smaller part number and slightly higher weight.

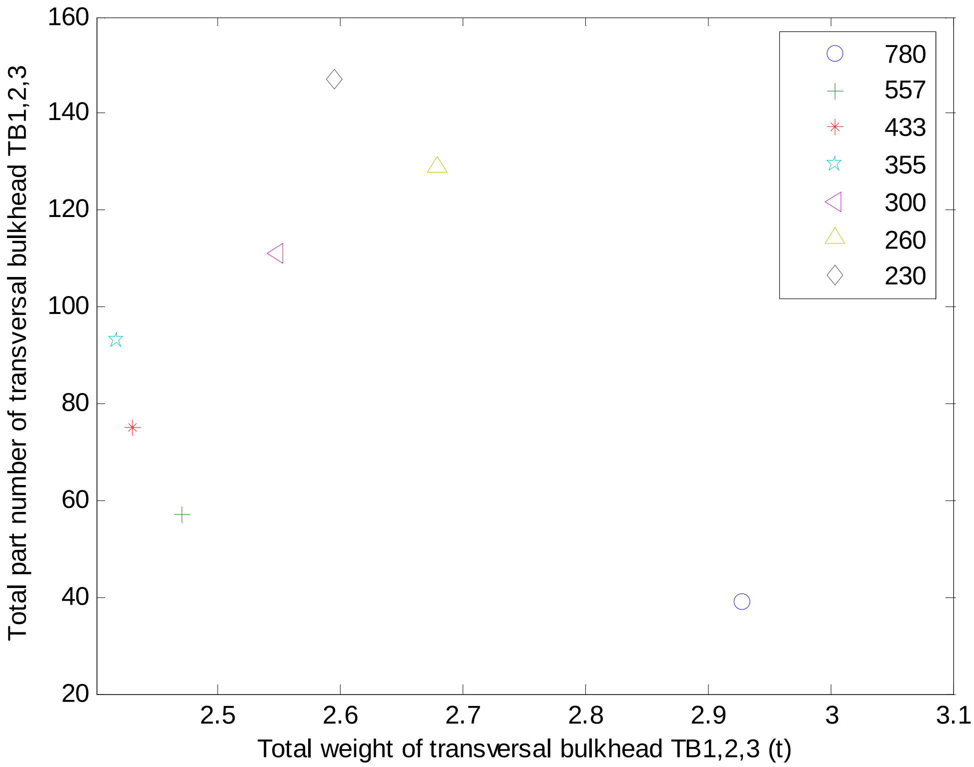


Figure 6.8 Total part number versus weight of panel (TB1,2,3)

According to the same theory, pareto frontier diagram is calculated for TB4,5,6 and TB7,8,9 are shown in Figure 6.9 and Figure 6.10.

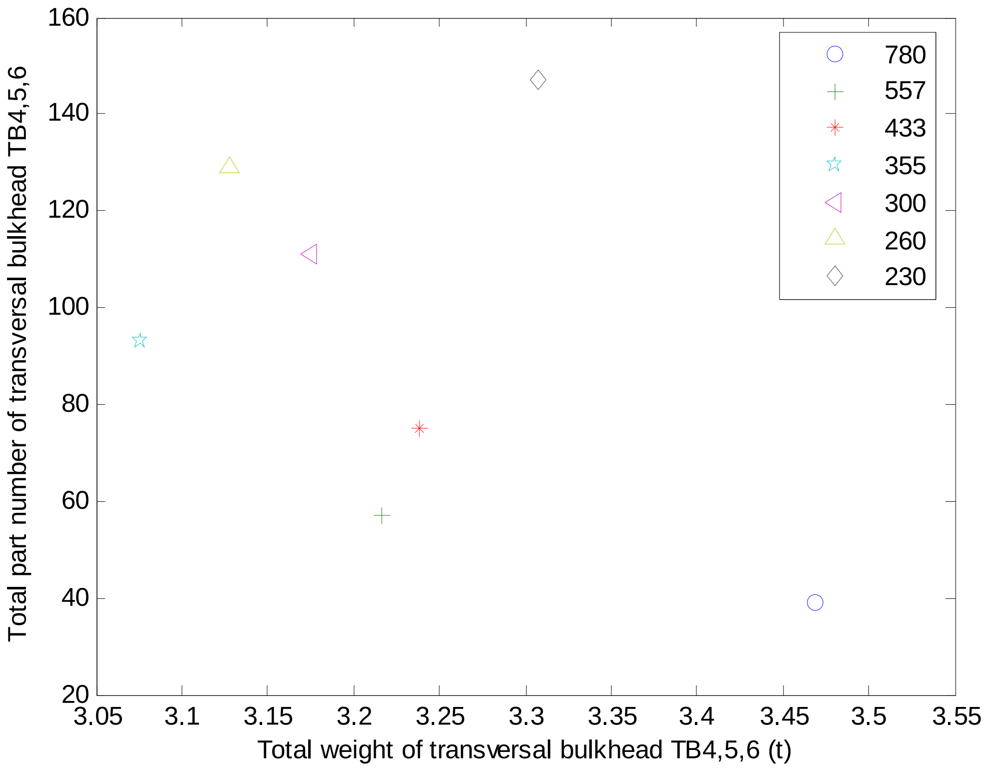


Figure 6.9 Total part number versus weight of panel (TB4,5,6)

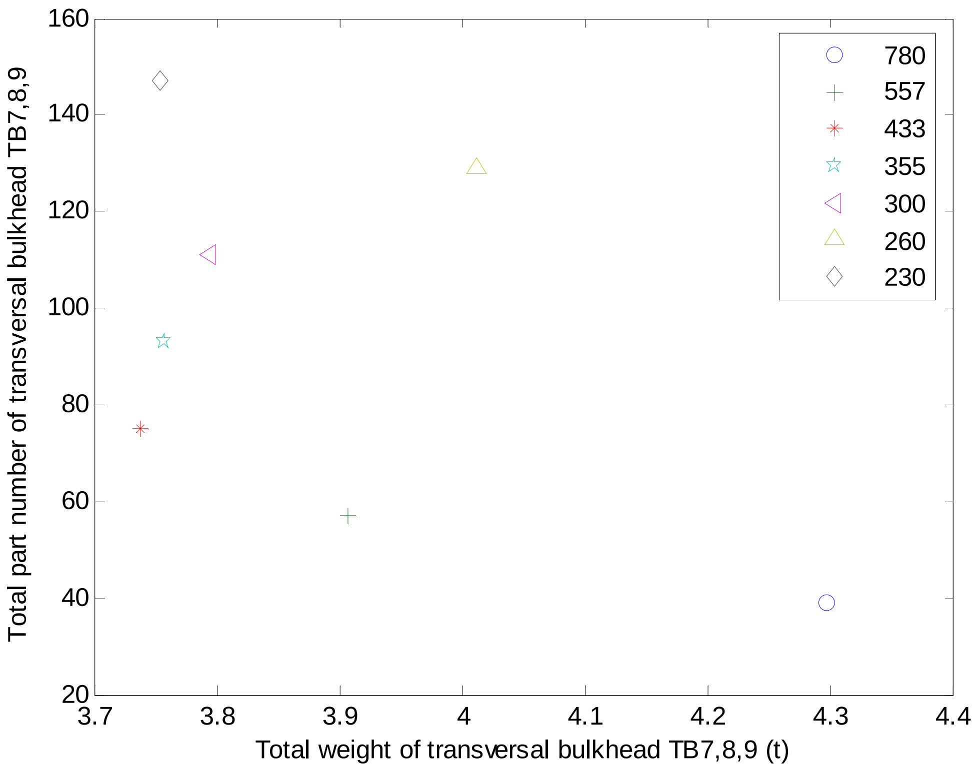


Figure 6.10 Total part number versus weight of panel (TB7,8,9)

As the result in Figure 6.9 shows, as to the panel group of TB4, TB5 and TB6, the case of stiffener spacing 780 mm, 557 mm and 355 mm occupy the dominant position. Nevertheless, the optimization calculation of panel group of TB7, TB8 and TB9 shows the dominant position are occupied by the case of stiffener spacing 780 mm, 557 mm and 433 mm.

6.3 The structure optimization considering weight and total welding length

6.3.1 Shell

The welding length includes the welding length of the connection of stiffener and plate, bracket and stiffener or plate. The result is shown in Figure 6.11 and 6.12.

From the Figures we can see the averagely dominant solutions change gradually. At stern intermediate segments, some of solutions lose dominant positions.

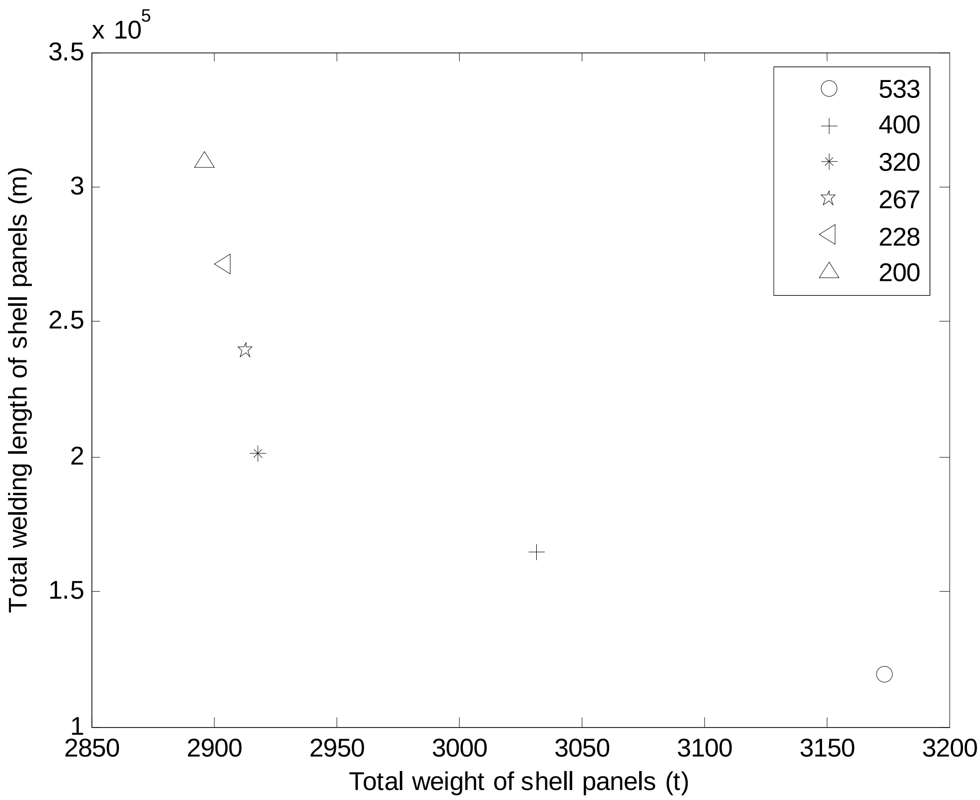


Figure 6.11 Total welding length versus weight of shell structure at midbody

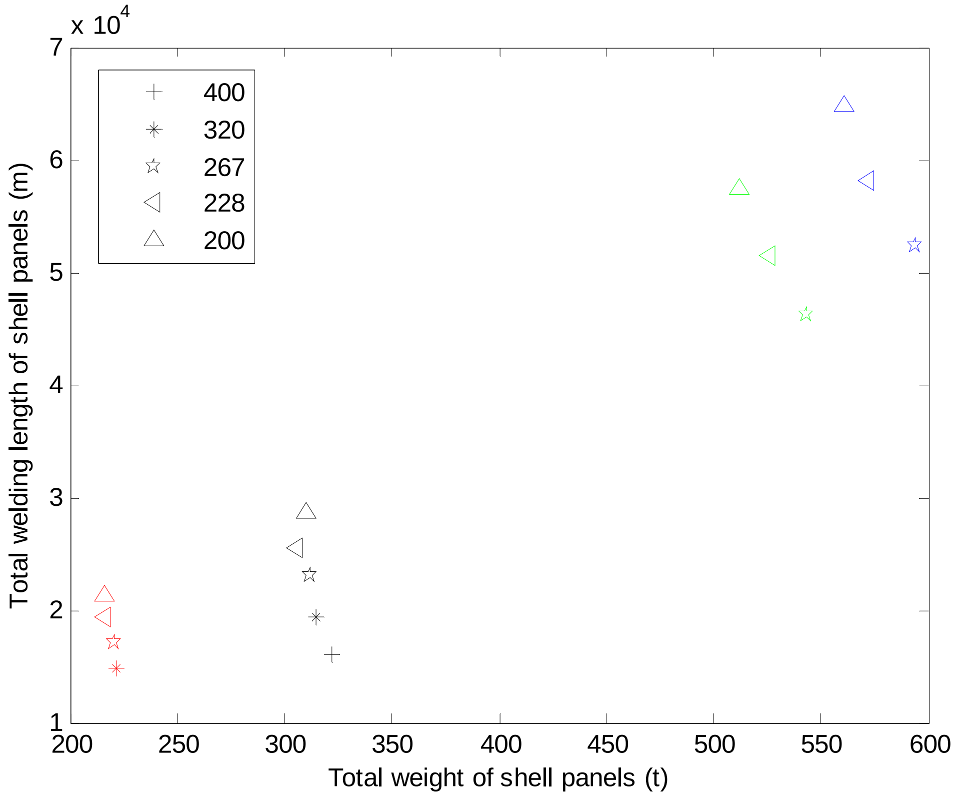


Figure 6.12 Total shell panel welding length versus weight of shell structure at intermediate (From right point group to left group: Shell of intermediate No1, 2, 3, 4)

6.3.2 Deck

Following the same method, the quantitative relationship of welding length and weight of deck panel is shown in Figure 6.13 and Figure 6.14. It is observed that bigger stiffener spacing seems more efficient in both weight and welding length, especially at intermediate segments.

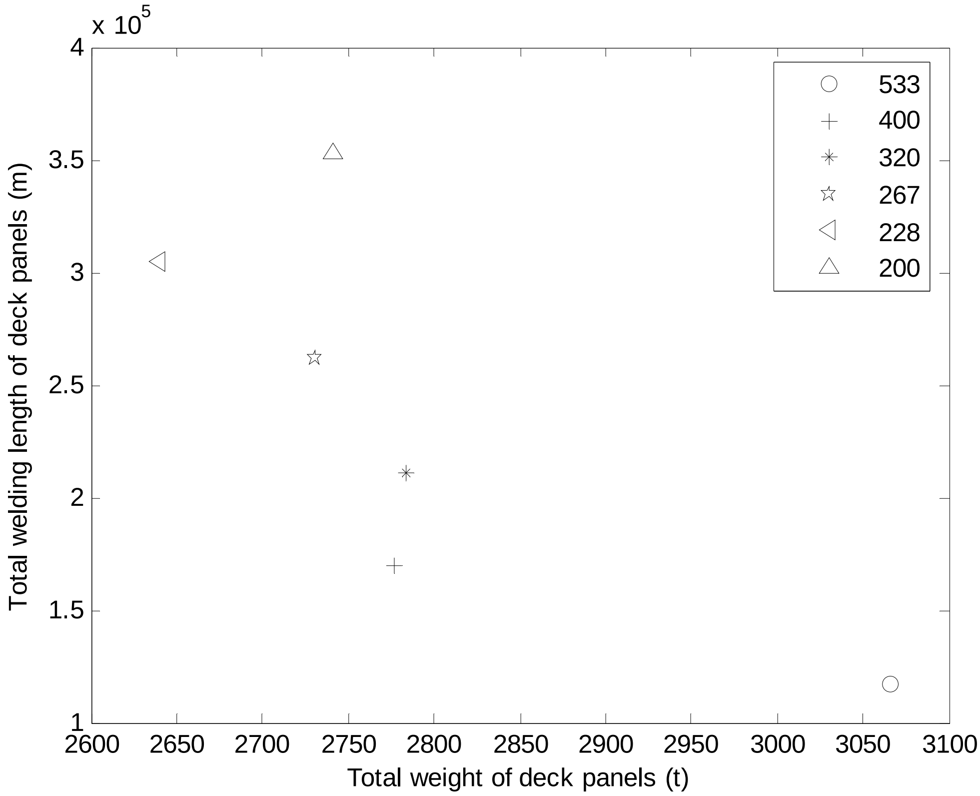


Figure 6.13 Total welding length versus weight of deck structure at midbody

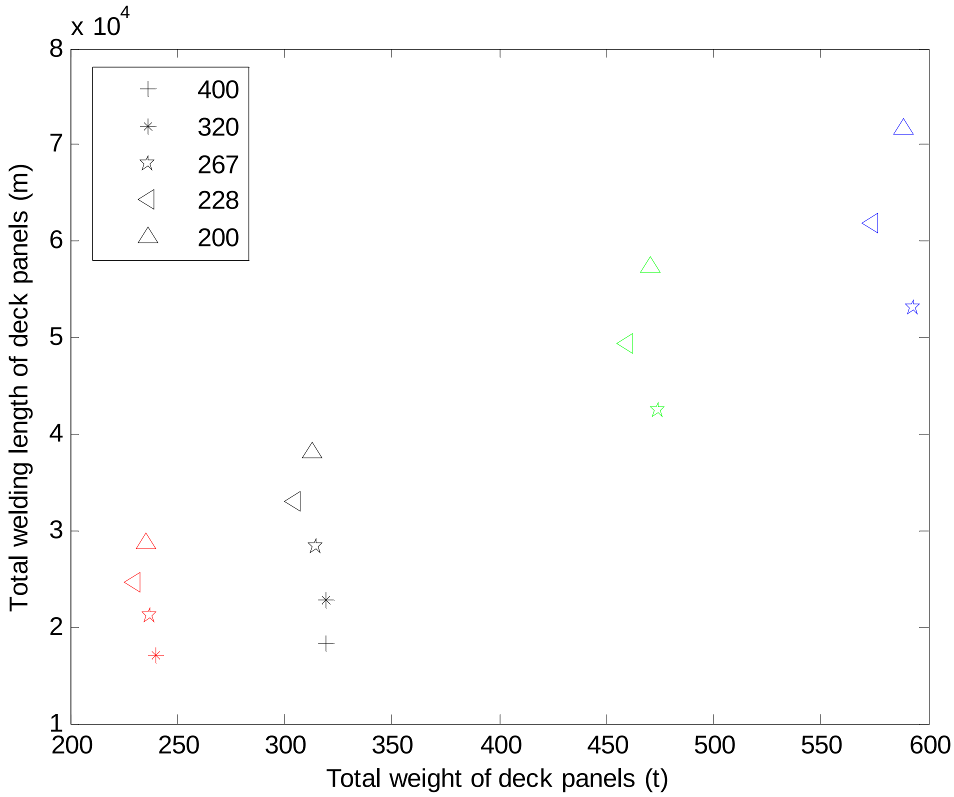


Figure 6.14 Total deck panel welding length versus weight of shell structure at intermediate (From right point group to left group: Shell of intermediate No1, 2, 3, 4)

6.3.3 Longitudinal bulkhead

The following diagram in Figure 6.15 quantitatively exhibits the relationship between panel weight and part number. Here, the result of different panel group is combined in one figure.

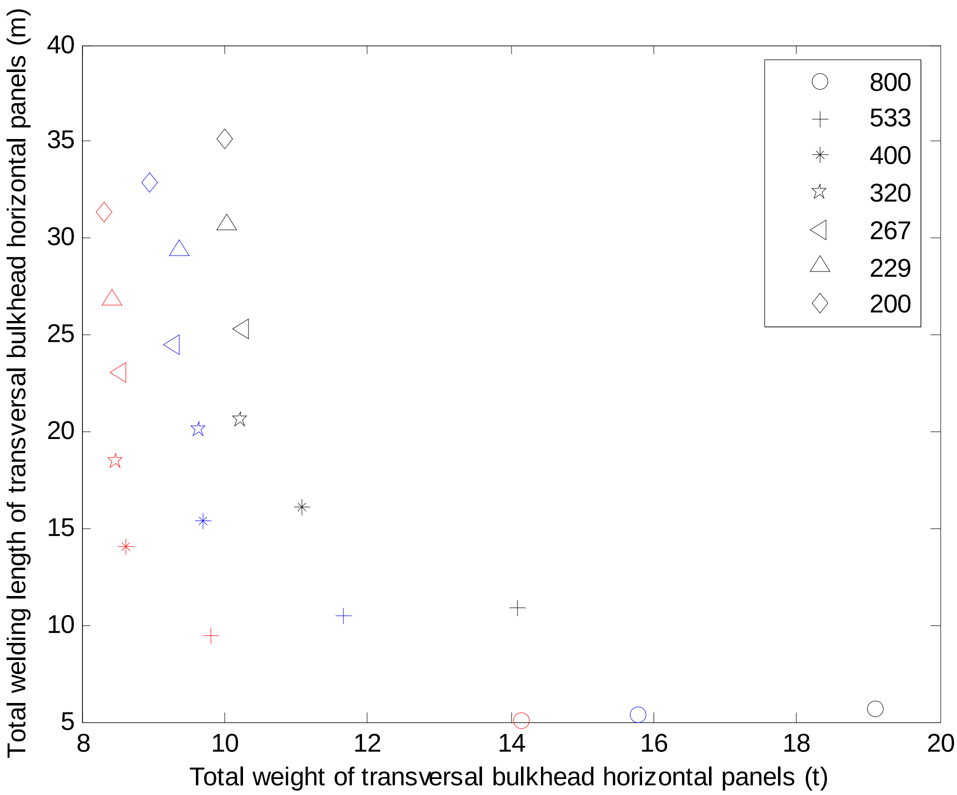


Figure 6.15 Total welding length versus weight of panel (Left: LB3; Middle: LB2; Right: LB1)

6.3.4 Transversal bulkhead

As to 3-horizontally-adjacent-panel case, the result can be observed in Figure 6.16. As it shows, the case in dominant position is the same with the one in the analysis of part number versus weight, which clearly prove the strong and direct relationship of part number and welding length, which differ from the number of stiffeners.

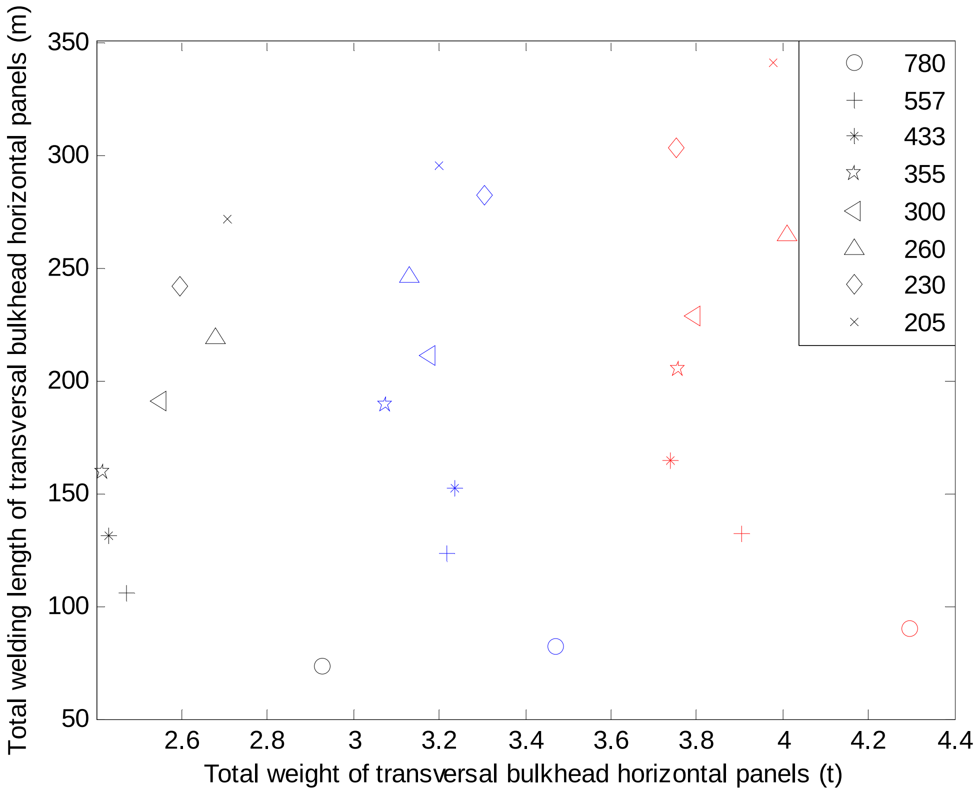


Figure 6.16 Total welding length versus weight of panel (Left: TB1,2,3; Middle: TB4,5,6; Right: TB7,8,9)

6.4 The global optimization

To summarize the analysis, we combine the main part, structure of shell (including web frame and floor), deck, longitudinal bulkhead which occupy about 75% of weight in total. Besides, structure at midbody and intermediate has relatively lower flexibility of design and optimization which is beneficial for optimization development. In this simplified model, we got tens of thousands of solutions. The result is shown in Figure 6.17 and Figure 6.18.

The result shows obvious conclusion that comparing with Figure 6.1 to Figure 6.4 and Figure 6.11 to Figure 6.14, higher similarity exists between these figures and the diagrams of deck panel. This prove the difference mainly come from deck panel. Besides, this again emphasize on the importance of stiffener spacing.

As result of weight shows, the weight of deck and shell in mentioned segments is quite similar, but the weight deck is more sensitive to stiffener spacing. Checking the optimization process, compressive load is the primary reason resulting in this phenomenon.

Analyzing from Figures, stiffener spacing 228, 320 and 400 mm could be more applicable.

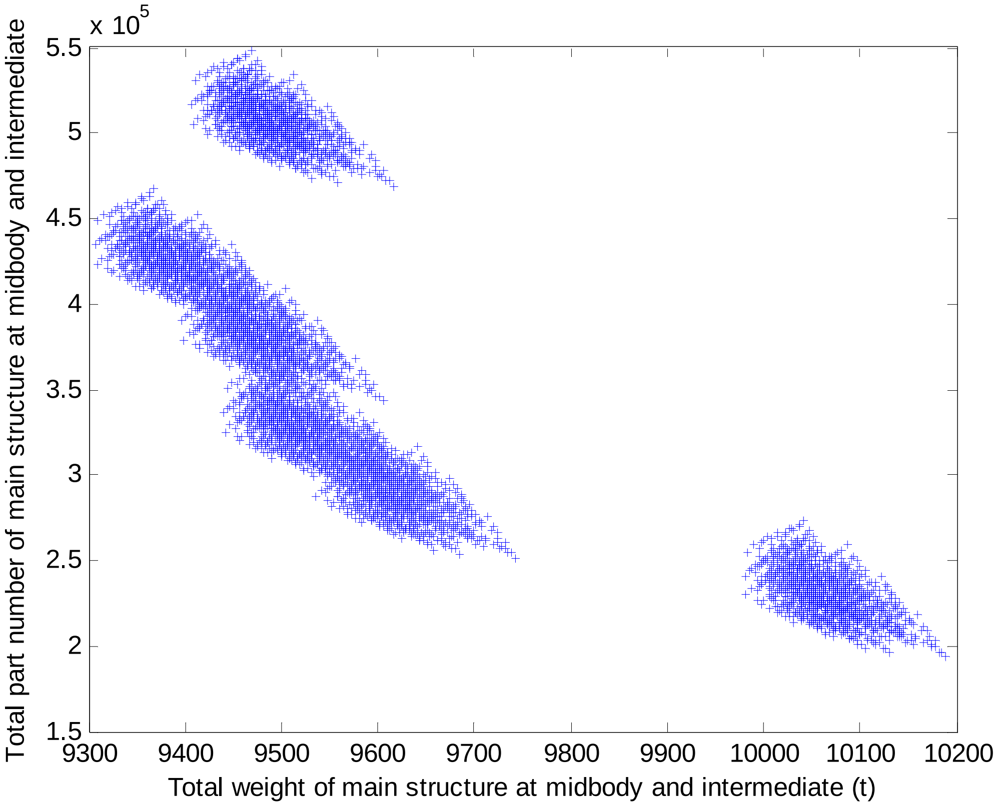


Figure 6.17 Total part number versus weight

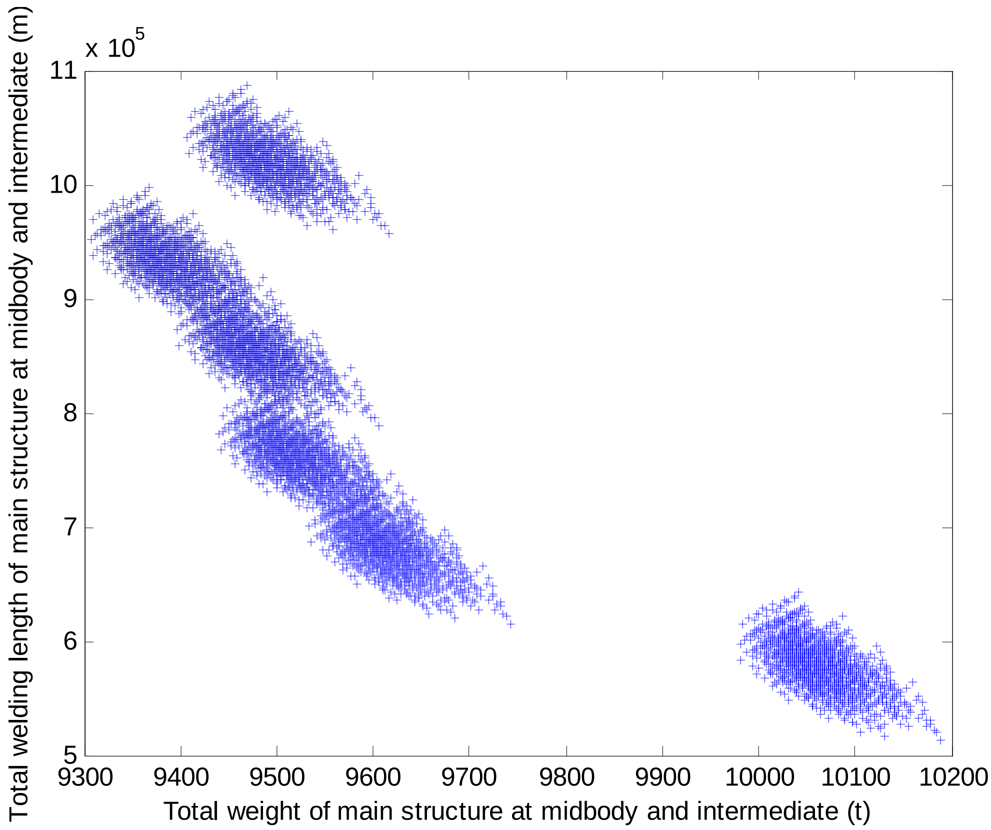


Figure 6.18 Total welding length versus weight

7 DESIGN CHECK

7.1 Scantling check in Rules Calc

This structural design optimization is processed according to the rules. Hence the first check should be operated following the rules.

RulesCalc is software developed by Llyod’s Register for scantling of ship. In this software, scantling modeling of different sections can be made and the design could be checked by automatically corresponded criteria in different panels. It can check the longitudinal scantling with respect to the longitudinal section modulus and longitudinal strength. The disadvantages are first, this software is only valid for longitudinal structure but not transversal elements, which means transversal frame can’t be checked, second, no additional rules for polar class ship are taken into account.

With respect to the design proposed, scantling check in RulesCalc is processed.

Taking ice load transversally executed into account, the thickness of plate is surely bigger than general ship need to check global bending moment and shear force. In other words, in fact, longitudinal strength is not issue of polar class ship. So ANSYS is inducted to prove the design undertaking the local loads in transversal direction.

7.2 Finite element analysis check

As the representative software processing finite element analysis, ANSYS is widely used in engineering, industry and scientific research worldwide, contributing persuasive analysis result in the field such as structure, thermal and so on. ANSYS is also widely used in ship design industry for stress and vibration analysis.

For ship structure analysis, elastic design theory is commonly used. While in polar class case, this design method is not recommended by no matter scientific researchers or classification societies.

7.2.1 Plastic design theory

According to the identification of ice load in the rules, ice load is glancing impact but not static pressure. But in fact, IACS identified the ice load as static pressure for calculation, which means compromised method needs to be operated. In scientific research, with respect to the critical transversal compression due to the ice, buckling and ultimate strength of plates should be checked by using a simplified model.

Plastic design has become the criteria for ice class ship design. Scientists developed different methods verifying the applicability of plastic hinge theory for polar class ship design. The new IACS unified polar rules employ plastic design methods [20].

Plastic theory is a unrealistic method since steel structures do not fail when the edge stress of cross section reaches the Yield point, and will continue to withstand the load as long as the central core of the section remains within the Elastic State. The stress-strain curve of plastic design theory is shown in Figure 7.1[21].

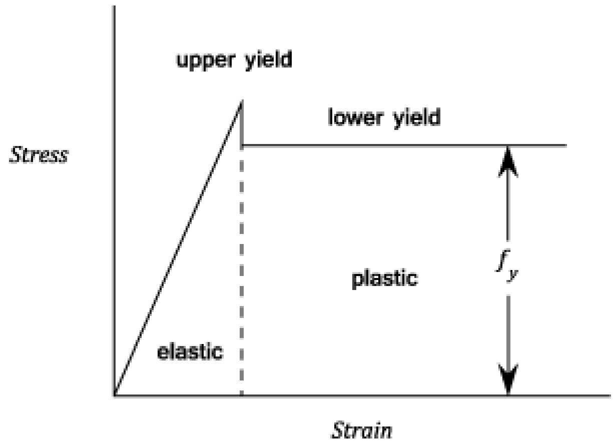


Figure 7.1 Stress-strain curve of plastic design theory

The difference of elastic theory and plastic theory can be explained with correspond with Figure 7.2. In real case, when stiffened panel is suffering bending moment, the strain on the section likes the figure in case (a). According to elastic theory, the relationship of strain and stress is linear, which means the diagram the maximum stress happens first on one of the end of the section which depends on the location of neutral axis, which means panel start the process to failure if the maximum stress reach yielding point. On the other hand, plastic theory assumes the stress is averagely distributed on the section as shown in (a). With the increase of bending moment, more region on section reach yielding point. To simplify the question, the extreme situation is considered as (b) shown [22].

In this simplification, when stress of the whole section reaches yielding point, allowing some plastic deformation, structure meets its ultimate bending moment. Regarding to this bending moment, panel could be designed.

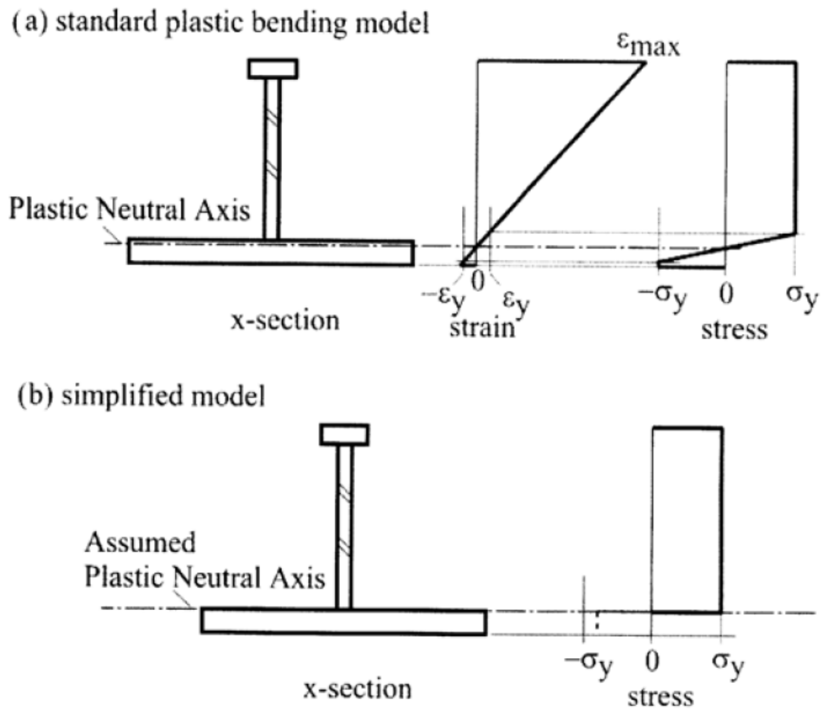


Figure 7.2 Plastic design theory

There are several main advantages using plastic hinge theory for ice class ship design. Compare with elastic design, plastic design ensures a considerable strength reservation in case of extreme ice loads, which can ensure a better balance of material distribution to resist design and extreme loads. Besides, plastic design allows considerably lighter structure, particularly when the return period for design loads is relatively long and when cumulative damage is not a major consideration. At last, this method is more applicable to damage analysis.

These considerations tie in well with actual operating practice for ice class ships. Occasional local deformation (denting) has tended to be an acceptable consequence of ice operations, provided that this does not compromise the overall strength or watertight integrity of the ship.

Scientific research shows that the selection of structural design criteria for plastic design is more difficult than in elastic design. In plastic design theory, many possible limit states ranging from yield through to final rupture are defined.

The IACS URs have selected a set of limit states for plating and framing design which allow substantial plastic stress but preclude the development of large plastic strains or structural deformation. The process for these requirements has devoted considerable effort to the selection of suitable design criteria [23]. These limit states are defined by analytical representations of mechanisms within the frame or plate due to the needs of design and classification process. The analytical solutions are based on energy methods, assuming the mechanisms shown in Figure 7.3 and Figure 7.4, for loads at the centre and near the ends of framing, respectively.

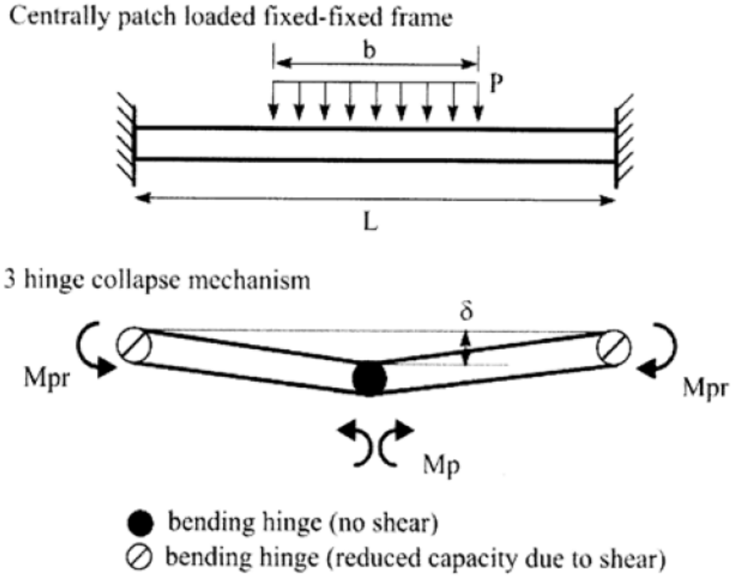


Figure 7.3 Symmetrical loading case, 3-hinge assumption

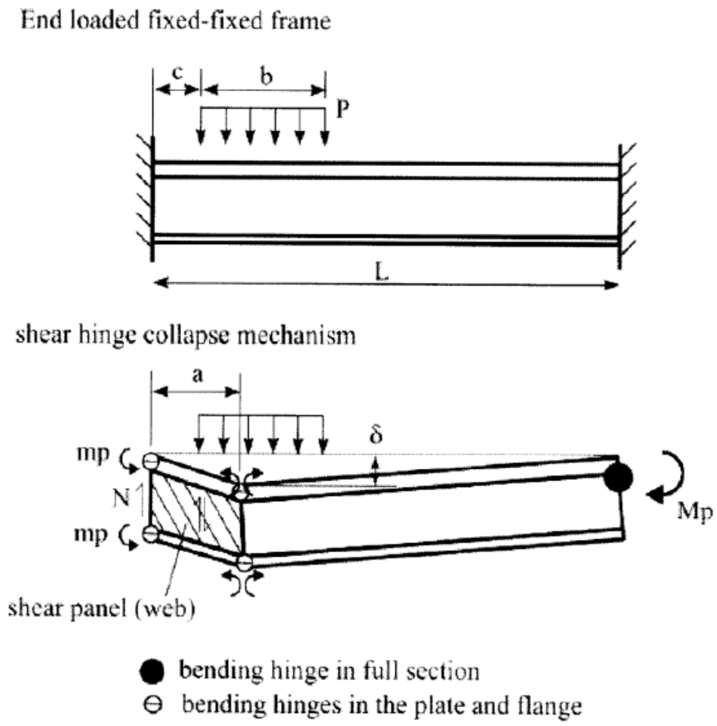


Figure 7.4 Asymmetrical loading case, 3-hinge assumption

The relationship of elastic and plastic theory could be explained by the following deduction: We assume *b* is width and d is depth of a rectangular section, total loads above and below the neutral axis are both *bdf*/2 that each acting at *d*/2 from the neutral axis. Hence, the plastic moment is:

$$M_P = (\frac{bd}{2})f \cdot \frac{d}{2} = \frac{bd^2 f}{4} \tag{7-1}$$

The working moment with load f_w is:

$$M_w = Zf_w = \frac{bd^2 f_w}{6} \tag{7-2}$$

While based on elastic theory, the moment is:

$$M_E = Zf = \frac{bd^2 f}{6} \tag{7-3}$$

According to Eqs. 7-1, Eqs. 7-2 and Eqs. 7-3, we have:

$$M_P = S\left(\frac{f}{f_w}\right)M_w = SZf \tag{7-4}$$

The ratio of M_P/M_E, which called the shape factor, for the rectangular section is S=1.5 according to Eqs. 7-3 and Eqs. 7-4. This means using plastic theory could take 50% more load f.

Besides, some researches show that plastic theory still reserves the strength of structure. Two main reasons are that the assumed mechanisms ignore the effects of membrane stresses and strain hardening. As a result the real structure will have a substantial reserve capacity. The design limit states represent a condition of substantial plastic stress, prior to the development of large plastic strains and deformations, but where the structural elements are starting to show significant losses in stiffness. Permanent deflections under the design loads should not require repair, and should not be sufficient to cause damage to internal or external coatings.

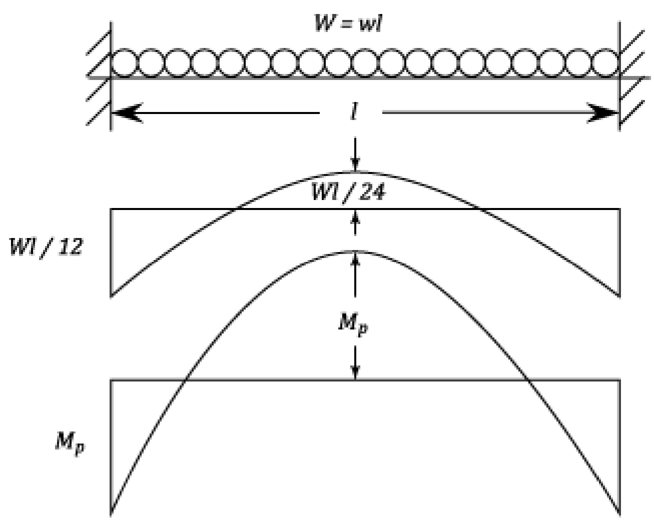


Figure 7.5 Beam with uniformly distributed load

With respect to deformation, there is difference between two theories as well. Here we take a beam with uniformly distributed load as an example (see Figure 7.5). In this example, as the loading is symmetrical, these will be at either end or in the centre. The Bending Moment diagram is then constructed by making the values at these points equal to M_P. l is the length of beam. By inspection it can be seen that the reactions at the ends are $6M_P/l$ and hence at the centre:

For plastic hinge theory, with collapse load W_c, we have:

$$M_P = \frac{lW_c}{16} \tag{7-5}$$

According to elastic theory,

$$M_E = \frac{lW}{12} \tag{7-6}$$

From Eqs. 7-5 and Eqs. 7-6, we have:

$$W_c = \frac{16S\left(\frac{f}{f_w}\right)M_E}{l} = \frac{4}{3}S\left(\frac{f}{f_w}\right)W \tag{7-7}$$

Hence load factor is:

$$\frac{W_c}{W} = \frac{4}{3}S\left(\frac{f}{f_w}\right) \tag{7-8}$$

To sum up, generally speaking, using plastic theory, the load capacity of structure could increase about 1 time, which greatly increase the allowed stress. In case of this design, the allowed stress increases from 355 MPa to 532.5 Mpa according to plastic hinge theory, and 710 MPa for collapse.

7.2.2 Finite Element Analysis using ANSYS

In finite element method, the process of plastic deformation is nonlinear, which needs much higher requirements and more time to get convergence. We first make analysis in ANSYS using elastic theory, the result shows the issue is on shell, which is quite similar with plastic hinge beam model with rectangular cross-section. Hence, elastic theory is acceptable for finite element analysis. Nevertheless, the result should be transferred and checked with the result in plastic theory criteria.

Considering the quantitative relationship between elastic and plastic theory, elastic finite element analysis can replace plastic analysis to save time. In this elastic analysis, shell63 (see

Figure 7.6) is selected as element type.

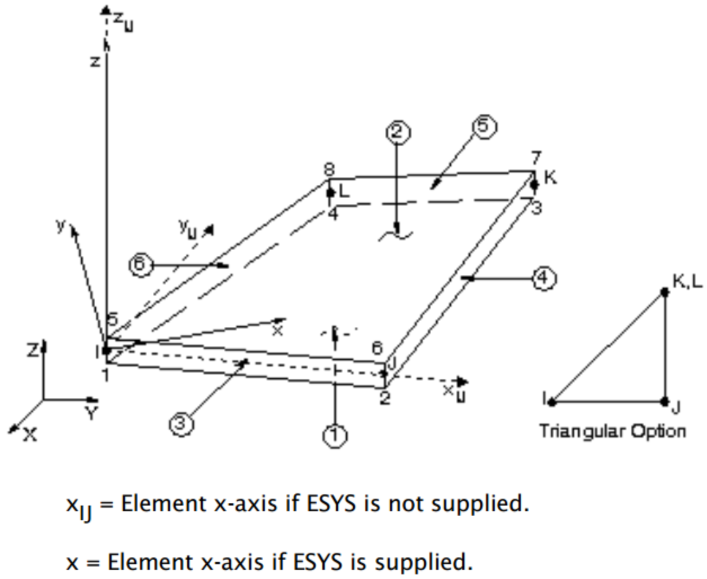


Figure 7.6 Shell63 geometry

SHELL63 element is a typical elastic shell element. The element has both bending and membrane capabilities. Both in-plane and normal loads are permitted. Shell63 has six degrees of freedom at each node: translations and rotation in or around the nodal x, y, and z directions. Stress stiffening and large deflection capabilities are included. A consistent tangent stiffness matrix option is available for use in large deflection (finite rotation) analyses.

This FEA is developed to check the strength of structure undertaking ice load in transverse direction. Hence one segment at midbody between two web frames is selected. Following the scantling mentioned in Table 5.12, geometry of model is built (see Figure 7.7).

Regarding the precision of analysis, the element size of meshing is defined as 30 mm at the region of ice load patch and adjacent area, and 50 mm at other region (see Figure 7.8). According to the identification of peak ice pressure in Table 2.3, we simplify that the peak pressure is loaded on a load patch of 400×400 mm, which is the second patch from right at the lower row (see Figure 7.9). Different boundary conditions are identified on the edge of panels and plates according to specific location. The ice load is following the value calculated in Table 2.2. The analysis result is shown From Figure 7.10 to Figure 7.11.

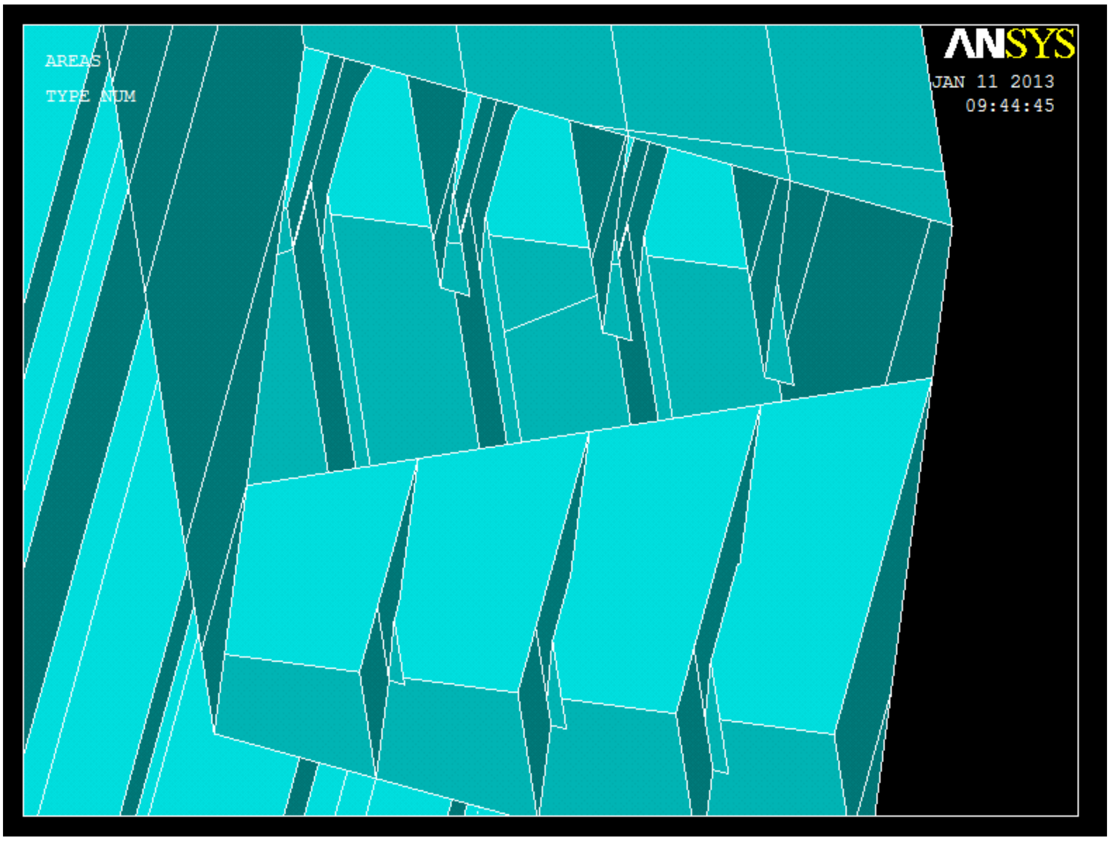


Figure 7.7 Model geometry

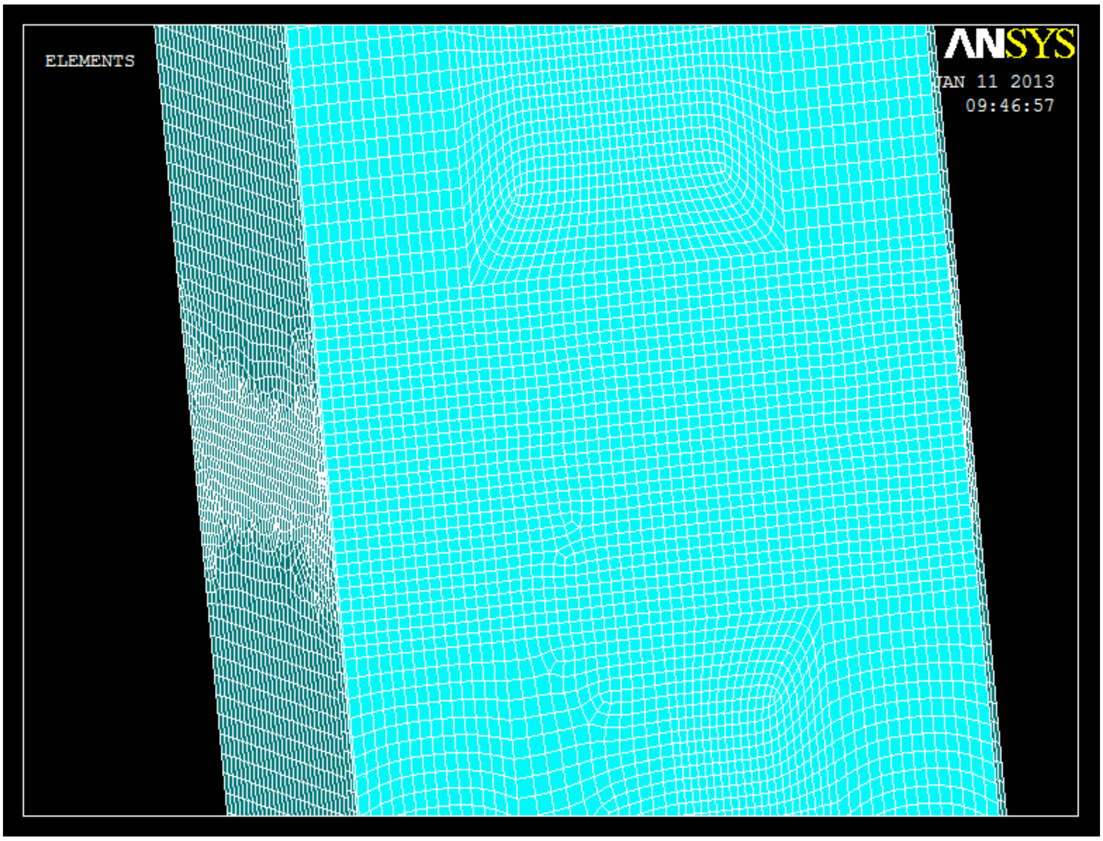


Figure 7.8 Model meshing

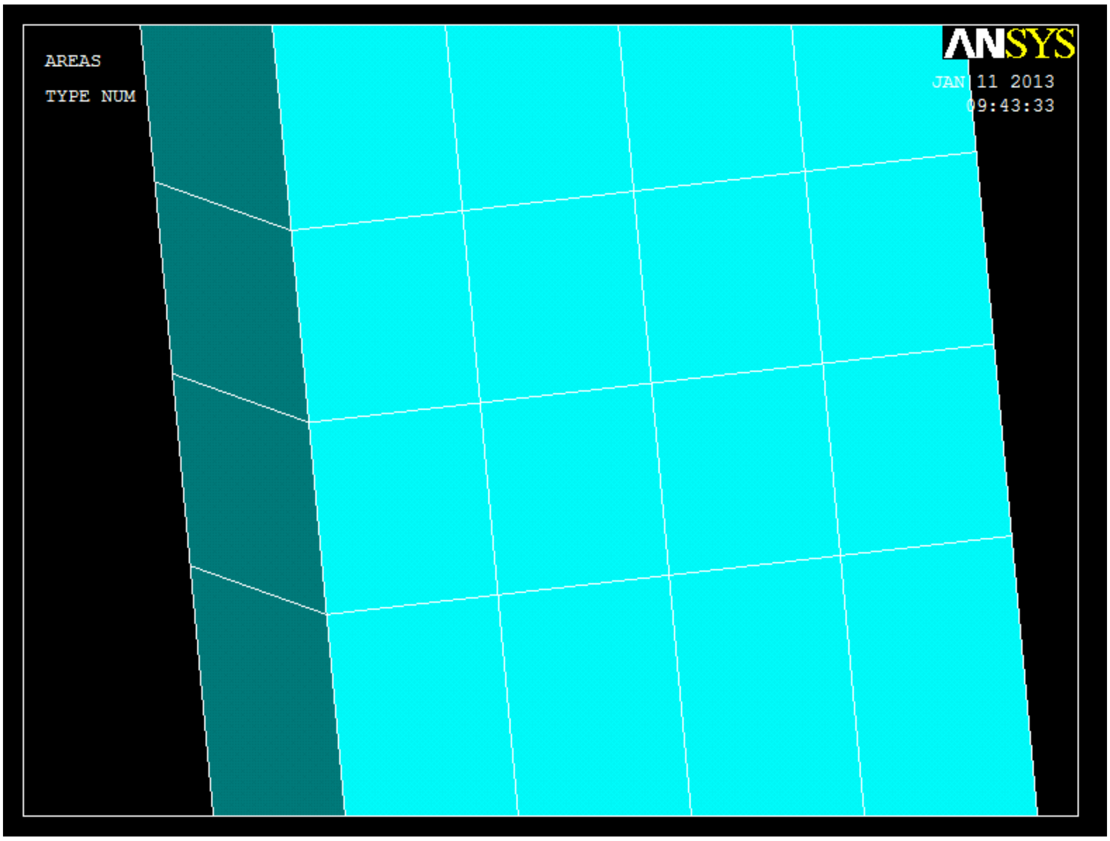
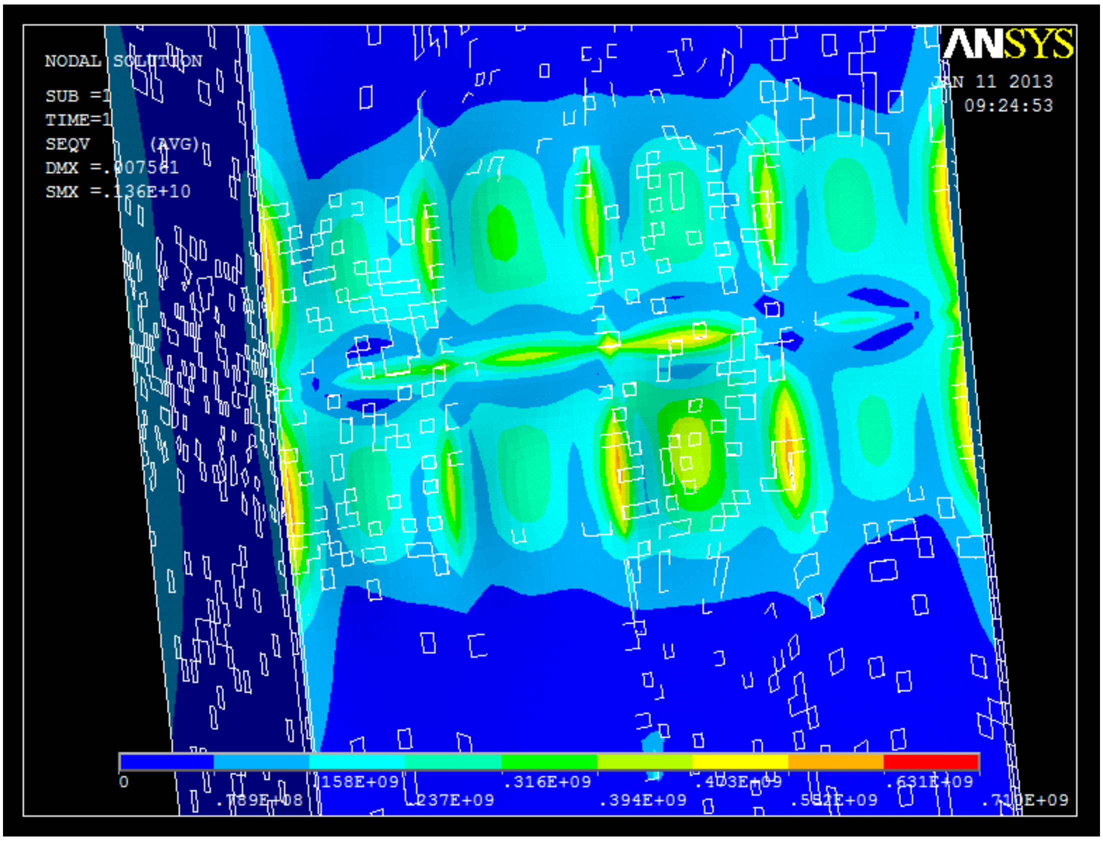
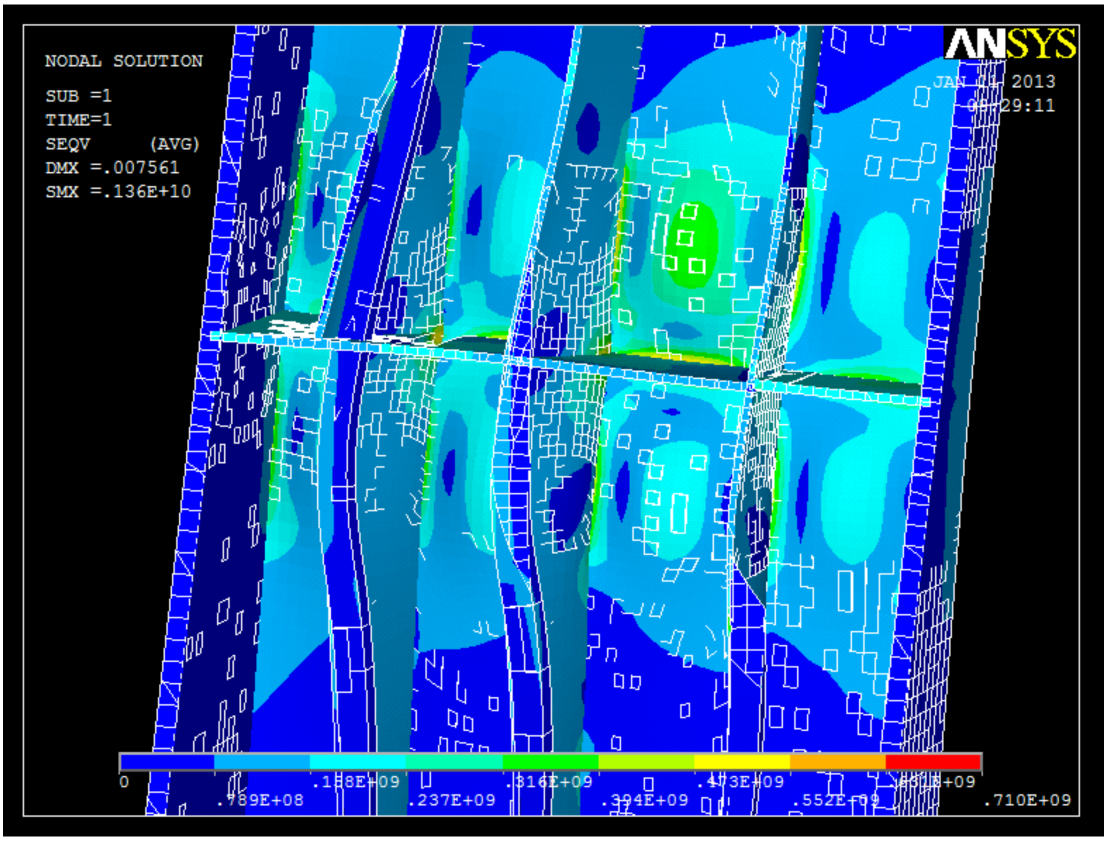


Figure 7.9 Ice load patch

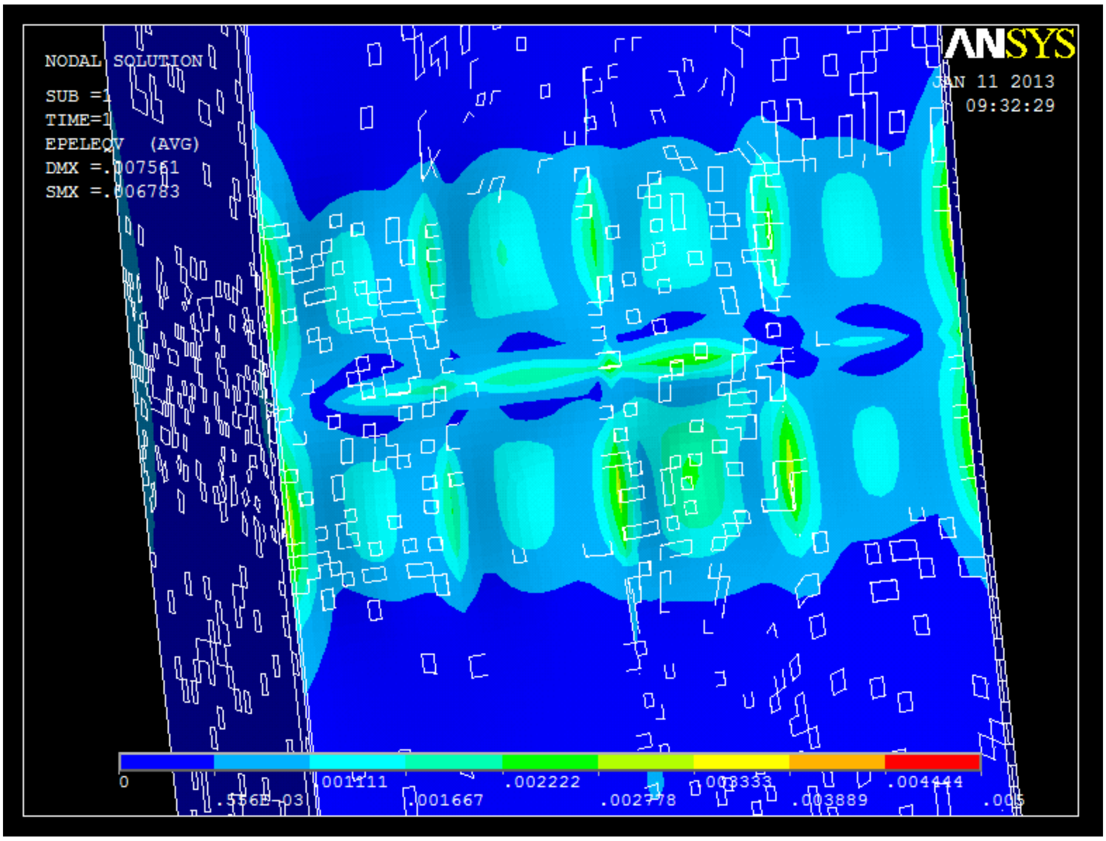


(a)

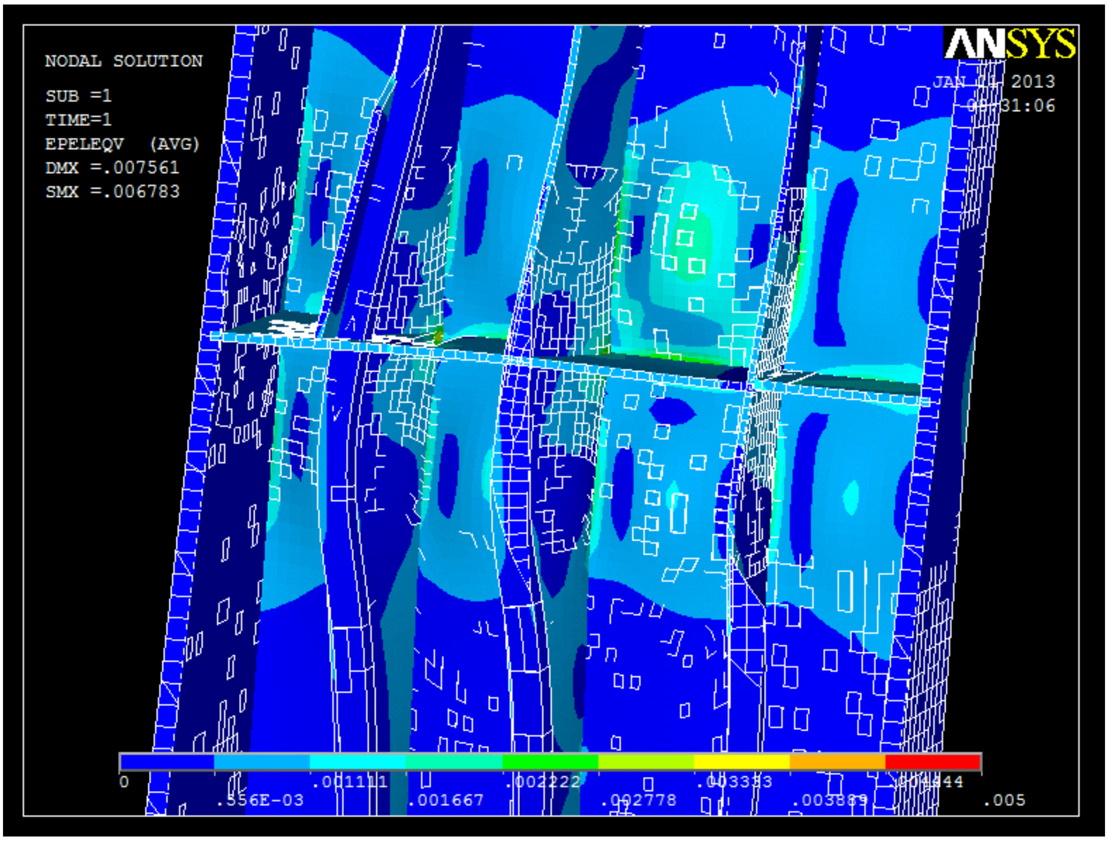


(b)

Figure 7.10 Stress of structure with ice load



(a)



(b)

Figure 7.11 Strain of structure with ice load

According to the result of FEM, the maximum stress on shell structure is around 532 MPa, and surely less than 710 MPa. The deformation is less than 5 mm. Moreover, in polar region, cold temperature will enhance the strength of material, which gives additional reservation for structure. Regarding the relationship analysis of elastic and plastic theory, the strength of design can be proved.

8 CONCLUSIONS

In this project, structural design, weight and cost optimization is processed based on rules. The design is developed according to the rules of classification society, and is proved by Rules Calc and finite element method. In the analysis of database, some law which is useful for design is concluded as follows.

In this thesis, a new rule-based structural optimization process was presented. The relationship of various parameters is analyzed. And the optimization solution was proved by FEM. By using MATLAB, Steel structure can be optimized with respect to weight and production cost to some extent. This thesis proves that rule based structural optimization can be processed by massive data processing. Some rules and tendency of parameters are concluded form the research and are shown as follows:

According to the calculation using rules, transversal structure in midbody and intermediate region is more efficient in weight because of the ice load. Mixed stiffening solution is used in bow and stern parts with respect to the hull form.

Corresponding with the general rules, smaller stiffener spacing could save weight globally (in the research on lower polar class, this tendency tends to be slighter and unacceptable gradually), especially reduce the thickness of plate. With increasing compressive stress, the relationship of stiffener spacing and panel weight is more unidirectional. While in polar class case, the weight reduction is not significant because of the unpredictable peak ice load which has higher possible average pressure added in smaller size panel. Moreover, generally speaking, in reasonable range of stiffener spacing, the reducing of total weight with the decreasing stiffener spacing is unidirectional as to polar class shell structure, but this law is unavailable for common panel structure.

For polar class ship, ice load in transversal direction plays a more critical role. Strong shell and inner transversal-effective structure should be well designed in case compressive load in transversal direction due to ice.

Buckling of transversal effective structure is the main issue of weight rising, which result in increasing of plate thickness and stiffener section area, especially at deck panels.

The ice load patch is much longer in horizontal direction, which realizes the fact that the stringer is not efficient in supporting transversal stiffeners until the stringer spacing is smaller than the height of ice load patch identified. Due to the limitation of breadth of double skin and man hole, stringer of side shell is not only effective in structure. Being replaced by plate girder, less stringer is recommended for polar class ship design.

Because of high ice load and the limitation of stiffener profile list, in bow region, stiffener and web frame are combined. If the stiffener spacing is smaller or the profile welds vertically on the plate, bulb profile is possible in some case.

As the supporting structure of stringer, web frame undertakes most of the ice load by stiffened panel and transfer the load to deck. In this case, the thickness of web frame plate is relatively high. For polar class ship, web frame spacing is limited in a low spacing range considering the thickness of plate.

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