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Aalesund University College

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New Structural Design Tool for Integration of Heavy Crane on Offshore Vessels

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PREFACE

In this thesis, a simple hand calculation tool is established for designing structure for heavy crane integration on offshore vessels at an early stage of design. This tool is developed for varying positions and diameters of the crane. Some assumptions and simplifications are used to establish the tool. NX and matlab are also used to find parameters and formulas for this tool. The hand calculation tool is verified by FEM analysis and an example case study.

This hand calculation tool is demonstrated to be feasible in this condition but still has some limitations.

This work has been carried out under the supervision of Arne Jan Sollied, Aalesund University.

I will thank Arne Jan Sollied for the brilliant ideas, engineering way of thinking and all the valuable discussions.

I will also thank Øyvind Seim for the help when I met problem with NX.

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ABSTRACT

In this thesis, a simple hand calculation tool is established for heavy crane integration on offshore vessels at an early stage of design. This tool can be used for varying positions and diameters of the crane. It is verified by FEM analysis and an example case study.

This hand calculation tool is demonstrated to be feasible in this condition but still has some limitations.

The most important is the assumptions and simplifications and the way of thinking and solving engineering problems.

KEYWORDS

Heavy crane, hand calculation, offshore vessel.

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TERMINOLOGY

Symbols

Md	Design moment [tm]
Fv	Design vertical force [t]
D	Crane diameter [m]
H	Height of longitudinal bulkhead [m]
R	Length of longitudinal bulkhead [m]
p	Position of crane from the end of longitudinal bulkhead [m]
B	Breadth of flange [m]
α	number of equivalent diameter which transmits horizontal reaction forces in the deck plane via shear and axial.
Ch	Horizontal fraction of design moment
Cv	Vertical fraction of design moment
Mh	Horizontal part of design moment
Mv	Vertical part of design moment
σ	Stress [MPa]
τ	Shear stress [MPa]

Abbreviations

FEM	Finite element method

1 INTRODUCTION

1.1 Project background

1.1.1 Offshore vessels

Offshore Vessels are specially designed ships for transporting goods and personnel to offshore oil platform that operate deep in oceans. The size of these vessels ranges between 20 meters and 100 meters. They are good at accomplishing a variety of tasks in the supply chain. The category may include Platform Supply Vessels (PSV), offshore barges, and all types of specialty vessels including Anchor Handling Vessels, Drilling Vessels, Well Intervention Vessels, Ice Breaking Vessels, Cable Laying Vessels, Seismic Vessels, and Fire Fighting Vessels.

Figure 1-1 OSCV

Anchor Handling Tug Supply (AHTS) vessels are designed and equipped for anchor handling and towing operations. They are also used for rescue purposes in emergency cases. Construction support vessels or CSVs are used to support complex offshore construction, installation, maintenance and other sophisticated operations. CSV's are significantly larger and more specialized than other offshore vessels.

A crane vessel, floating crane or crane ship is a ship equipped with large crane specialized in lifting heavy loads. The largest crane vessels are used for offshore construction. Because of their increased stability catamaran or semi-submersible types are often used, but also, conventional mono hulls are used too.

A diving support vessel is a ship used as a floating base for professional diving projects which are often performed around oil platforms and related installations in open water.

Offshore barges are used for a wide range of marine tasks. They can be equipped with heavy lifting cranes, firefighting system, or can be used for pipe laying (Derrick Barge), or even can serve as an offshore accommodation to personnel.

As the name suggests, Platform Supply Vessels (PSV) are used to carry crew and supplies to the oil platform deep inside oceans, and bring cargo and personnel back to shore. Their size varies from small 20 meter long ship to 100 meters large ship. These vessels are designed to transport a wide range of cargo such as drilling fluids, cement, mud, and fuel in tanks beneath the deck. The open deck on PSVs is normally used to carry other materials like casing, drill pipe, tubing and miscellaneous deck cargo to and from offshore platforms. Platform Supply Vessels are often equipped with firefighting equipment to deal with emergency situations.

1.1.2 Offshore vessel design

The most common way to describe the ship design can be shown by a spiral model, capturing the sequential and iterative nature of the process. The task structure is “design-evaluate-redesign”. Below is a figure showing the process of system based design of an offshore vessel.

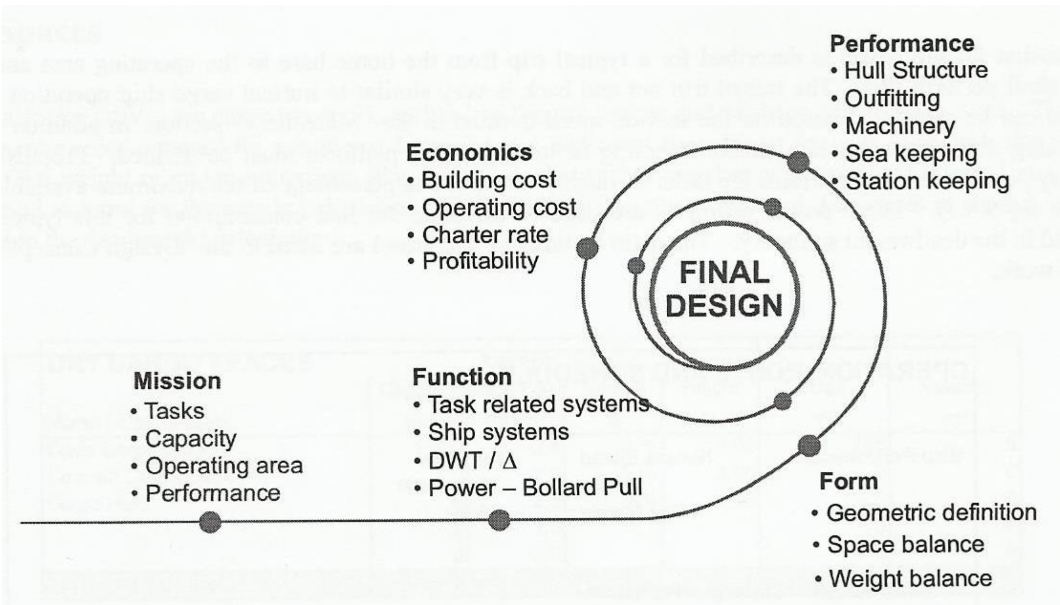


Figure 1-2 Offshore vessel design process

1.2 Problem formulation

A heavy crane is integrated on a vessel. Design loads include a vertical force of 800 ton and a moment of 12000 tm at longitudinal direction.

The crane is penetrated into tween deck which is 3 meters from main deck or penetrated into the third deck which is 6 meters from main deck. Both conditions will be analysed.

A longitudinal bulkhead supported by transverse bulkheads on both sides is used to support the crane. The length between the transverse bulkheads is 12 meters.

The breadth of the ship is 24 meters and the position of the crane is 8 meters from ship side.

In the thesis, different positions at the longitudinal bulkhead and different crane diameters are analysed to find a general solution to the problem.

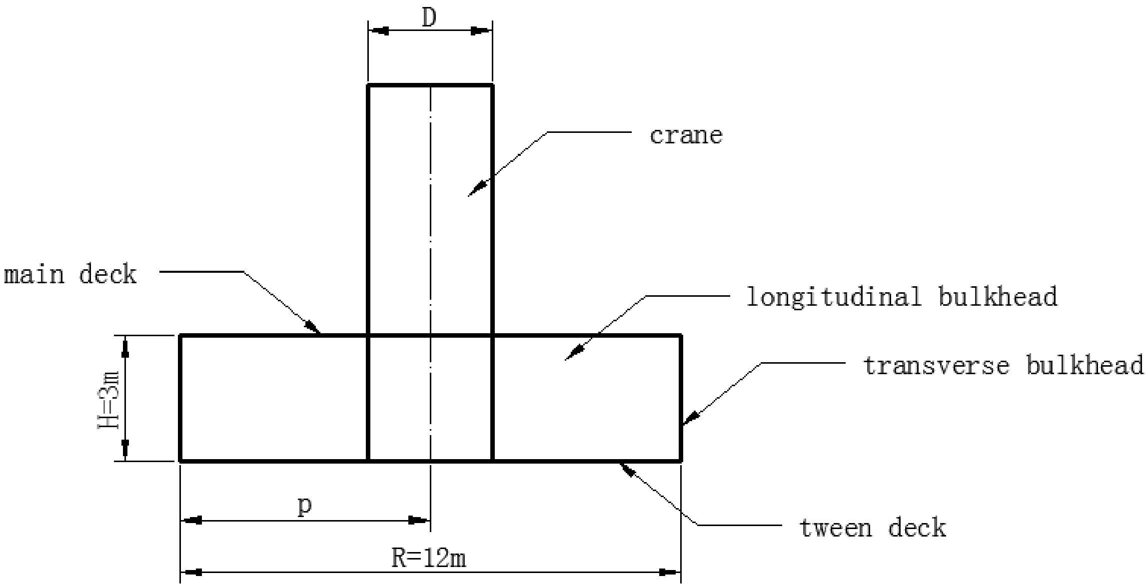


Figure 1-3 Crane penetrating into two decks

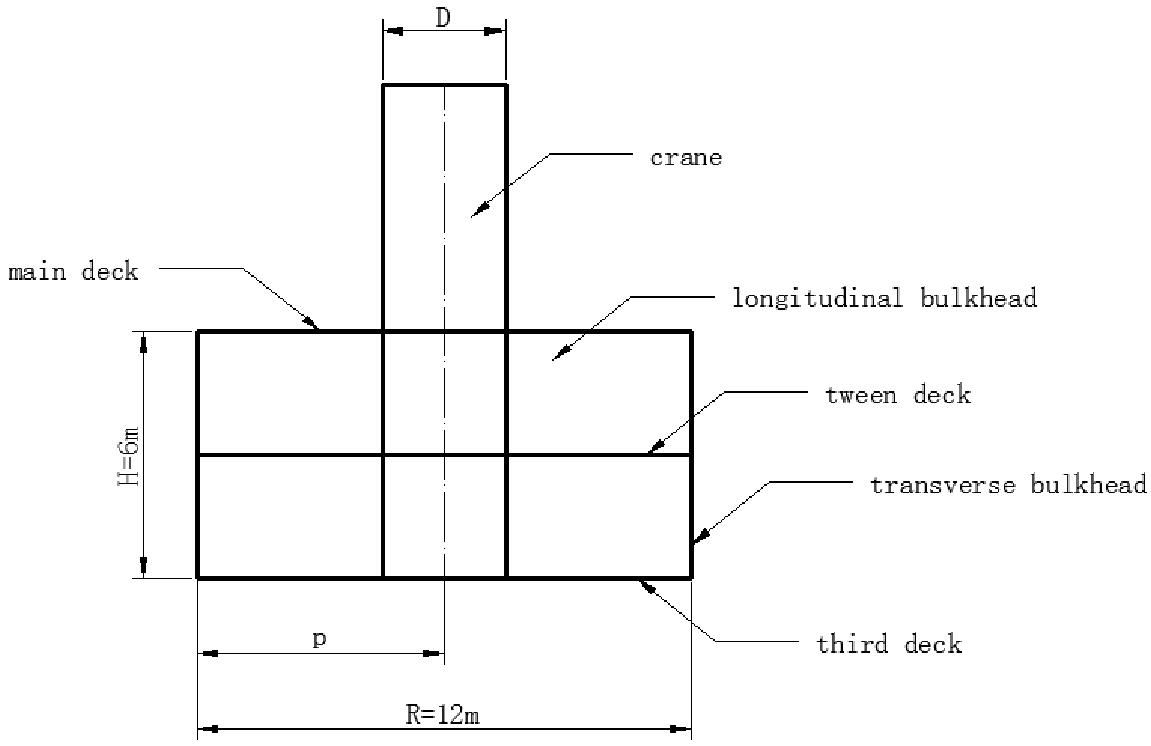


Figure 1-4 crane penetrating into three decks

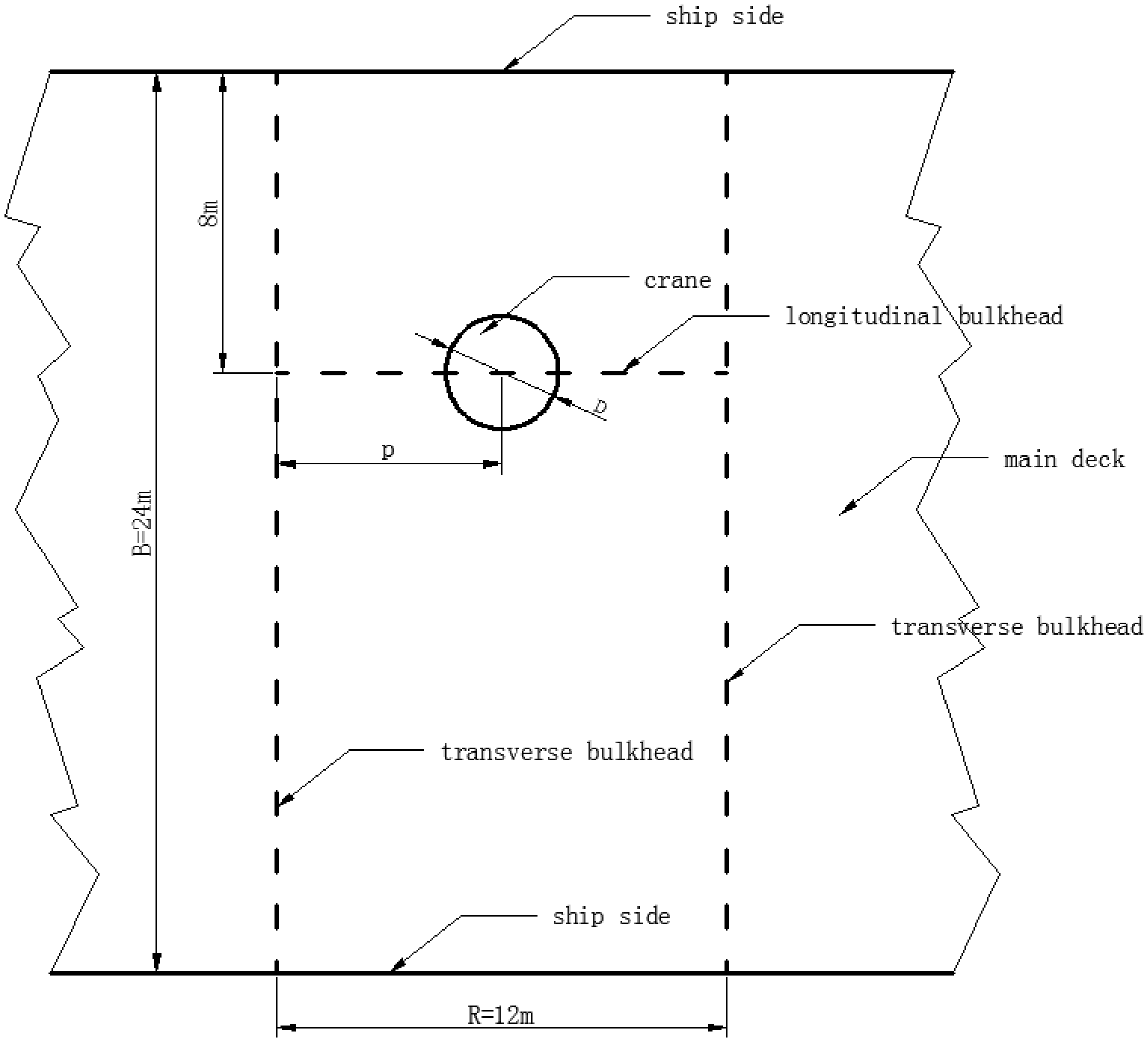


Figure 1-5 Topview

1.3 Objectives

This master thesis will develop a design hand calculation tool for the structural integration of heavy crane at an early stage in the general design process. Variation of new parameters such as column diameter and position of the heavy crane are to be achieved in detailed solutions. The general goal of achieving an appropriate design guideline can be divided into 3 parts.

1. Develop a hand calculation system to determine the deck plating and bulkhead profile
2. Verify the result of calculation with finite element analysis
3. Test the hand calculation tool with a real case

2 BACKGROUND AND THEORETICAL BASIS

2.1 Arrangement of cranes on OSV

According to Section 5, Lifting Appliances and Foundations for Heavy Equipment, Deck Machinery and Towing Equipment, ts303_2013-07, DNV rules, and support of heavily loaded crane pedestals shall preferably be provided by at least 2 deck levels. The supporting structure shall have continuity and allow safe access for survey of its interior. Below is a figure showing the recommended arrangement.

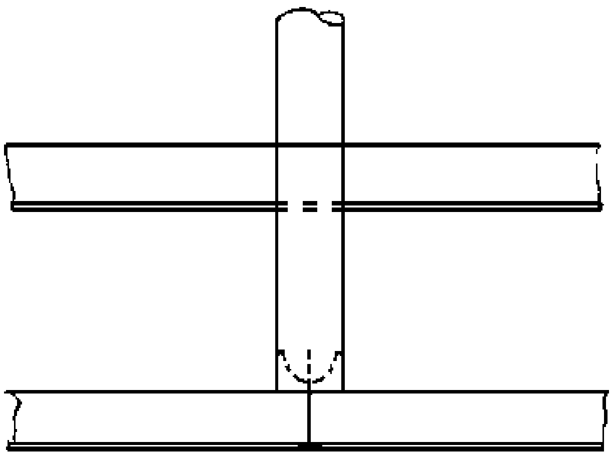


Figure 2-1 Recommended support

When the crane is only integrated on one deck, the deck will buckle or collapse easily as shown in figure below.

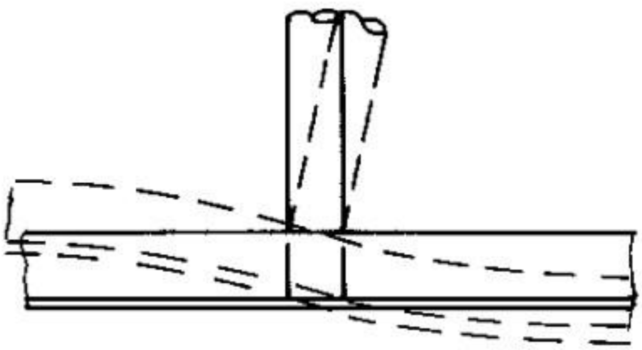


Figure 2-2 Not recommended support

2.2 Previous study in this field

Because the structural design is usually determined based on previous vessels and finite element analysis, the hand calculation estimate method is rarely mentioned. The only correlative work in this field could be found is Jon Egil Sollied's thesis, structural design tool for the integration of heavy cranes on offshore vessels.

His work is to develop a structural design tool for integration of heavy cranes. The crane in his thesis has a fixed diameter of 3 meters and is located at a fixed position, which means the distance from crane centerline to transverse bulkhead is fixed to 9 meters.

But in reality, both the diameter and the position of the crane will vary from vessels to vessels. So in this thesis, his work will be continued to develop a more general structural design tool which can be applied to OSVs with various sizes and different position of cranes.

In Jon Egil Sollied's study, he first established simple design rules for the dimensioning of important strength elements of the crane supporting structure. Then he verified his work by using Nauticus 3D beam for 3 dimensional beam element analyses and GeniE for finite element analysis.

From his study it can be observed that for the deck plating when the crane is penetrated to two decks, the results from beam and finite element analysis are rather consistent and the hand calculation results are slightly non-conservative within a range of approximately 10%.

For the longitudinal bulkhead, the general tendency is the same as above. The exception is for shorter bulkheads where the hand calculations show conservative values.

3 METHODS

3.1 Hand calculation

3.1.1 Beam problem establishment & some assumptions and simplifications

To establish a hand calculation system, a problem should be defined and described by creating simple beam problems. Some assumptions and simplifications are also required.

a. Critical loads

The critical loads include a vertical force of 800t and a moment in longitudinal direction of 12000tm.

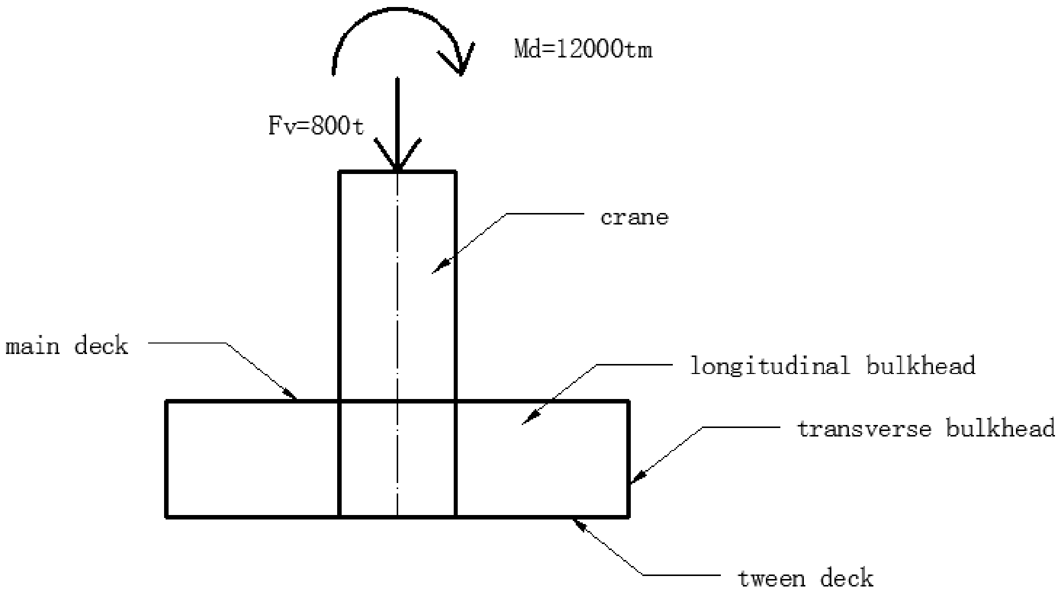


Figure 3-1 Design loads

Because the crane is penetrated like the picture shown below, some assumptions of how the loads act on deck and bulkhead can be made.

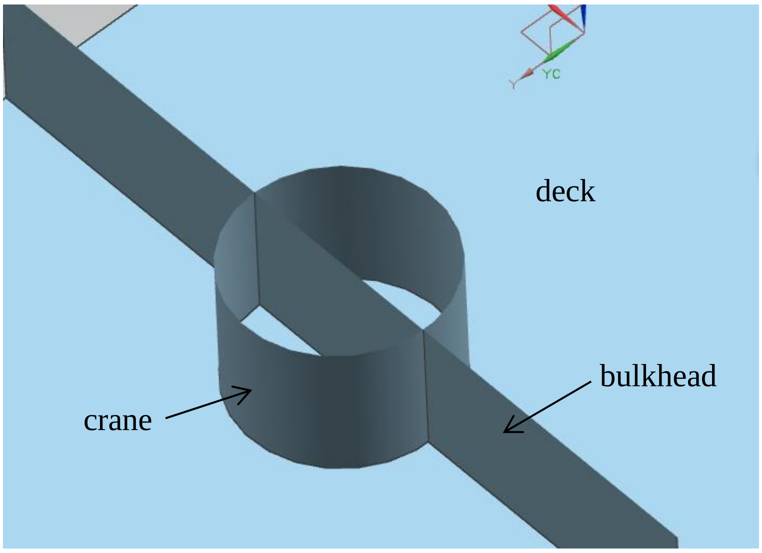


Figure 3-2 Cut-open view of the structure

Assume the vertical force is evenly distributed on two sides of the crane, which means two vertical point loads of 400t each.

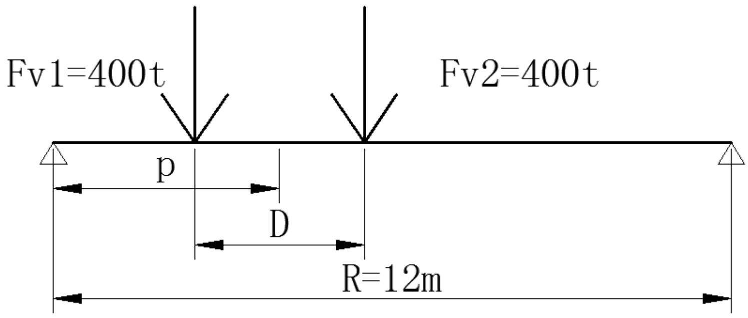


Figure 3-3 Vertical loads

Assume the moment consists of two force couples. One horizontal force couple supported by two decks and one vertical force couple supported by longitudinal bulkhead.

The horizontal fraction (Ch) and vertical fraction (Cv) of design moment will be found by using FEM analysis.

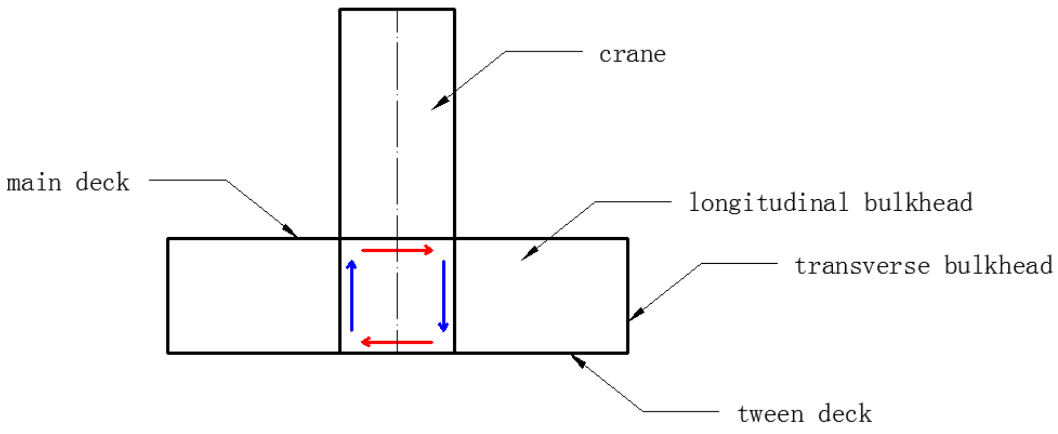


Figure 3-4 Force couples from design moment

The arrows in red and blue are horizontal and vertical force couples respectively.

b. Supporting system

The structure is supported by two transverse bulkheads on each end; the boundary condition is between simply supported and all fixed. Here it is assumed to be simply supported for hand calculation.

c. Beam profile

The beam to be analyzed is an I-beam.

The length of the beam is the distance between transverse bulkheads.

The upper flange is the main deck. The lower flange is the tween deck for crane penetrating into two decks and the third deck for crane penetrating into 3 decks.

The breadths of the flanges are assumed to be 2 times of diameter. This assumption will be verified in FEM analysis.

The web is the longitudinal bulkhead, the height of the bulk head is 3 meters for cranes penetrating to tween deck and 6 meters for cranes penetrating to third deck.

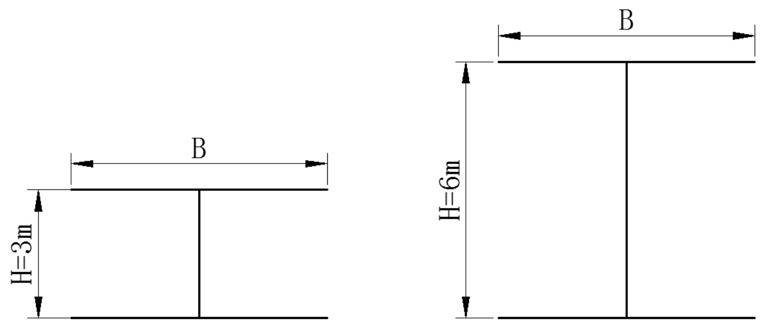


Figure 3-5 Cross sections of the beam

d. Assume the stress allocation on decks

Normally, the stress of a horizontal force at deck consists of normal stress (tensile stress and compressive stress) and shear stress.

In the first stage of hand calculation, it is assumed that tensile stress and compressive stress takes 1/3 of the total stress each and the two shear stresses takes 1/6 of the total stress each. So the maximum stress which to be used in hand calculation should be 1/3 of the total one. So α should be 3.

This assumption will be verified in FEM analysis.

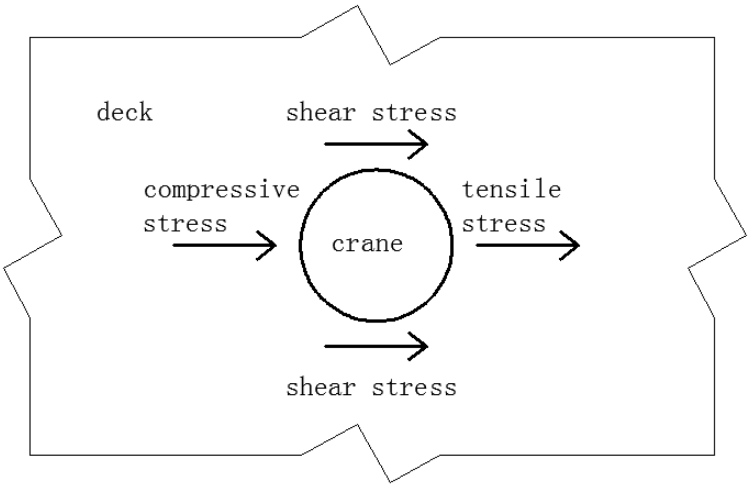


Figure 3-6 Stress allocation on deck

3.1.2 Acceptance criteria

For the structure to be analyzed, normal steel is used. Usually for normal steel:

$$\sigma_{\text{allow}} = 160\ N/mm^2$$

$$\tau_{\text{allow}} = 90\ N/mm^2$$

But in reality, the main deck will take care of deck load and global strength as well, so the acceptance of main deck should be lower for safety consideration.

So for main deck:

$$\sigma_{\text{allow}} = 120\ N/mm^2$$

For tween deck:

$$\sigma_{\text{allow}} = 160\ N/mm^2$$

For longitudinal bulkhead:

$$\tau_{\text{allow}} = 90\ N/mm^2$$

3.1.3 Basic theories

To determine the thicknesses of decks, the bending moment created by Fv and the horizontal force caused by Mh should be considered.

For the bending moment,

$$\sigma_{allow} = \frac{M}{Z}$$

Where

M is the maximum bending moment created by the design vertical force.

Z is the section modulus of the beam.

For the horizontal force,

$$\sigma_{allow} = \frac{F_h}{\alpha A}$$

Where

Fh is the horizontal force of the horizontal force couple representing horizontal part of the design bending moment.

α is number of equivalent diameter which transmits horizontal reaction forces in the deck plane via shear and axial.

A is the area of deck cross section where the stress is checked.

To determine the thickness of longitudinal bulkhead, the shear force caused by Fv and the vertical force couple representing Mv is to be considered.

$$\tau_{allow} = \frac{Q}{A}$$

Where

Q is the maximum shear force caused by the design vertical load and the vertical force couple representing vertical part of design moment

A is the area of bulkhead cross section.

3.2 FEM analysis

3.2.1 Model description

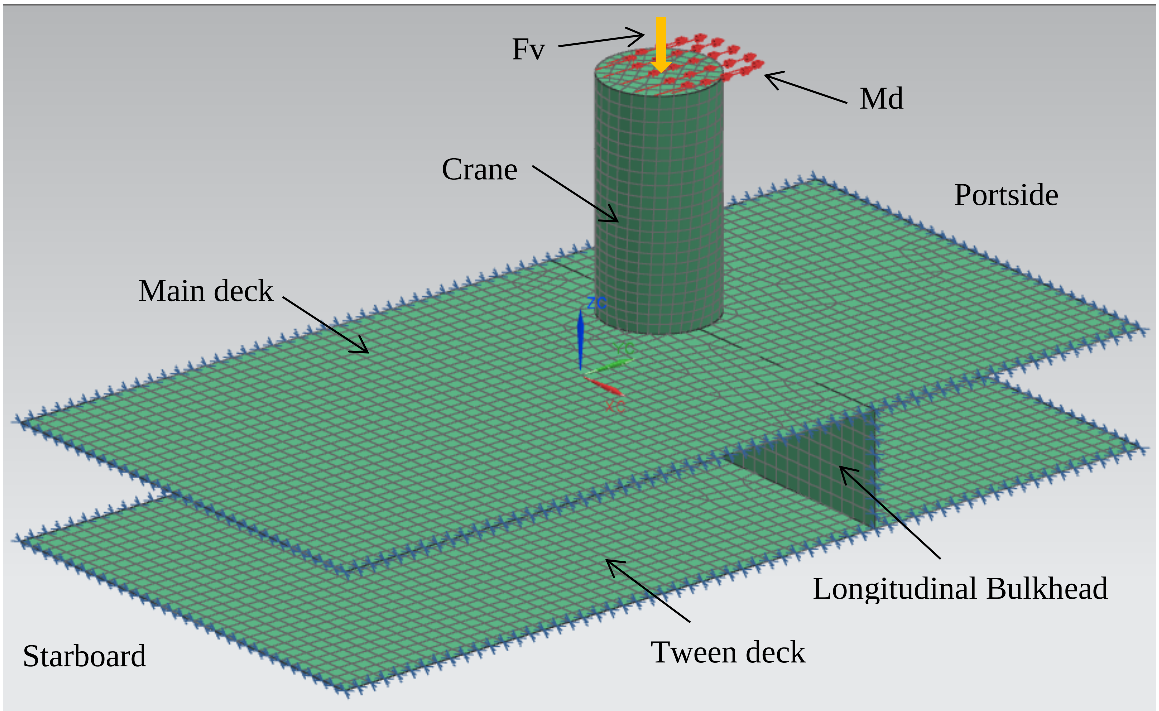


Figure 3-7 Model in NX

Figure 3-7 is one example of a NX model. This model is a crane penetrating to tween deck with a position 4 meters from the aft end of longitudinal bulkhead and with a crane diameter of 3 meters. These are variables which will be different in each model.

The breadths of decks here use the breadth of the ship, which is 24 meters. The position of the longitudinal bulkhead is 8 meters from the portside.

For cranes penetrating to two decks, the thicknesses of main deck and tween deck are 10mm and the thickness of longitudinal bulkhead is 20mm in the models. For cranes penetrating to 3 decks, the thicknesses for main deck and third deck are 20mm and the thickness of bulkhead is 40mm in the models.

2D mesh is used for all parts of the structure. The element size is 400 mm for all parts of the structure.

The portside and the starboard of the structure are supported by ship sides while the forward side and aft side are supported by two transverse bulkheads. Assume the support from ship sides and transverse bulkheads are all fixed. So, all fixed boundary condition is used for all the four sides of the decks and two sides of the longitudinal bulkhead as shown in the picture. The vertical design load and the design bending moment are on top of the crane.

3.2.2 Calculate parameters to be used in hand calculation

a. Calculate Ch & Cv

To calculate Ch and Cv, Mh and Mv should be calculated according to the stresses found in FEM analysis first.

Below is the method of calculating Mh from the stresses found at decks.

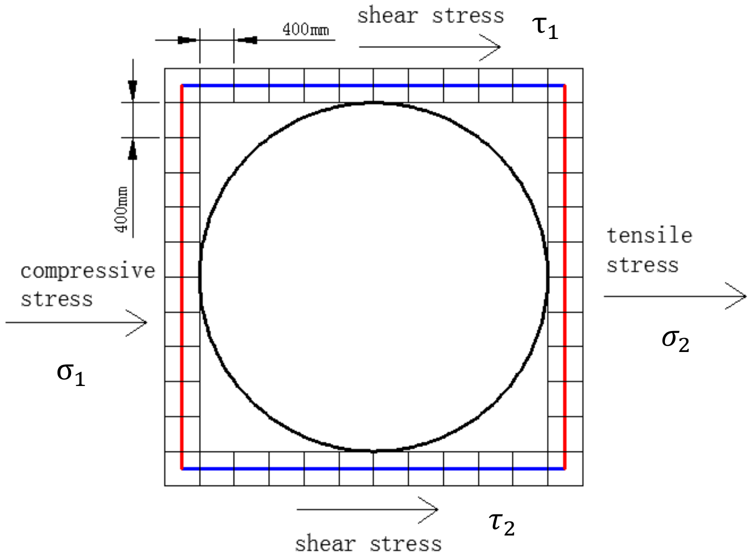


Figure 3-8 Elements checked for calculating stress

The picture above shows the elements to use for calculating stresses on deck. The mean stress values of the elements with red lines are used as compressive stress and tensile stress (σ_1, σ_2) while the mean stress values of the elements with blue lines are used as shear stresses (τ_1, τ_2).

The cross section areas of these four stresses are the same:

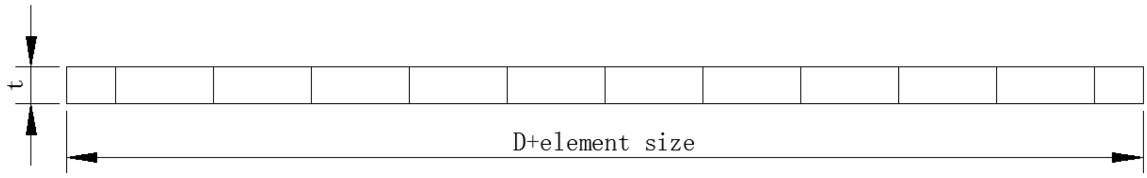


Figure 3-9 Cross section area

So the horizontal force on one deck can be calculated:

$$F_h = (\sigma_1 + \sigma_2 + \tau_1 + \tau_2) * (D + \text{element size}) * t$$

Calculate the Fh for both decks and then the horizontal part of the design moment Mh can be calculated:

$$M_h = F_{h1} * y_1 + F_{h2} * y_2$$

Where

F_{h1} is the horizontal force on main deck

y_1 is the vertical distance from main deck to the middle of the longitudinal bulkhead

F_{h2} is the horizontal force on tween deck or third deck

y_2 is the vertical distance from tween deck or third deck to the middle of the longitudinal bulkhead

Then calculate the vertical part of design moment Mv by the shear stress found in bulkhead.

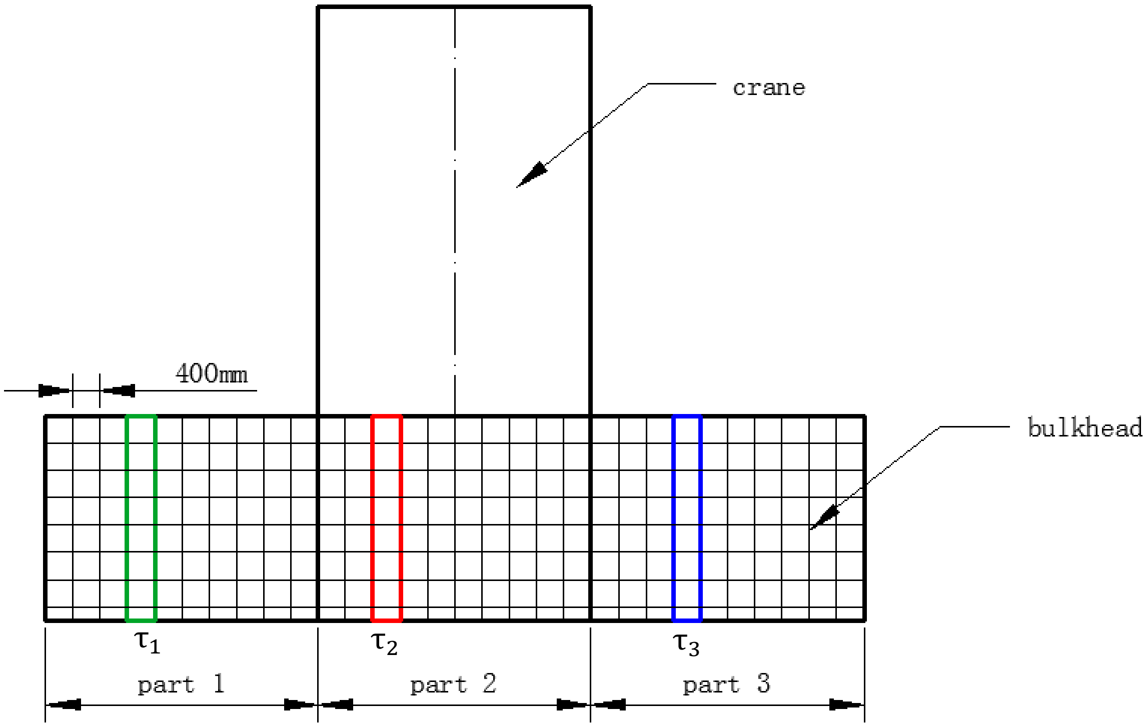


Figure 3-10 Elements checked for calculating stress

The mean shear stress of one column of elements is used for calculating. The bulkhead can be divided into 3 parts by the crane. In each part, the mean stresses of each element column are constant. So choose a random column of elements of each part and the maximum mean value of the three is used in following calculations.

For these cases the maximum value is always in part 2.

Define the mean shear stress at part 2 is τ_2.

Calculate the shear force for part 2.

First, calculate shear force from the shear stress found in FEM analysis and the cross section area of bulkhead:

$$Q_2 = \tau_2 * A = \tau_2 * t * H$$

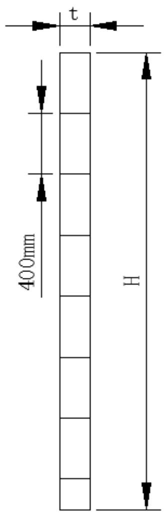


Figure 3-11 Cross section area of bulkhead

Then, calculate the shear force from Fv and Mv:

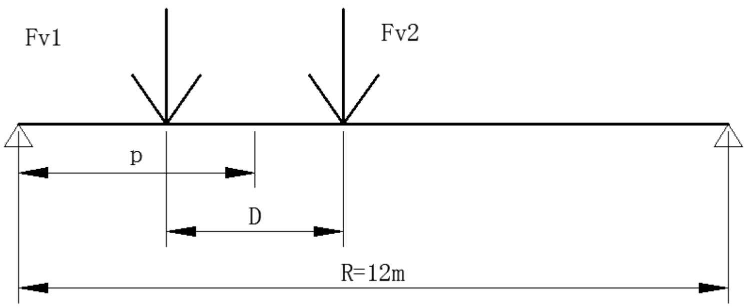


Figure 3-12 Design vertical force Fv

Where

$$F_{v1} = F_{v2} = \frac{F_v}{2}$$

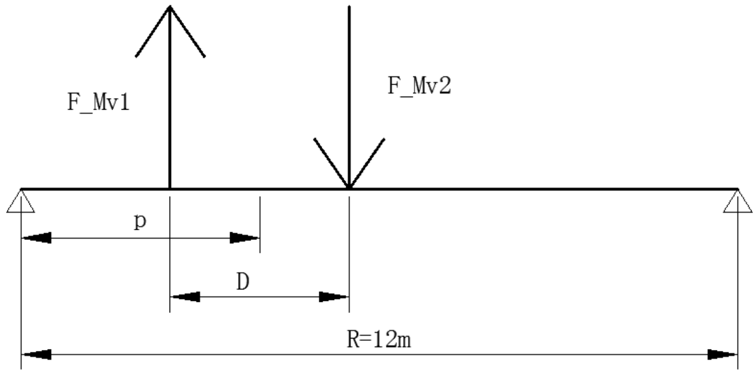


Figure 3-13 Force couple from Mv

Where

$$F_{Mv1} = F_{Mv2} = \frac{M_v}{D}$$

Then the load condition of this beam can be established by combine the forces of Fv and Mv.

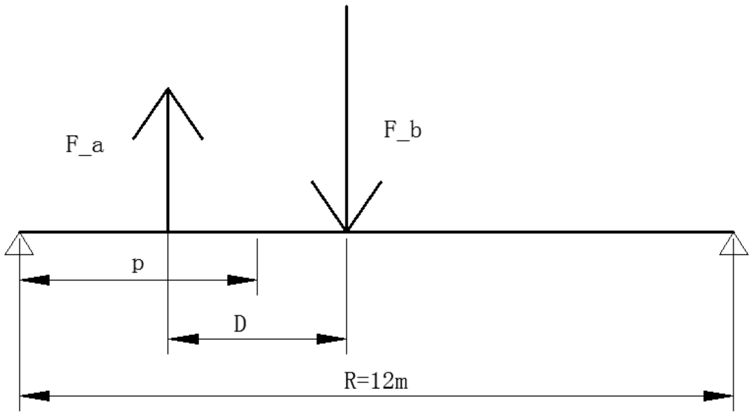


Figure 3-14 Combined vertical forces

Where

$$F_a = F_{Mv1} - F_{v1}$$

$$F_b = F_{Mv2} + F_{Mv2}$$

Divide the beam into 3 parts (1, 2, 3) by point a and point b.

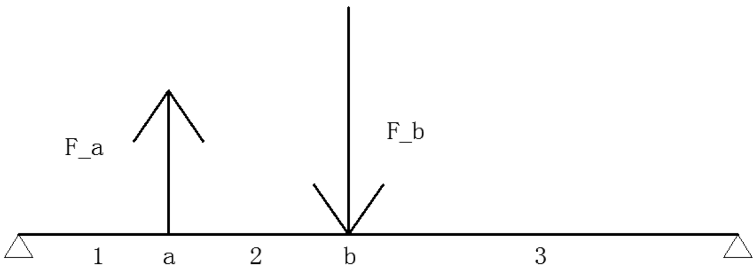


Figure 3-15 Divide the beam into 3 parts

Where

$$a = p - \frac{D}{2}$$

$$b = p + \frac{D}{2}$$

Calculate the shear force in part 2 created by Fa:

$$Q_{Fa_2} = F_a * \frac{a}{R}$$

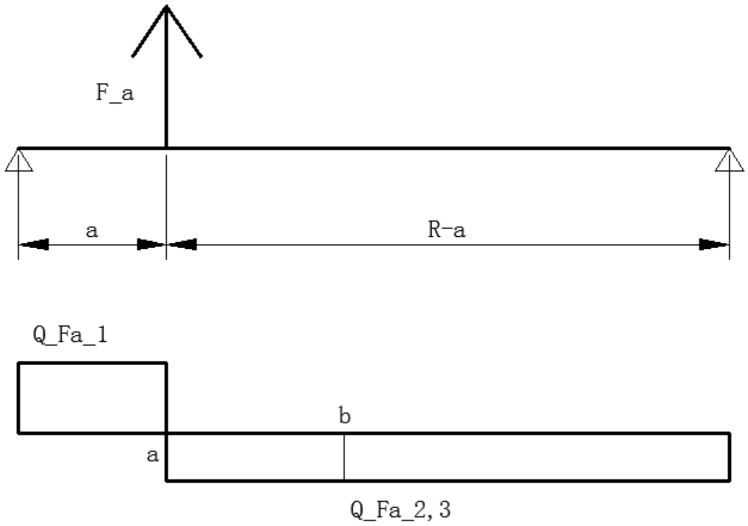


Figure 3-16 Shear force of Fa

Calculate the shear force created by Fb:

$$Q_{Fb_2} = F_b * \frac{R-b}{R}$$

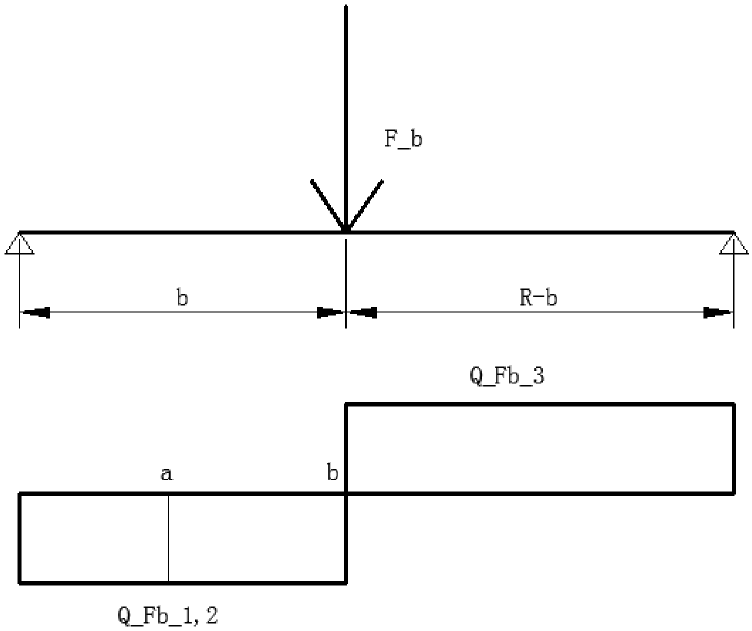


Figure 3-17 Shear force of Fb

Then the combined shear force of part 2:

$$Q_2 = Q_{Fa_3} + Q_{Fb_2} = \left(\frac{M_v}{D} - \frac{F_v}{2}\right) * \frac{p - \frac{D}{2}}{R} + \frac{M_v}{D} + \frac{F_v}{2}) * \frac{R - (p + \frac{D}{2})}{R}$$

According to previous calculation,

$$Q_2 = \tau_2 * t * H$$

So, the Mv can be calculated by using the shear stress found in FEM analysis and other parameters used in the model.

$$\mathrm{M_v} = \left[\tau_2 * \mathrm{t} * \mathrm{H} - \frac{\mathrm{F_v}}{2} * \left(1 - \frac{2p}{R}\right)\right] * \frac{D}{1 - \frac{D}{R}}$$

After Mh and Mv are calculated, the fraction of the horizontal part and vertical part of design moment can be found.

Theoretically, the sum of Mh and Mv should be the same as Md, but in reality it would be slightly different due to some reasons like simplifications in hand calculation and mesh is twisty to some extent. To get a more exact value of Ch and Cv, the sum of calculated sum of Mh and Mv is used as the new design moment instead of the original Md.

So the Ch and Cv can be calculated as following:

$$\mathrm{C_h} = \frac{M_h}{M_h + M_v}$$

$$\mathrm{C_v} = \frac{M_v}{M_h + M_v} = 1 - C_h$$

b. Check α

α can be checked by using the stresses found from Figure 3-8.

The compressive stress and tensile stress are close to each other and both much larger than the shear forces. So the mean value of σ_1 and σ_2 is used to calculate α.

$$\alpha = \frac{(\sigma_1 + \sigma_2 + \tau_1 + \tau_2)}{\frac{\sigma_1 + \sigma_2}{2}}$$

c. Check B

The effective flange breadth can be checked directly by observing the result FEM model which will be showed in the result part.

3.2.3 Calculate required thicknesses

Some appropriate fixed values of deck and bulkhead thicknesses are used for building the models. The required thickness regarding to the acceptance criteria can be calculated by using the thicknesses in the model and the stresses found in FEM analysis.

To have a better comparison and understanding of the result in FEM analysis, both the maximum stress and mean stress found from Figure 3-8 are used to calculate the required thickness of decks.

$$t_{req} = t * \frac{\sigma}{\sigma_{allow}}$$

Where

t is the actual thickness for deck used in the model;

σ is the stress found in FEM analysis;

σ_{allow} is the acceptance criteria for deck;

t_{req} is the result required thickness for deck.

While for bulkhead thickness, the largest mean value τ_2 found from Figure 3-10 is used.

$$t_{req} = t * \frac{\tau}{\tau_{allow}}$$

3.3 *Establish parameters and variables*

3.3.1 Parameters

Given parameters for all cases for both hand calculations and FEM analysis are shown in the table below:

Table 3-1 Parameters-1

Parameter	Value	Unit
Md	12000	tm
Fv	800	t
R	12	m

The parameters to be found or verified in FEM analysis and used in hand calculations are shown in the table below:

Table 3-2 Parameters-2

Parameter	Assumption or range of value
Ch	0<Ch<1
Cv	0<Cv<1, Cv=1-Ch
α	α ≈3
B	B≈2*D

The parameters only to be used in FEM analysis:

Table 3-3 Parameters-3

Parameter	Value	Unit
Ship breadth	24	m
Position of crane in transverse direction	8	m

3.3.2 Variables

This thesis is to establish a hand calculation method for varying positions of crane on longitudinal bulkheads and varying crane diameters for crane penetrating into two decks and three decks. So the variables are p, D and H.

For the varying positions of crane on longitudinal bulkheads, the values are:

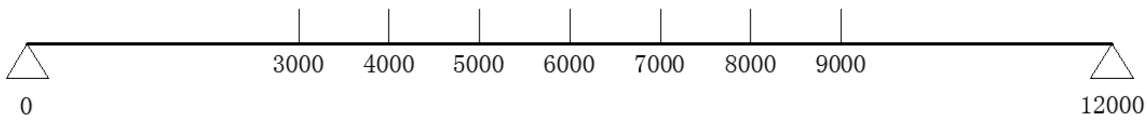
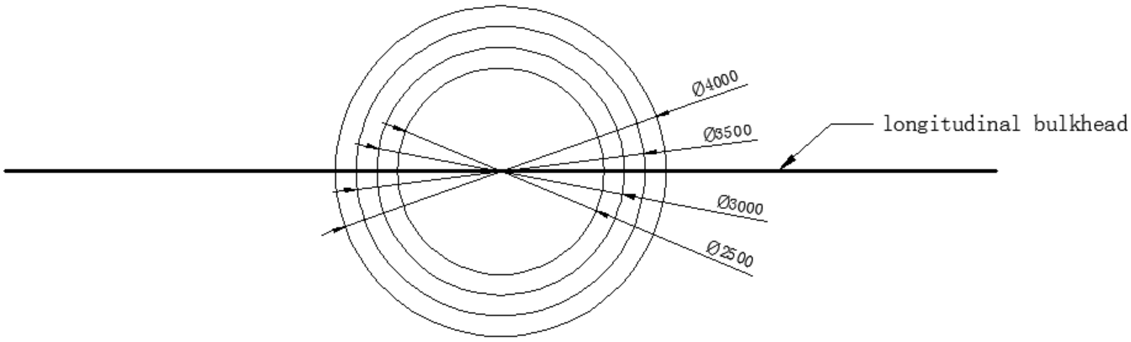


Figure 3-18 Positions of crane centerline on longitudinal bulkhead

The unit is mm in the picture.

For varying diameters of crane, 2500mm, 3000mm, 3500mm and 4000mm are used.



The crane penetrates into 2 decks or 3 decks. Assume the height between each deck is 3m. So 3m and 6m are used for the height of longitudinal bulkhead

3.3.3 Variable control

Except for those parameters in 3.1.1, when analyzing each case, the variables not being analyzed should be controlled.

When doing analysis for cranes for varying diameters, the position of crane is fixed as 6000 mm.

When doing analysis for cranes for varying diameters, the position of crane is fixed as 3000 mm.

Both 3m and 6m height of longitudinal bulkhead are used for both analyses of varying positions and varying diameter.

4 RESULTS

4.1 FEM analysis

4.1.1 Result parameters calculated from each model

a. Parameters for varying positions when H is 3m

Table 4-1 Parameters for varying positions when H is 3m

posotion	Ch	Cv	alpha_1	alpha_2
3000	70%	30%	2.8	2.8
4000	67%	33%	3.0	3.0
5000	67%	33%	2.9	2.9
6000	65%	35%	2.9	2.9
7000	64%	36%	2.9	2.9
8000	61%	39%	2.9	2.9
9000	62%	38%	2.9	2.9

Where alpha_1 is α for main deck and alpha_2 is α for tween deck

b. Parameters for varying diameters when H is 3m

Table 4-2 Parameters for varying diameters when H is 3m

diameter	Ch	Cv	alpha_1	alpha_2
2500	67%	33%	3.0	3.0
3000	65%	35%	2.9	2.9
3500	65%	35%	3.0	3.0
4000	61%	39%	2.9	2.9

c. Parameters for varying positions when H is 6m

Table 4-3 Parameters for varying positions when H is 6m

posotion	Ch	Cv	alpha_1	alpha_2
3000	79%	21%	3.1	3.1
4000	77%	23%	3.1	3.1
5000	76%	24%	3.2	3.2
6000	74%	26%	3.2	3.2
7000	72%	28%	3.2	3.2
8000	70%	30%	3.2	3.2
9000	69%	31%	3.1	3.1

Where alpha_2 is α for third deck.

d. Parameters for varying diameters when H is 6m

Table 4-4 Parameters for varying diameters when H is 6m

diameter	Ch	Cv	alpha_1	alpha_2
2500	75%	25%	3.3	3.3
3000	74%	26%	3.2	3.2
3500	73%	27%	3.1	3.1
4000	72%	28%	3.2	3.2

4.1.2 Formulas for Ch & Cv

For all cases, Cv can be calculated according to Ch.

$$\mathrm{C_v} = 1 - \mathrm{C_h}$$

Matlab is used to establish formulas to calculate Ch for varying positions and varying diameters for different height of penetrating.

a. Ch for varying crane positions when H is 3m

The result curve is:

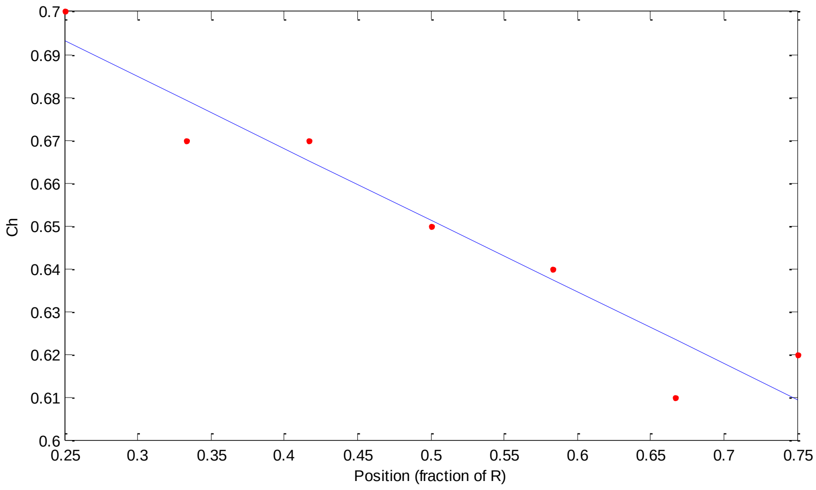


Figure 4-1 Ch for varying position when H=3m

The result formula for Ch is:

$$\mathrm{C_h} = -0.167C_p + 0.735$$

Where

$$C_p = \frac{p}{R}$$

b. Ch for varying crane diameters when H is 3m

The result curve is:

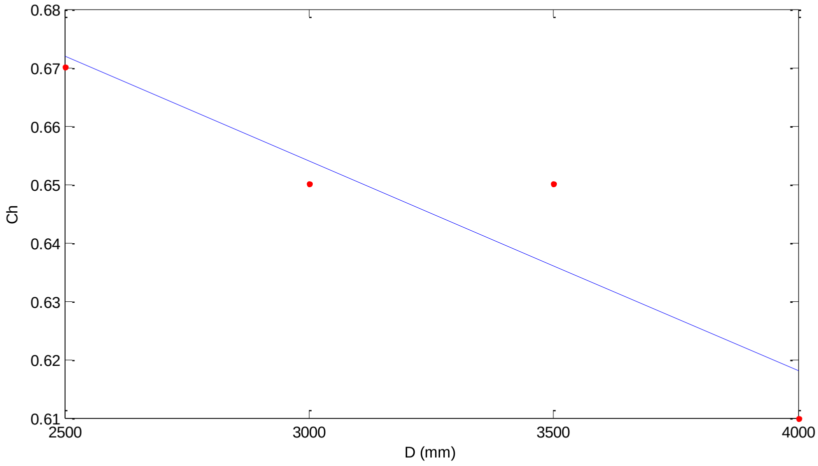


Figure 4-2 Ch for varying diameters when H=3m

The result formula for Ch is:

$$C_h = -3.6 * 10^{-5} * D + 0.762$$

Where D is the crane diameter with unit of mm.

c. Ch for varying crane positions when H is 6m

The result curve is:

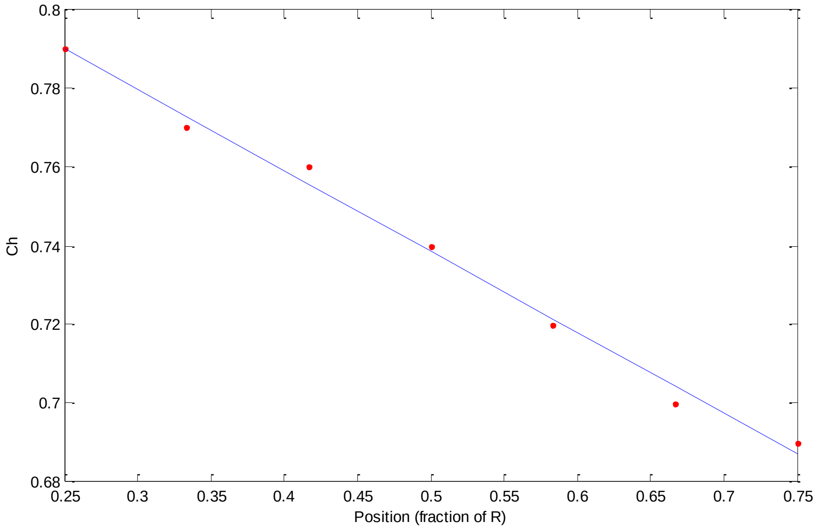


Figure 4-3 Ch for varying positions when H=6m

The result formula for Ch is:

$$C_h = -0.206 * p + 0.841$$

d. Ch for varying crane diameters when H is 6m

The result curve is:

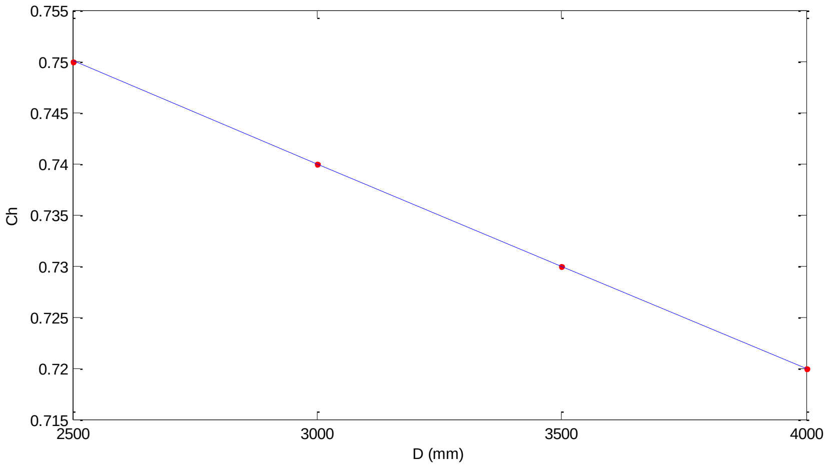


Figure 4-4 Ch for varying diameters when H=6m

The result formula for Ch is:

$$C_h = -2 * 10^5 * D + 0.5$$

4.1.3 Value of α to use in hand calculations

From the α values found in 4.1.1, it can be found that α for all the cases are between 2.8 and 3.2. For simplification, 3 will be used for the value of α for hand calculation for all cases.

4.1.4 Effective breadth of flange

Figure 4-5 is the stress of deck from FEM analysis for one case. The left are the tensile and compressive stresses and the right are the shear stresses. The black line in the middle is the longitudinal bulkhead and the circle in the middle is the crane. The area in the white line is the approximate effective area at deck and the length between the two red lines is the effective flange breadth to use.

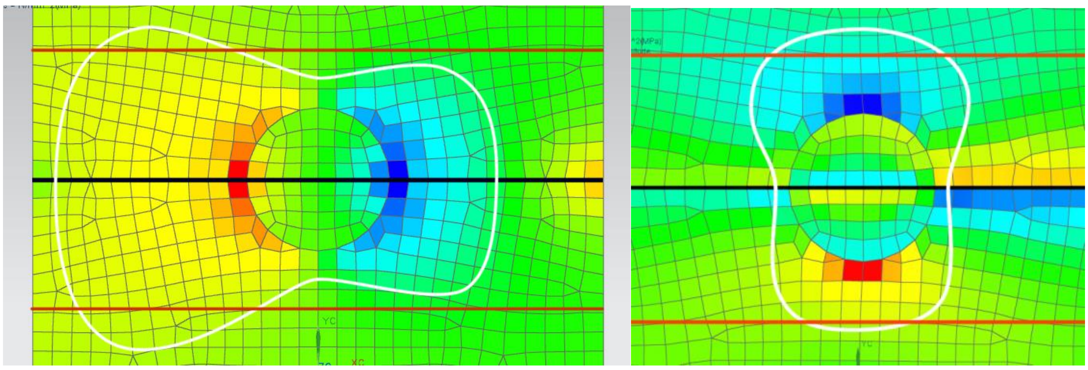


Figure 4-5 Effective flange breadth

After observing the results in all cases, it can be estimated that the effective flange breadth is around 1.5 to 2 times of the crane diameter.

So, 2D will be used for flange breadth in the hand calculations later.

4.1.5 Required thicknesses calculated from each model

a. Required thicknesses for varying crane positions when H is 3m

Table 4-5 Required thicknesses for varying crane positions when H is 3m

posotion	t_md_mean	t_td_mean	t_bh	t_md_max	t_td_max
3000	30.8	21.4	43.6	40.2	27.4
4000	26.7	16.9	43.6	42.5	23.3
5000	28.0	17.4	39.1	42.8	21.9
6000	28.0	16.8	38.2	42.5	22.3
7000	27.5	16.6	36.9	40.0	21.9
8000	27.5	16.1	38.2	40.8	21.1
9000	28.8	17.8	36.4	41.5	23.3

Where

Position is the position of crane centreline on the longitudinal bulkhead in mm.

t_md_mean is the required thickness of main deck calculated according to the larger stress of σ_1 and σ_2 found from the method shown in Figure 3-8.

t_td_mean is the required thickness of tween deck calculated according to the larger stress of σ_1 and σ_2 found using the method shown in Figure 3-8.

t_bh is the required thickness of bulkhead calculated according to the stress found using the method shown in Figure 3-10.

t_md_max is the required thickness of main deck calculated according to the largest stress of main deck found in FEM analysis.

t_td_max is the required thickness of tween deck calculated according to the largest stress of tween deck found in FEM analysis.

b. Required thicknesses for varying crane diameters when H is 3m

Table 4-6 Required thicknesses for varying crane diameters when H is 3m

diameter	t_md_mean	t_td_mean	t_bh	t_md_max	t_td_max
2500	34.7	20.4	47.1	50.3	27.0
3000	28.0	16.8	38.2	42.5	22.3
3500	23.8	14.8	32.0	37.7	18.5
4000	17.5	12.0	28.4	33.2	16.8

Where

diameter is the crane diameter in mm.

c. Required thicknesses for varying crane positions when H is 6m

Table 4-7 Required thicknesses for varying crane positions when H is 6m

posotion	t_md_mean	t_td_mean	t_bh	t_md_max	t_td_max
3000	16.9	10.5	15.1	22.8	14.6
4000	14.6	8.4	14.4	21.4	13.3
5000	14.6	8.0	14.0	22.5	11.5
6000	14.8	8.0	13.6	22.8	13.6
7000	15.2	8.3	13.1	23.2	11.8
8000	15.0	7.6	12.9	22.8	13.1
9000	16.1	9.1	12.9	23.7	12.8

Where

t_td_mean is the required thickness of third deck calculated according to the larger stress of σ_1 and σ_2 found using the method shown in Figure 3-8.

t_td_max is the required thickness of third deck calculated according to the largest stress of third deck found in FEM analysis.

d. Required thicknesses for varying crane diameters when H is 6m

Table 4-8 Required thicknesses for varying crane diameters when H is 6m

diameter	t_md_mean	t_td_mean	t_bh	t_md_max	t_td_max
2500	19.3	8.4	16.2	29.4	14.0
3000	14.8	8.0	13.6	22.8	13.6
3500	12.5	7.3	11.6	19.4	11.9
4000	10.6	6.3	10.0	16.4	9.5

4.2 Hand calculation

4.2.1 Calculation procedure

a. Calculate required thickness for longitudinal bulkhead

The longitudinal bulkhead endures two part of forces – one is vertical load Fv and the other is the vertical force couple represents vertical part of design moment Mv.

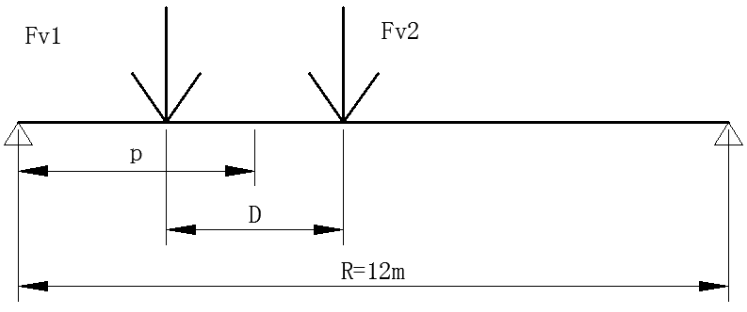


Figure 4-6 Design vertical force Fv

Where

$$F_{v1} = F_{v2} = \frac{F_v}{2}$$

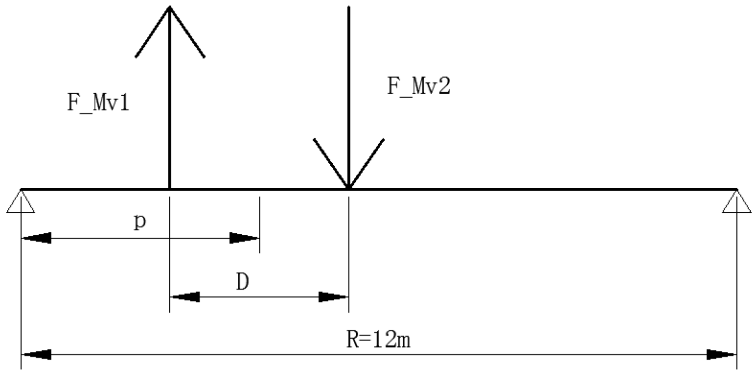


Figure 4-7 Force couple from Mv

Where

$$F_{Mv1} = F_{Mv2} = \frac{M_v}{D}$$

Where

$$M_v = M_d * C_v$$

Where Cv of each case will be found by using FEM analysis.

Then the load condition of this beam can be established by combine the forces of Fv and Mv.

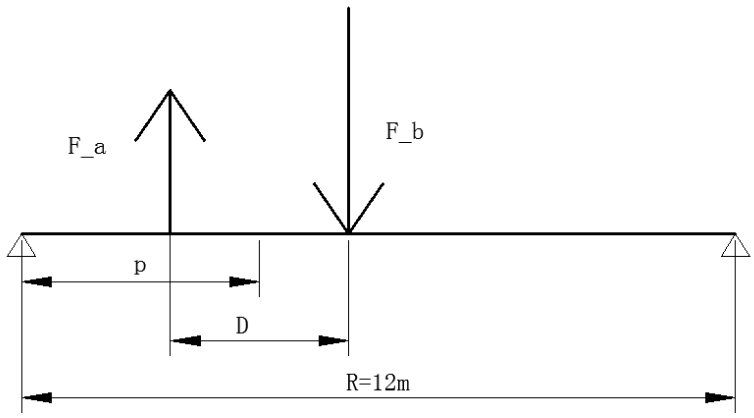


Figure 4-8 Combined vertical forces

Where

$$F_a = F_{Mv1} - F_{v1}$$

$$F_b = F_{Mv2} + F_{v2}$$

In order to calculate the required thickness of the longitudinal bulkhead, the maximum shear force should be calculated. But the maximum shear force cannot be calculated directly for this condition. Below shows the procedure of calculating the maximum shear force step by step.

First, separate the vertical forces at position a and position b into two simple beam problems and calculate the shear forces of each position respectively.

Divide the beam into 3 parts (1, 2, 3) by point a and point b.

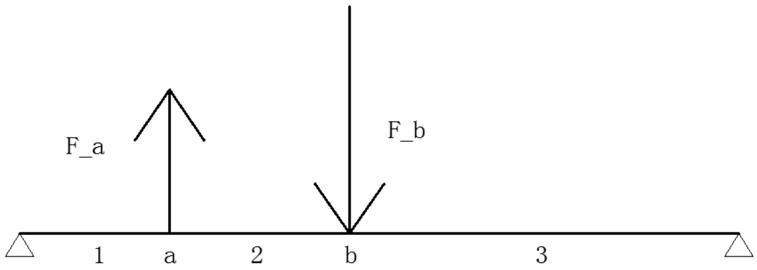


Figure 4-9 Divide the beam into 3 parts

Where

$$a = p - \frac{D}{2}$$

$$b = p + \frac{D}{2}$$

Calculate the shear force created by Fa:

$$Q_{Fa_1} = F_a * \frac{R - a}{R}$$

$$Q_{Fa_2} = Q_{Fa_3} = F_a * \frac{a}{R}$$

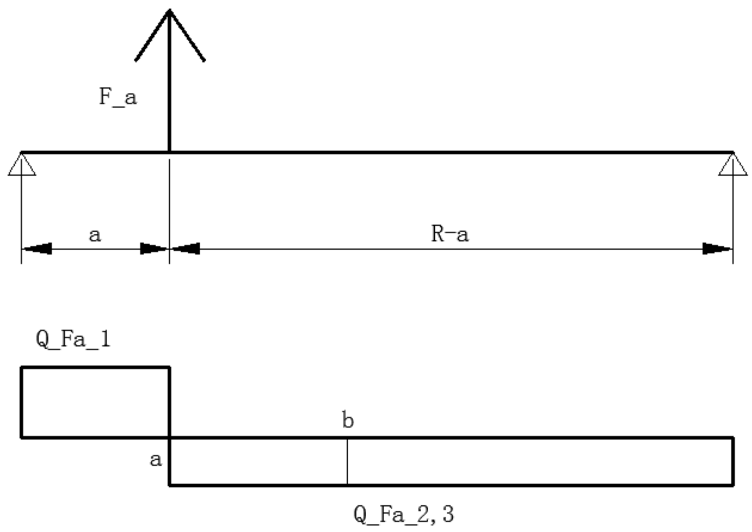


Figure 4-10 Shear force of Fa

Calculate the shear force created by Fb:

$$Q_{Fb_1} = Q_{Fb_2} = F_b * \frac{R - b}{R}$$

$$Q_{Fb_3} = F_b * \frac{b}{R}$$

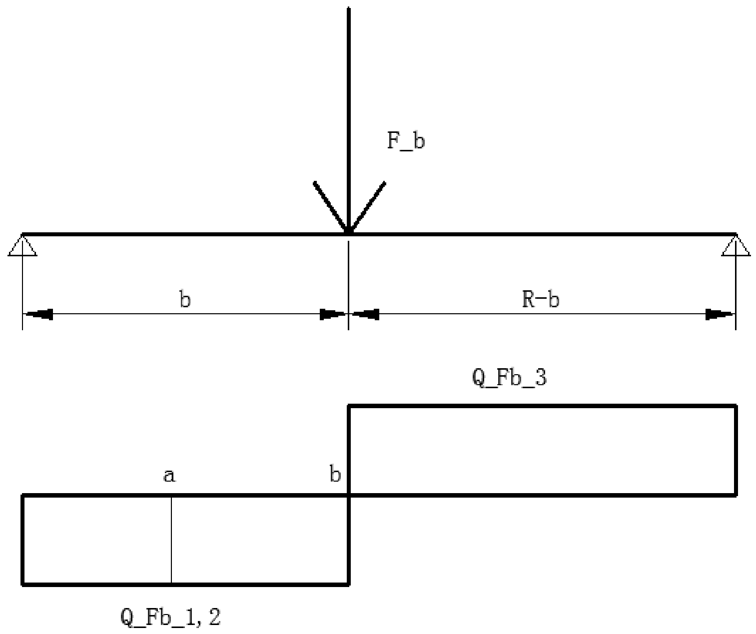


Figure 4-11 Shear force of Fb

Then the combined shear force of each part can be calculated:

$$Q_1 = \left|Q_{Fa_1} - Q_{Fb_1}\right|$$

$$Q_2 = Q_{Fa_2} + Q_{Fb_2}$$

$$Q_3 = \left|Q_{Fa_3} - Q_{Fb_3}\right|$$

Use the maximum shear force to calculate the required thickness of longitudinal bulkhead.

$$Q_{max} = \max(Q_1, Q_2, Q_3) = Q_2$$

The required section area of longitudinal bulkhead is:

$$A_{req} = \frac{Q_{max}}{\tau_{allow}}$$

So the required thickness of longitudinal bulkhead is:

$$t_{bulkhead} = \frac{A_{req}}{H} = \frac{\left(\frac{M_v}{D} - \frac{F_v}{2}\right) * \frac{p - \frac{D}{2}}{R} + \left(\frac{M_v}{D} + \frac{F_v}{2}\right) * \frac{p + \frac{D}{2}}{R}}{H * \tau_{allow}}$$

b. Calculate required thickness for deck plating

The thickness of deck plating consists of two parts - thickness taking care of vertical load Fv and thickness taking care of horizontal part of moment.

For vertical load, the load condition for a random position and crane diameter is shown in the picture below:

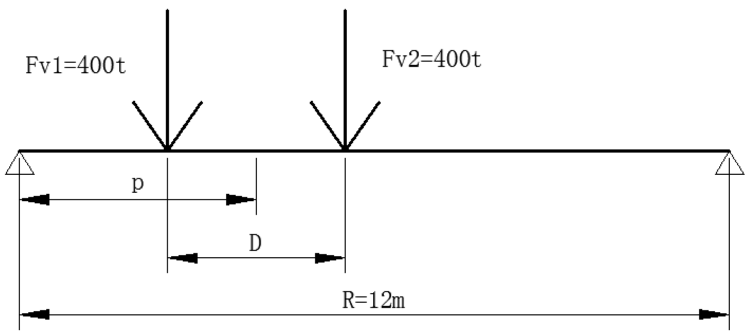


Figure 4-12 Load condition of Fv

The maximum bending moment cannot be calculated directly for this case. But it can be calculated by calculating the bending moment for Fv1 and Fv2 separately and then combine them.

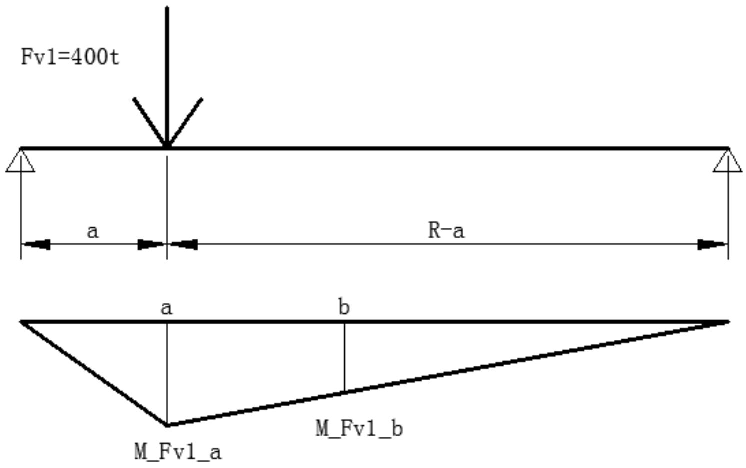


Figure 4-13 Bending moment for Fv1

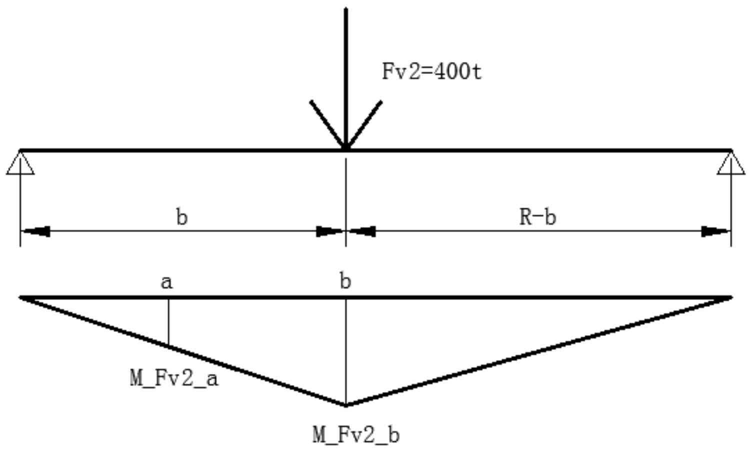


Figure 4-14 Bending moment for Fv2

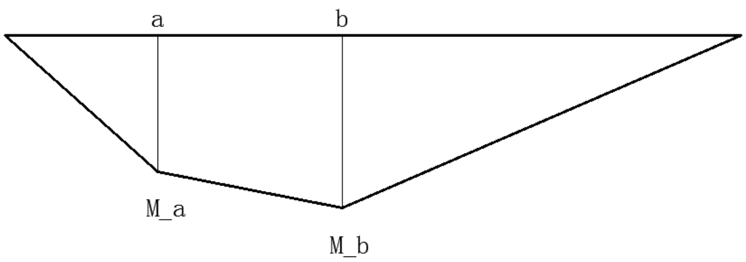


Figure 4-15 Combined bending moment of Fv1 and Fv2

From the picture of combined bending moment above, it can be found that the maximum bending moment of this case is either at position a or position b.

So in the hand calculation procedures of each position and diameter, the bending moment of these two points should be calculated and the larger one should be used to calculate the required thickness.

Below is the procedure to calculate the maximum bending moment.

First, calculate the bending moment at point a due to F_{v1}:

$$M_{Fv1_a} = -\frac{F_{v1} * a * (R - a)}{R}$$

Where

$$F_{v1} = F_v/2$$

$$a = p - \frac{D}{2}$$

Then, the bending moment at point b due to F_{v1} can be calculated since it's linear:

$$M_{Fv1_b} = M_{Fv1_a} * \frac{R - b}{R - a}$$

Where

$$b = p + \frac{D}{2}$$

Calculate the bending moment at point b & a due to F_{v2} in the same way:

$$M_{Fv2_b} = -\frac{F_{v2} * b * (R - b)}{R}$$

$$M_{Fv2_a} = M_{Fv2_b} * \frac{a}{b}$$

Where

$$F_{v2} = F_v/2$$

Then the combined bending moment at point a & b can be calculated:

$$M_a = M_{Fv1_a} + M_{Fv2_a}$$

$$M_b = M_{Fv1_b} + M_{Fv2_b}$$

So the maximum bending moment is the larger one of these two:

$$M_{Fv} = \max(M_a, M_b)$$

After the maximum bending moment is calculated, the required section modulus can be calculated accordingly:

$$Z_{req} = \frac{M_{Fv}}{\sigma_{allow}}$$

The required thickness of decks can be calculated from the required section modulus then.

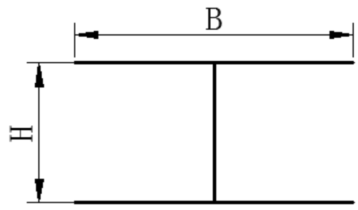


Figure 4-16 Cross section of beam

Assume the main deck and tween deck (or third deck) has the same thickness to simplify the calculation procedure. So the neutral axis is at the height of H/2. So the section modulus can be calculated as below:

$$Z = \frac{B * t_d * \left(\frac{H}{2}\right)^2 + \frac{1}{12} * H^3 * t_{bh}}{\frac{H}{2}} = B * t_d * H + \frac{1}{6} H^2 * t_{bh}$$

Where t_d is the thickness of decks and t_{bh} is the thickness of longitudinal bulkhead.

So the required thickness for deck plating due to vertical force can be calculated:

$$t_{d_v} = \frac{Z_{req} - \frac{1}{6} H^2 * t_{bh}}{B * H}$$

($t_{d_v} = 0$ if $Z_{req} - \frac{1}{6} H^2 * t_{bh} < 0$)

For deck thickness due to vertical part of design moment, the horizontal force of the force couple can be calculated as following:

$$F_h = \frac{M_h}{H} = \frac{M_d * C_h}{H}$$

Because

$$\sigma_{allow} = \frac{F_h}{\alpha * A}$$

$$A = D * t_{d_h}$$

So

$$t_{d_h} = \frac{F_h}{\alpha * D * \sigma_{allow}}$$

So the total thickness of deck is:

$$t_d = t_{d_v} + t_{d_h}$$

4.2.2 Calculation results

a. Thicknesses for varying positions when H is 3m

Table 4-9 Thicknesses for varying positions when H is 3m

position	t_md	t_td	t_bh
3000	38.7	29.0	41.5
4000	38.3	28.7	40.6
5000	37.2	27.9	39.6
6000	35.4	26.6	38.7
7000	32.9	24.6	37.8
8000	29.5	22.2	36.9
9000	25.4	19.0	36.7

Where t_md is the thicknesses for main deck, t_td is the thicknesses for tween deck and t_bh is the thicknesses for bulkhead.

b. Thicknesses for varying diameters when H is 3m

Table 4-10 Thicknesses for varying diameters when H is 3m

diameter	t_md	t_td	t_bh
2500	43.9	32.9	43.7
3000	35.5	26.6	38.4
3500	29.6	22.2	34.7
4000	25.2	18.9	31.8

c. Thicknesses for varying positions when H is 6m

Table 4-11 Thicknesses for varying positions when H is 6m

position	t_md	t_td	t_bh
3000	18.3	13.7	15.4
4000	18.4	13.8	15.1
5000	18.1	13.5	14.8
6000	17.3	13.0	14.5
7000	16.2	12.2	14.2
8000	14.4	10.8	15.4
9000	12.7	9.5	16.9

Where t_td is the thicknesses for third deck.

d. Thicknesses for varying diameters when H is 6m

Table 4-12 Thicknesses for varying diameters when H is 6m

diameter	t_md	t_td	t_bh
2500	21.0	15.7	16.7
3000	17.4	13.0	14.4
3500	14.8	11.1	12.9
4000	12.8	9.6	11.7

5 EXAMPLE CASE

An example case is used to show how to use this design tool and to demonstrate whether this design tool is effective.

5.1 Determine original parameters

5.1.1 Determine design loads and the crane diameter

Assume the design loads and crane diameter.

Table 5-1 Parameters

Parameter	Value	Unit
Md	6000	tm
Fv	500	t
D	3000	mm

Check the required thickness of the crane to see if the design loads and crane diameter are proper.

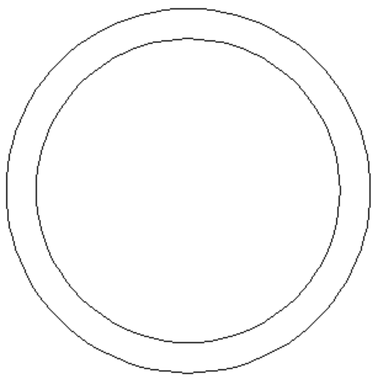


Figure 5-1 Cross section of crane

$$\sigma_{\mathrm{vert}} = \frac{F_v}{2 * \pi * R * t} + \frac{M}{Z}$$

$$\mathrm{A} = \pi * D * t$$

$$\mathrm{Z} = \frac{1}{2} \pi * D^2 * t$$

Usually, high stress steel is used for heavy crane cylinder, so 200 MPa is used as required thickness.

So the required thickness then can be calculated.

$$\mathrm{t_{req}} = 24mm$$

This thickness is reasonable so the assumed design loads and crane diameter can be used.

5.1.2 Establish all the parameters for calculation

Table 5-2 Parameters

Parameter	Value	Unit
Md	6000	tm
Fv	500	t
D	3000	mm
R	15	m
p	5000	mm
α	3	
Ship breadth	25	m
Position of crane in transverse direction	10	m
Height between two decks	3	m
σ_{allow} for main deck	120	MPa
σ_{allow} for tween deck or third deck	160	MPa
τ_{allow}	90	MPa

5.2 Calculating procedure

First, check the required thicknesses when the crane is penetrated into two decks.

5.2.1 Determine Mh, Mv & B

Because the diameter is 3000mm, position is 5000mm and the height is 3m, the formula below should be used to calculate Ch.

$$\mathrm{C_h} = -0.167C_p + 0.735$$

Where

$$C_p = \frac{p}{R} = 0.33$$

So

$$\mathrm{C_h} = 0.68$$

So

$$\mathrm{C_v} = 1 - \mathrm{C_h} = 0.32$$

So

$$\mathrm{M_h} = \mathrm{C_h} * \mathrm{M_d} = 4.08 * 10^{10} Nmm$$

$$\mathrm{M_v} = \mathrm{C_v} * \mathrm{M_d} = 1.92 * 10^{10} Nmm$$

The flange breadth can be calculated using crane diameter:

$$\mathrm{B} = 2\mathrm{D} = 6000\mathrm{mm}$$

5.2.2 Calculating bulkhead thickness

According to the calculating procedure in 4.2.1, the required thickness of bulkhead can be calculated by the following formula:

$$\mathrm{t_{bulkhead}} = \frac{(\frac{\mathrm{M_v}}{\mathrm{D}} - \frac{\mathrm{F_v}}{2}) * \frac{\mathrm{p} - \frac{\mathrm{D}}{2}}{\mathrm{R}} + (\frac{\mathrm{M_v}}{\mathrm{D}} + \frac{\mathrm{F_v}}{2}) * \frac{\mathrm{p} + \frac{\mathrm{D}}{2}}{\mathrm{R}}}{H * \tau_{allow}}$$

So

$$\mathrm{t_{bulkhead}} = 17.7mm$$

5.2.3 Calculating deck thicknesses

According to the calculating procedure in 4.2.1, the required thickness of decks can be calculated by the following procedure:

First, calculate the required thicknesses due to Fv:

$$\mathrm{M_{Fv1_a}} = -\frac{\mathrm{F_{v1}} * \mathrm{a} * (\mathrm{R} - \mathrm{a})}{\mathrm{R}} = 6.7 * 10^9 Nmm$$

$$\mathrm{M_{Fv1_b}} = \mathrm{M_{Fv1_a}} * \frac{R - b}{R - a} = 5.0 * 10^9 Nmm$$

$$\mathrm{M_{Fv2_b}} = -\frac{\mathrm{F_{v2}} * \mathrm{b} * (\mathrm{R} - \mathrm{b})}{\mathrm{R}} = 9.2 * 10^9 Nmm$$

$$\mathrm{M_{Fv2_a}} = \mathrm{M_{Fv2_b}} * \frac{a}{b} = 5.0 * 10^9 Nmm$$

$$\mathrm{M_a} = \mathrm{M_{Fv1_a}} + \mathrm{M_{Fv2_a}} = 1.2 * 10^{10} Nmm$$

$$\mathrm{M_b} = \mathrm{M_{Fv1_b}} + \mathrm{M_{Fv2_b}} = 1.4 * 10^{10} Nmm$$

$$\mathrm{M_b} = \mathrm{M_{Fv1_b}} + \mathrm{M_{Fv2_b}} = 1.4 * 10^{10} Nmm$$

For main deck:

$$\mathrm{Z_{req}} = \frac{\mathrm{M_{Fv}}}{\sigma_{\mathrm{allow}}} = 1.2 * 10^8 mm^3$$

$$\mathrm{t_{md_v}} = \frac{\mathrm{Z_{req}} - \frac{1}{6} H^2 * t_{bh}}{B * H} = 5.1mm$$

For tween deck:

$$\mathrm{Z_{req}} = \frac{\mathrm{M_{Fv}}}{\sigma_{\mathrm{allow}}} = 8.9 * 10^7 mm^3$$

$$t_{td_v} = \frac{Z_{req} - \frac{1}{6}H^2 * t_{bh}}{B * H} = 3.4mm$$

Then calculate the thicknesses caused by Mh:

$$F_h = \frac{M_h}{H} = \frac{M_d * C_h}{H} = 1.36 * 10^7 N$$

For main deck:

$$t_{md_h} = \frac{F_h}{\alpha * D * \sigma_{allow}} = 12.6mm$$

For tween deck:

$$t_{td_h} = \frac{F_h}{\alpha * D * \sigma_{allow}} = 9.4mm$$

So the total thicknesses of main deck and tween deck can be calculated.

For main deck:

$$t_{md} = t_{md_v} + t_{md_h} = 17.7mm$$

For tween deck:

$$t_{td} = t_{td_v} + t_{td_h} = 12.9mm$$

5.3 Evaluating the thicknesses and decide whether the crane should penetrate in 2 or 3 decks

According to the result thicknesses calculated from 5.2,

Table 5-3 Required thicknesses

Parameter	Value	Unit
$t_{bulkhead}$	17.7	mm
t_{md}	17.7	mm
t_{td}	12.9	mm

All the required thicknesses are below 20mm. So it does not need to penetrate into 3 decks.

5.4 Check the results by FEM analysis

5.4.1 Model description

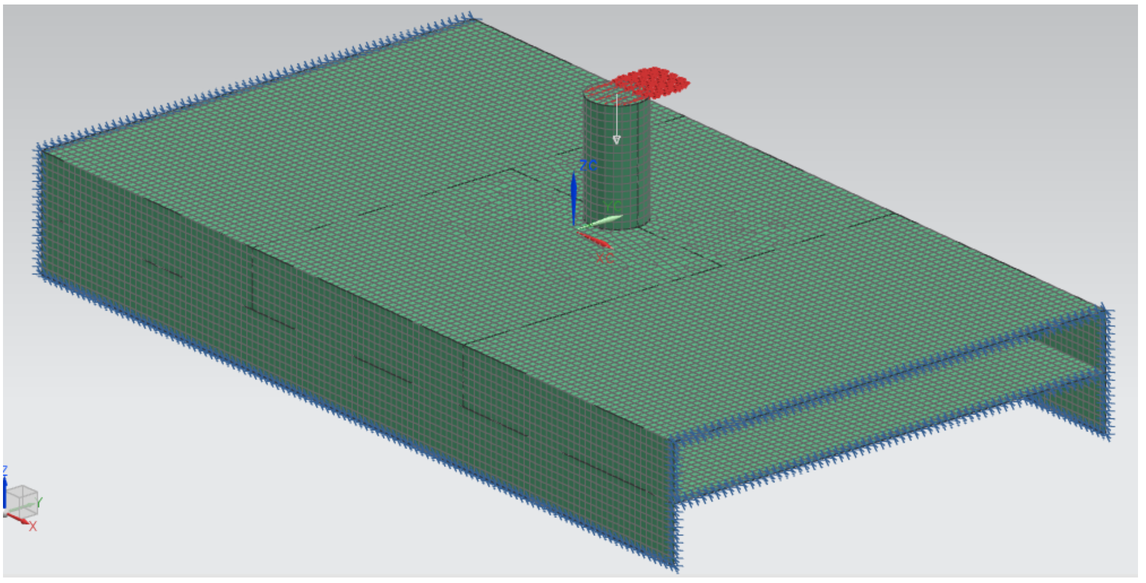


Figure 5-2 Model in NX

Above is a full scale model of the structure. The longitudinal bulkhead is supported by two transverse bulkheads and the two decks are supported by the ship sides.

The boundary condition can be seen from the picture, all the free edges of ship sides and decks are fixed. The design loads act on the top of the crane.

2D mesh with element size of 400mm is used for all parts of the structure. The thicknesses of the decks and longitudinal bulkhead from hand calculations are used. 30mm is used for the crane; 20mm is used for the transverse bulkheads and ship sides.

5.4.2 Result stresses

According to the stress allocation, the elements highlighted are the elements checked and the mean value of these elements is used to verify the hand calculation.

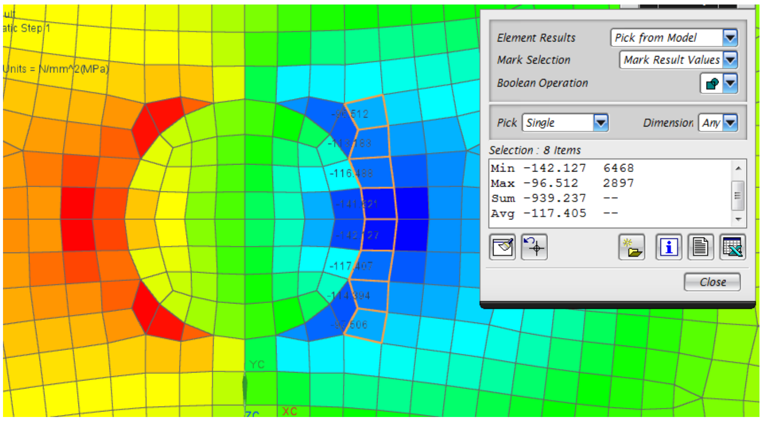


Figure 5-3 Elements checked for main deck

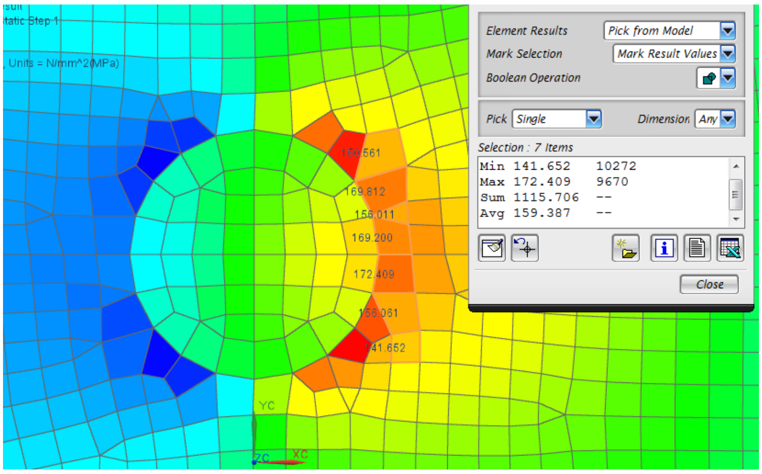


Figure 5-4 Elements checked for tween deck

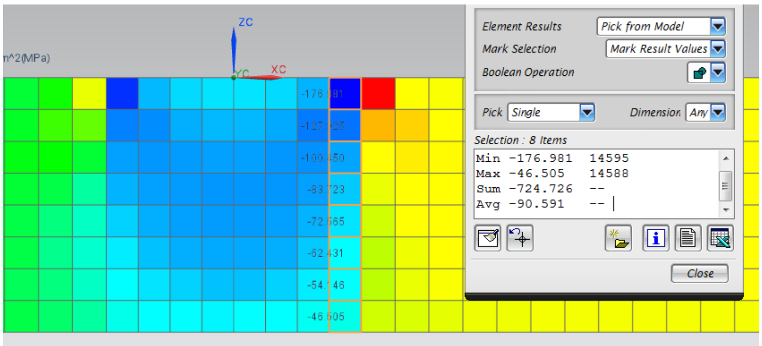


Figure 5-5 Elements checked for longitudinal bulkhead

Below is the comparison of the stresses found from FEM analysis and the required stresses used in hand calculation to calculate the thicknesses.

Table 5-4 Comparison of the stresses

Parameter	Allowable value	Actual value	Unit
σ for main deck	120	117	MPa
σ for tween deck or third deck	160	159	MPa
τ for bulkhead	90	91	MPa

From Table 5-4 it can be seen that the stresses from FEM analysis are very close to the allowable stresses used in hand calculation. So in this case, the hand calculation procedure is proved to be feasible.

6 DISCUSSION

6.1 Comparison of the thicknesses from hand calculations and FEM analysis

From the comparison of the thicknesses calculated from hand calculation and FEM analysis in the appendix, it can be seen that the results are generally in good corresponding, which proves that the hand calculation tool established in this thesis is feasible in such conditions. However, the results also have some level of discrepancy. These discrepancies can be caused by various reasons. Below are detailed analyses of the comparison of thicknesses.

First, for all positions, diameters and heights of bulkhead, the hand calculated thicknesses for main deck are mostly between the required thicknesses calculated from the mean stress and the maximum stress found from FEM analysis, and are more close to the thicknesses calculated from mean stresses. While for tween deck, the hand calculated thicknesses are more close to the thicknesses calculated from the maximum stresses found in FEM analysis. This phenomenon means that in FEM analysis, the main deck has a higher stress than tween deck when using the same thickness. But from the hand calculation procedure, the stresses of main deck and tween deck should be the same in this situation. The reason for this phenomenon in FEM analysis can be inferred as the boundary condition and load application in NX model. The boundary condition in NX model is fixed at all free edges of decks and bulkhead. Since the load application is at top of the crane and the main deck is fixed at all edges, it tends to take more of the moment than the tween deck. However, this doesn't cause a big difference so it can be ignored for early stage estimation.

Second, for both main deck and tween deck for varying positions, the hand calculated thicknesses go downwards at the right end while the required thicknesses calculated from FEM analyses go upwards. Meanwhile the required thicknesses due to hand calculation are going upwards or steady at the right end while the required thicknesses calculated from FEM analyses are going downwards or steady. This phenomenon is supposed to be mainly caused by the inaccuracy of the Ch formulas for varying positions. In this case, the diameter of crane is 3m while the length of the bulkhead is only 12m, 4 times of crane diameter. What's more the positions been taken into consideration are from 0.25R to 0.75R, which is only twice of crane diameter. So the asymmetry caused by the difference of load on each end of the crane cannot be ignored. And the data was not enough for getting a proper quadratic formula for Ch for varying positions. So, linear formulas which caused some inaccuracy are used instead to describe Ch in this case.

Third, the decreasing rate of thicknesses are almost the same by both hand calculations and FEM analyses for varying diameters for all the three parts at both heights. So it can be derived that the Ch formula should be linear according to varying diameters.

Forth, from the overview of all the results, the crane is recommended to penetrate into 3 decks for these cases.

Fifth, some high values of maximum stress in FEM analyses can be ignored because it can be taken care of by adding local structures and the values are not too high in this case.

Last, some other reasons that might cause inaccuracy of results:

a. Element size is comparatively large and the mesh is not very regular at the joints of the crane and ship structures.

   For example, the highlighted elements in the Figure 6-1 are used for calculating the compressive stress while the ideal elements to use is shown in Figure 3-8.

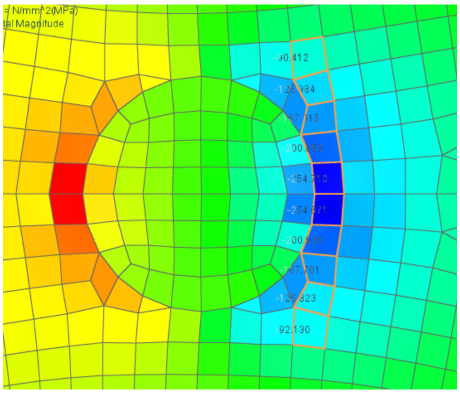


Figure 6-1 Elements used for calculating stress

b. When calculating thicknesses on deck according to Mh in hand calculation procedure, the length of cross area is D while in FEM analysis, the length of cross area of the elements used to calculating mean stress is D + element size.

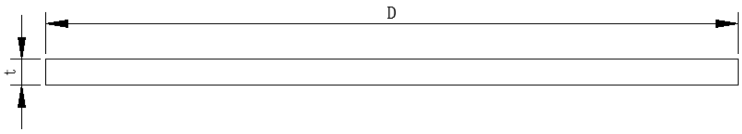


Figure 6-2 Cross section for hand calculation

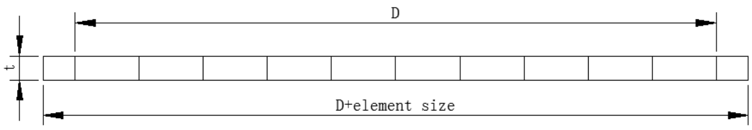


Figure 6-3 Cross section for FEM analysis

6.2 Discussion about some assumptions and simplifications

First, the reason of assuming the Fv to two point loads at each side of the crane is that the crane diameter is large enough comparing to the length of longitudinal bulkhead, which cannot be ignored. For those bulkhead lengths very long comparing to crane diameter, the Fv can be simplified as one point load.

Second, the simplification of Md is essential to developing this hand calculation tool. After establish the Ch and Cv values, the required thicknesses of decks and bulkhead can be calculated by simple hand calculations then.

Third, about the value of α, it is to some extent constant as 3 in the studied cases, because the positions near the end of bulkhead are avoided. This value can be lower if the crane is penetrated near the end of the longitudinal bulkhead or deck, which will cause higher stress.

Forth, for the flange breadth, the value is approximately from D to 2D, 2D is used fro simplification.

Last, the boundary conditions both in hand calculations and FEM analysis are simplified. Because in reality, it should be a combination of simply supported and fixed boundary condition while both in hand calculation and FEM analysis, the boundary conditions should be explicitly defined.

6.3 Comments on the example case study in Chapter 5

The results in the example case study are very conservative, which can prove that this hand calculation is feasible to some extent. However, this tool still has some potential limits.

First, for calculation Ch, D and p cannot be variables at the same time because in the formulas for varying position, the diameter is fixed and in the formulas for varying diameter the position is fixed.

The formula for calculating Ch for varying positions won’t be useful if the length of bulkhead is very long comparing to crane diameter.

6.4 Comments on the work of this thesis

The crucial things in this project work are the assumptions and simplifications. Sometimes by making an assumption, impossible works become possible or complex works become simple. However, sometimes improper assumptions or simplifications will lead to non-conservative results so they need to be verified and adjusted sometimes.

7 CONCLUSIONS

In this thesis, a simple hand calculation tool is established for designing structure for heavy crane integration on offshore vessels at an early stage of design. This tool is developed for varying positions and diameters of the crane. Some assumptions and simplifications are used to establish the tool. NX and matlab are also used to find parameters and formulas for this tool. The hand calculation tool is verified by FEM analysis and an example case study.

This hand calculation tool is demonstrated to be feasible in this condition but still has some limitations.

The most important is the assumptions and simplifications and the way of thinking and solving engineering problems.

8 FURTHER WORK

In this thesis, the hand calculation tool could handle varying positions for a fixed diameter and varying diameters for a fixed position. In the further work, the Ch formula for varying positions for varying diameter can be investigated.

Also, quadratic formulas for Ch for varying positions can be developed for structures with longer bulkheads.

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[3] Ship Structural Mechanics [M]. Defense Industry Press, China, 1984.

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[5] Structural design tool for the integration of heavy cranes on offshore vessels. Jon Egil Sollied

APPENDIX

Appendix A Thicknesses comparisons from hand calculation and FEM analysis

Thicknesses of main deck of varying positions when penetrating to 2 decks:

Table 0-1 Thicknesses of main deck of varying positions when penetrating to 2 decks

Position(mm)	Hand(mm)	NX_mean(mm)	NX_max(mm)
3000	38.7	30.8	40.2
4000	38.3	26.7	42.5
5000	37.2	28.0	42.8
6000	35.4	28.0	42.5
7000	32.9	27.5	40.0
8000	29.5	27.5	40.8
9000	25.4	28.8	41.5

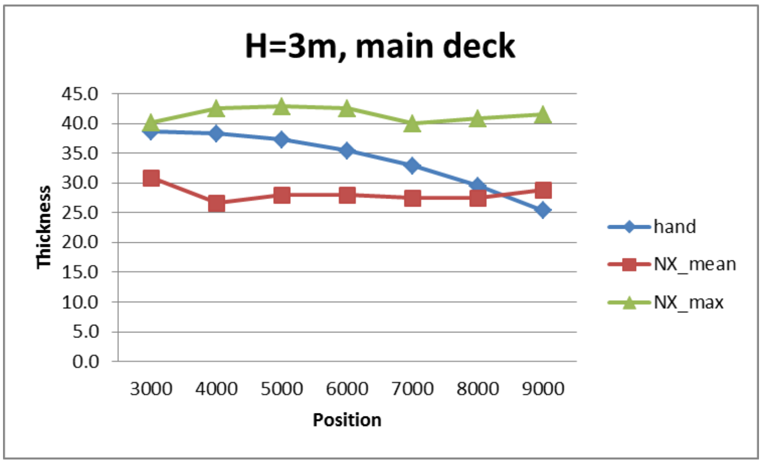

Figure 0-1 Thicknesses of main deck of varying positions when penetrating to 2 decks

Thicknesses of tween deck of varying positions when penetrating to 2 decks:

Table 0-2 Thicknesses of tween deck of varying positions when penetrating to 2 decks

Position(mm)	Hand(mm)	NX_mean(mm)	NX_max(mm)
3000	29.0	21.4	27.4
4000	28.7	16.9	23.3
5000	27.9	17.4	21.9
6000	26.6	16.8	22.3
7000	24.6	16.6	21.9
8000	22.2	16.1	21.1
9000	19.0	17.8	23.3

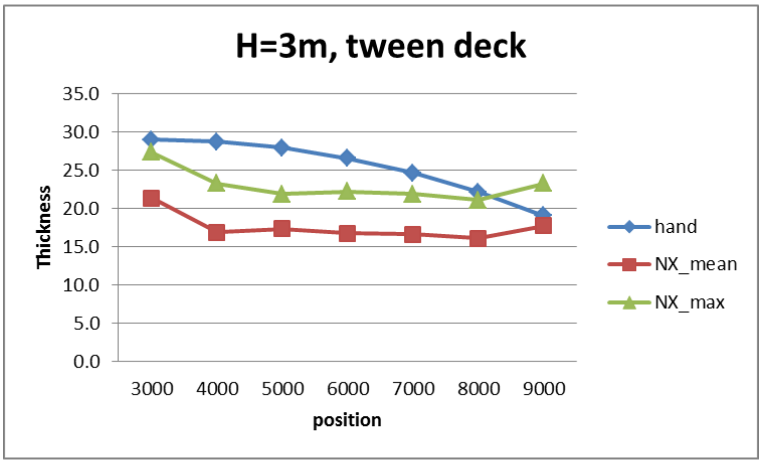

Figure 0-2 Thicknesses of tween deck of varying positions when penetrating to 2 decks

Thicknesses of bulkhead of varying positions when penetrating to 2 decks:

Table 0-3 Thicknesses of bulkhead of varying positions when penetrating to 2 decks

Position(mm)	Hand(mm)	NX_mean(mm)
3000	41.5	43.6
4000	40.6	43.6
5000	39.6	39.1
6000	38.7	38.2
7000	37.8	36.9
8000	36.9	38.2
9000	36.7	36.4

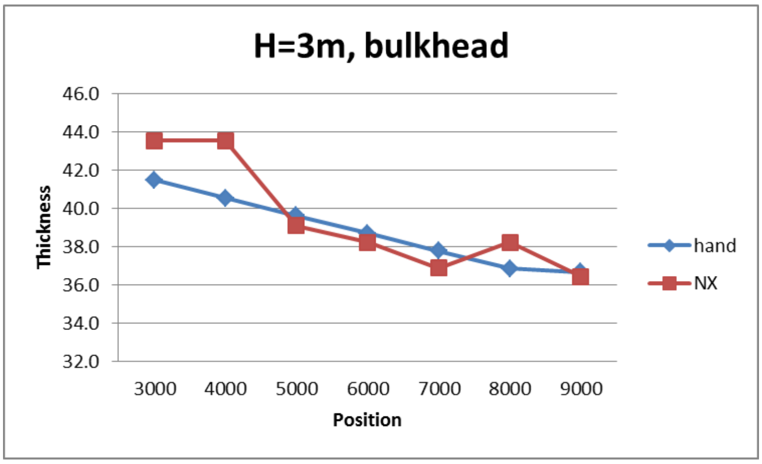

Figure 0-3 Thicknesses of bulkhead of varying positions when penetrating to 2 decks

Thicknesses of main deck of varying diameters when penetrating to 2 decks:

Table 0-4 Thicknesses of main deck of varying diameters when penetrating to 2 decks

Diameter(mm)	Hand(mm)	NX_mean(mm)	NX_max(mm)
2500	43.9	34.7	50.3
3000	35.5	28.0	42.5
3500	29.6	23.8	37.7
4000	25.2	17.5	33.2

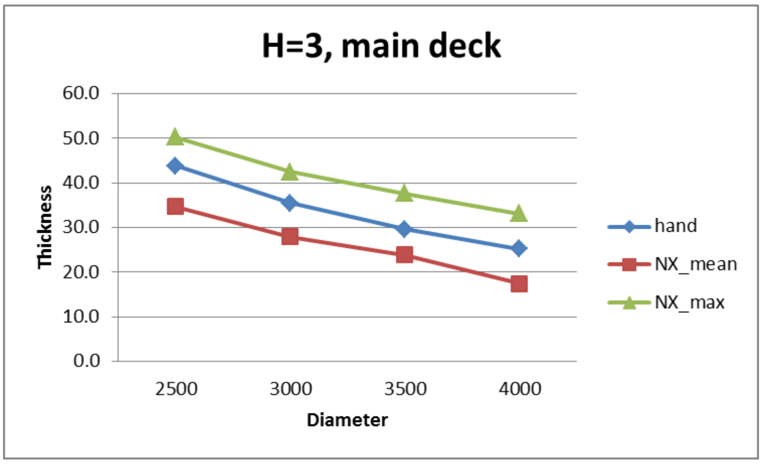

Figure 0-4 Thicknesses of main deck of varying diameters when penetrating to 2 decks

Thicknesses of tween deck of varying diameters when penetrating to 2 decks:

Table 0-5 Thicknesses of tween deck of varying diameters when penetrating to 2 decks

Diameter(mm)	Hand(mm)	NX_mean(mm)	NX_max(mm)
2500	32.9	20.4	27.0
3000	26.6	16.8	22.3
3500	22.2	14.8	18.5
4000	18.9	12.0	16.8

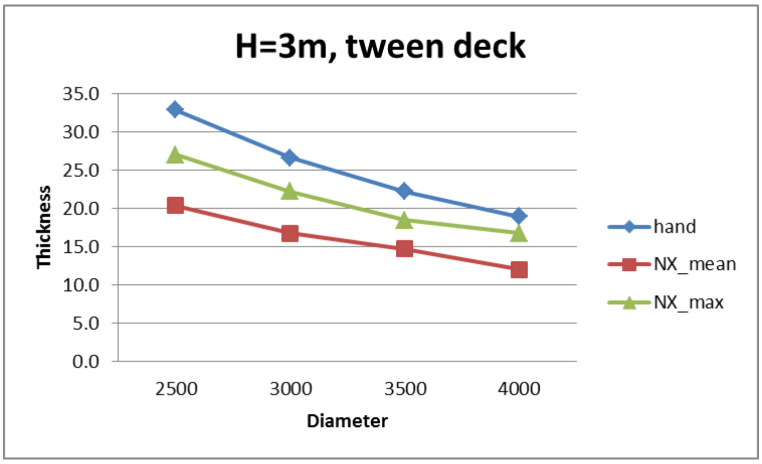

Figure 0-5 Thicknesses of tween deck of varying diameters when penetrating to 2 decks

Thicknesses of bulkhead of varying diameters when penetrating to 2 decks:

Table 0-6 Thicknesses of bulkhead of varying diameters when penetrating to 2 decks

Diameter(mm)	Hand(mm)	NX_mean(mm)
2500	43.7	47.1
3000	38.4	38.2
3500	34.7	32.0
4000	31.8	28.4

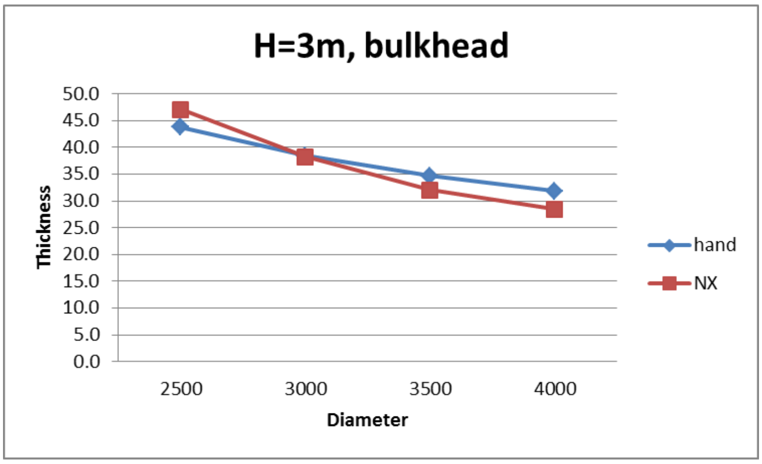

Figure 0-6 Thicknesses of bulkhead of varying diameters when penetrating to 2 decks

Thicknesses of main deck of varying positions when penetrating to 3 decks:

Table 0-7 Thicknesses of main deck of varying positions when penetrating to 3 decks

Position(mm)	Hand(mm)	NX_mean(mm)	NX_max(mm)
3000	18.3	16.9	22.8
4000	18.4	14.6	21.4
5000	18.1	14.6	22.5
6000	17.3	14.8	22.8
7000	16.2	15.2	23.2
8000	14.4	15.0	22.8
9000	12.7	16.1	23.7

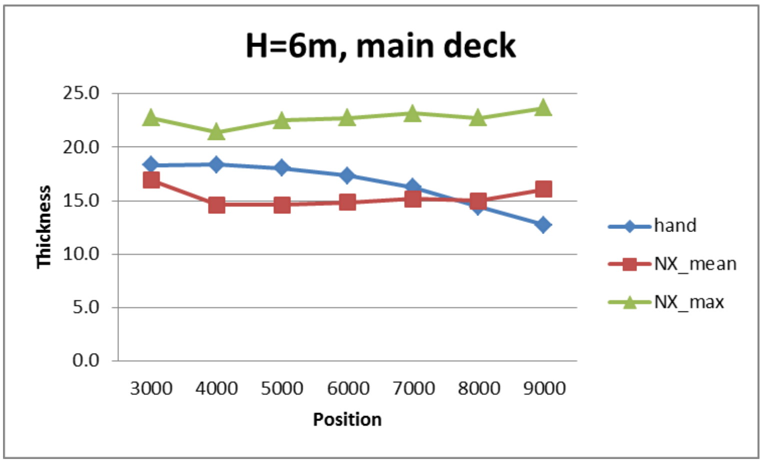

Figure 0-7 Thicknesses of main deck of varying positions when penetrating to 3 decks

Thicknesses of tween deck of varying positions when penetrating to 3 decks:

Table 0-8 Thicknesses of tween deck of varying positions when penetrating to 3 decks

Position(mm)	Hand(mm)	NX_mean(mm)	NX_max(mm)
3000	13.7	10.5	14.6
4000	13.8	8.4	13.3
5000	13.5	8.0	11.5
6000	13.0	8.0	13.6
7000	12.2	8.3	11.8
8000	10.8	7.6	13.1
9000	9.5	9.1	12.8

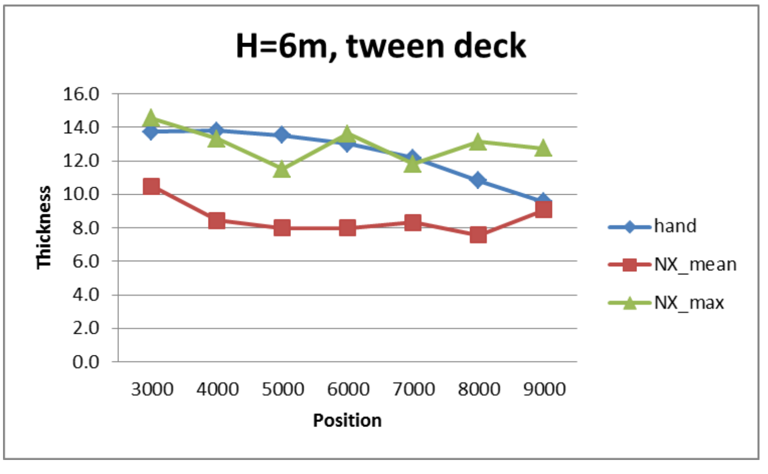

Figure 0-8 Thicknesses of tween deck of varying positions when penetrating to 3 decks

Thicknesses of bulkhead of varying positions when penetrating to 3 decks:

Table 0-9 Thicknesses of bulkhead of varying positions when penetrating to 3 decks

Position(mm)	Hand(mm)	NX_mean(mm)
3000	15.4	15.1
4000	15.1	14.4
5000	14.8	14.0
6000	14.5	13.6
7000	14.2	13.1
8000	15.4	12.9
9000	16.9	12.9

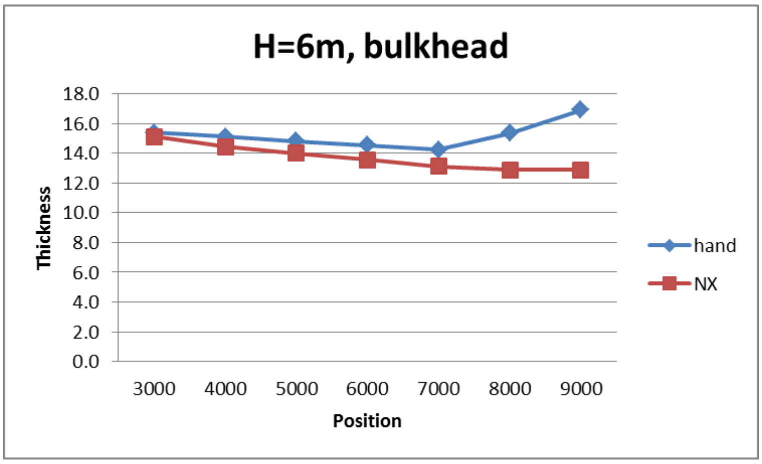

Figure 0-9 Thicknesses of bulkhead of varying positions when penetrating to 3 decks

Thicknesses of main deck of varying diameters when penetrating to 3 decks:

Table 0-10 Thicknesses of main deck of varying diameters when penetrating to 3 decks

Diameter(mm)	Hand(mm)	NX_mean(mm)	NX_max(mm)
2500	21.0	19.3	29.4
3000	17.4	14.8	22.8
3500	14.8	12.5	19.4
4000	12.8	10.6	16.4

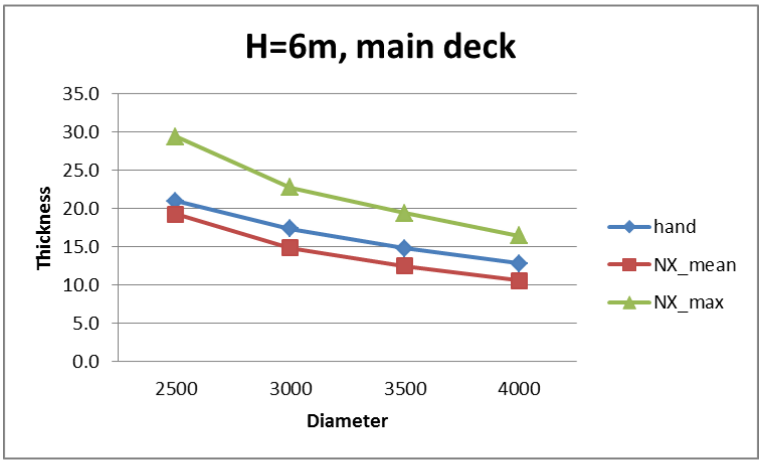

Figure 0-10 Thicknesses of main deck of varying diameters when penetrating to 3 decks

Thicknesses of tween deck of varying diameters when penetrating to 3 decks:

Table 0-11 Thicknesses of tween deck of varying diameters when penetrating to 3 decks

Diameter(mm)	Hand(mm)	NX_mean(mm)	NX_max(mm)
2500	15.7	8.4	14.0
3000	13.0	8.0	13.6
3500	11.1	7.3	11.9
4000	9.6	6.3	9.5

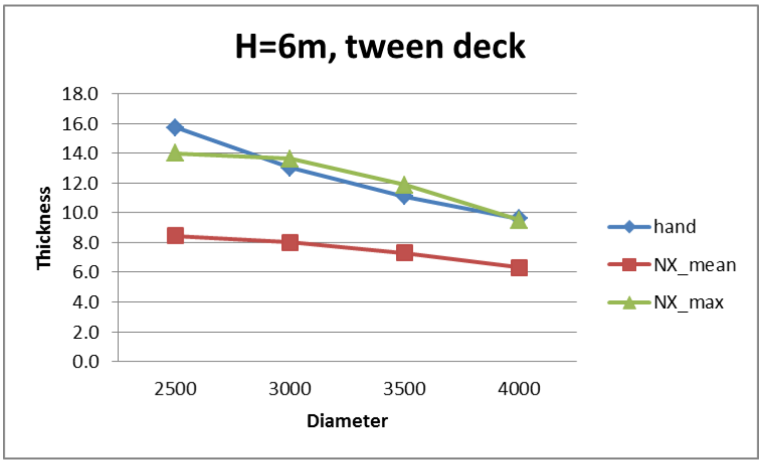

Figure 0-11 Thicknesses of tween deck of varying diameters when penetrating to 3 decks

Thicknesses of bulkhead of varying diameters when penetrating to 3 decks:

Table 0-12 Thicknesses of bulkhead of varying diameters when penetrating to 3 decks

Diameter(mm)	Hand(mm)	NX_mean(mm)
2500	16.7	16.2
3000	14.4	13.6
3500	12.9	11.6
4000	11.7	10.0

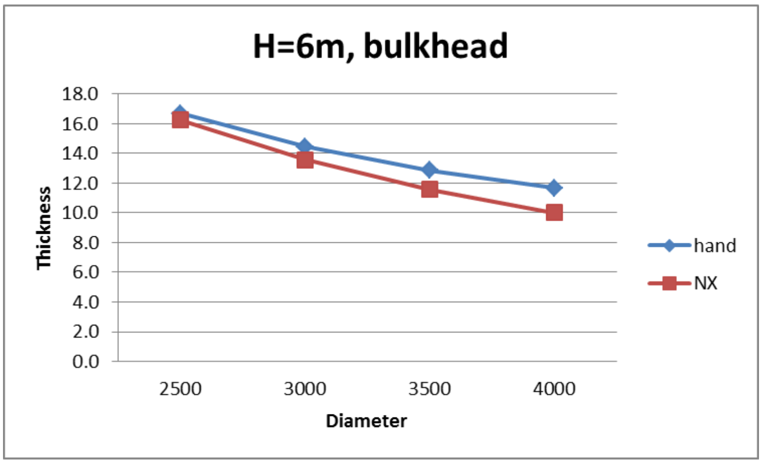

Figure 0-12 Thicknesses of bulkhead of varying diameters when penetrating to 3 decks

Appendix B Matlab codes for getting Ch formulas

Ch for varying crane positions when H is 3m

```
function h3pos
x=0.25:(1/12):0.75;
y1=[0.70,0.67,0.67,0.65,0.64,0.61,0.62];
plot(x,y1,'r.')
hold on;
a=polyfit(x,y1,1);
y2=polyval(a,x);
plot(x,y2);
disp(['y =' poly2str(a,'x')]);
```

Ch for varying crane diameters when H is 3m

```
function h3dia
x=2500:500:4000;
y1=[0.67,0.65,0.65,0.61];
plot(x,y1,'r.')
hold on;
a=polyfit(x,y1,1);
y2=polyval(a,x);
plot(x,y2);
disp(['y =' poly2str(a,'x')]);
```

Ch for varying crane positions when H is 6m

```
function h6pos
x=0.25:(1/12):0.75;
y1=[0.79,0.77,0.76,0.74,0.72,0.70,0.69];
plot(x,y1,'r.')
hold on;
a=polyfit(x,y1,1);
y2=polyval(a,x);
plot(x,y2);
disp(['y =' poly2str(a,'x')]);
```

Ch for varying crane diameters when H is 6m

```
function h6dia
x=2500:500:4000;
y1=[0.75,0.74,0.73,0.72];
plot(x,y1,'r.')
hold on;
a=polyfit(x,y1,1);
y2=polyval(a,x);
plot(x,y2);
disp(['y =' poly2str(a,'x')]);
```