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Development of Racking calculations in Concept Design Phase for a ROPAX Vessel

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Development of Racking calculations in Concept Design Phase for a ROPAX Vessel

Introduction
The main dimensions decide many of the ship's characteristics, e.g. stability, hold capacity, power requirements and economic efficiency. Determining the main dimensions is therefore a particularly important phase in the overall design. In the conceptual design phase, a preliminary scantling of the construction is also made. The selection of an appropriate scantlings is important for approximate assessment of structural weight and achievable clearances. The achievable clearances are affected by the height of deck beams and girders, and may result in a lower displacement/deadweight ratio.

ROPAX and RO/RO ships consists of multiple decks and few effective transverse strength members. The transverse bulkheads primarily resist the transverse deformation, referred to as racking, which is caused when a ship is rolling. Racking is normally compensated by deep web frames, which affects the spatial requirements for cargo. A more slender structure is beneficial, but the required calculations to determine a typical midship section like this, is not applied in the concept design phase.

Motivation
Where the transverse bulkheads are widely spaced, or not present at all, deep web frames and beams is introduced to compensate. The deep web frames are the commonly design today, but it demands a lot of space which could be used for cargo. This must be compensated by increasing the breadth of the ship, or the capacity of vehicles/cargo must be reduced. The advantage of this simplified method is that you early can determine the need for space, and thus the dimension required, and also calculate a provisional weight for a new design.
There is a second method for racking calculations, which is more time demanding and not suitable for use in an early design phase. The advanced method for a racking strength assessment should give a more slender structure, which is space and weight saving.
The referred methods are the necessary calculation approaches for racking, given by the rules and regulations from DNV GL. In this project, DNV GL is chosen as the class society. The methods applied will be evaluated and used to find a new method to efficiently determine a typical midship section without doing the full analysis scope. The midship section should be applicable to use in the concept design phase to determine size and weight of the ship.

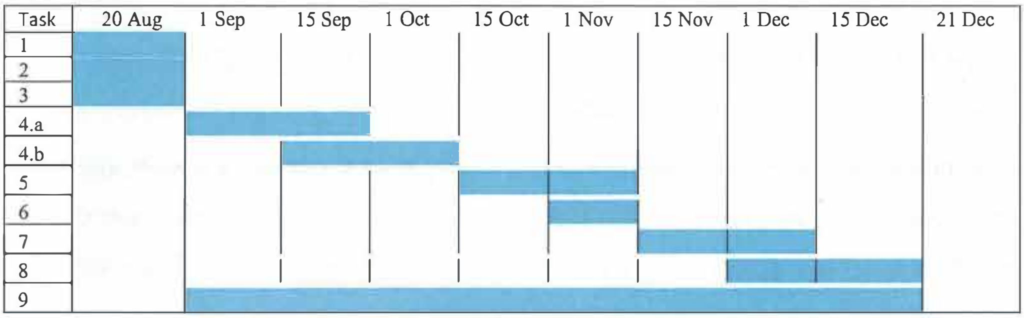
Objectives / Research Questions
Research questions:
Objectives:

1. Investigate the current practice in the industry with respect to design solutions and methods, and relevant regulations.
2. Compare and evaluate the consequences and the opportunities with the advanced method against the simplified method.

3. Investigate the effect of global loads (torsion) vs local loads (sea pressure, deck cargo/vehicles) on racking, to determine the governing impact.
4. Evaluate the strong web frames (commonly design today/prerequisite for a simplified method) against a more slender structure which is beneficial for vehicle lane width and weight for a specific ship.
5. Combine the results in 3 and 4 to find a method to efficiently/quickly determine a typical midship section (hence size and weight of the vessel) in concept/initial design phase without doing the full analysis scope.

Milestones:
Tasks:
1. Identification of the current practice in the industry with respect to design solutions and methods, and relevant regulations.
2. Literature survey on racking problematics today, and solutions.
3. Define test case.
4. Racking strength assessment.
    a. Simplified beam model
    b. Global FE strength analysis
5. Evaluate the consequences and the opportunities with the simplified and advanced method.
6. Investigate effect of loads to determine governing impacts.
7. Find method to efficiently determine a typical midship section in concept design phase.
8. Present results
9. Report

Schedule



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Abstract

Two racking strength calculations methods have been used to calculate the bending stresses which occurs on a car carrier when a ship is rolling in waves. The accelerations on the ship's structure and deck load will create a force tending to distort the structure transversally and may cause deformation at the corners. To investigate the deformation which occurs at the corners, the given methods from DNV GL, a beam analysis in 3D Beam and a full global FE model in Sesam GeniE is used.

It was found that the beam analysis gives a conservative result, with stresses over the permissible values for bending stress. As the beam analysis is very simplified, structural members contributing to the racking strength is not contributing. The beam analysis can be considered conservative due to the calculations with effective breadths of plates, which reduces the section modulus. Another reason for the conservative results from the beam analysis may be that the method is not intended for ship sizes such as the ship studied in this case. As the stress results from the beam analysis is above the acceptance criteria, the dimensions must be bigger to cope with the large bending moment. Meaning that using the simple method for deciding the cross section, the ship's light weight will be much higher than when using the advanced method.

The results for the full global model showed that the yield criteria for racking ULS was fulfilled, and the structural design could be further improved. As the global FE model is the only calculation method that have approved results, it is the method which should be applied for defining the cross section and calculate the light weight. The amount of work required to apply the global FE model is a disadvantage, but it may still be the most cost efficient solution considering steel weight savings and ship performance.

Acknowledgements

I would like to express my appreciation to Svein Gigernes at Rolls-Royce Marine AS for all the help regarding the GeniE-model and the shared knowledge about ship's structural design, and also for the challenge with this thesis topic. I will also like to thank Svein's other colleagues Robert Guzdzik and Knut Krøvel who have helped me with the import of the hull shape in GeniE, and as well as all the modelling help to solve all my model errors.

I must also express my gratitude towards my supervisor, Professor Henry Piehl for being so patient with me.

I would also like to thank Lars Dessen at Wallenius Willhelmsen for the provided information about racking and RO/RO ships.

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Acronyms

DNV GL Det Norske Veritas Germanisher Lloyd

BC Boundary Condition

FEA Finite Element Analysis

FEM Finite Element Method

DWT Deadweight tonnage

HBM Horizontal Bending Moment

HGLA Hull Girder Load Adjuster

HSF Horizontal Shear Force

LR Lloyds Register Ltd.

NTNU Norwegian University of Technology.

ROPAX Roll on/roll of passenger vessel

TM Torsion Moment

UDL Uniformly distributed load

ULS Ultimate limit state

VBM Vertical Bending Moment

VSF Vertical Shear Force

Latin Symbols

Symbol	**Unit**	**Description**
B	m	Breadth
C_B	-	Block Coefficient
D	m	Draft

E	Pa	Youngs' Modulus
GM		metacentric height
I	m^4	Moment of Inertia
k		material factor
L	m	Rule Length
l	mm/m	stiffener span
M_{SW}	Nm	Vertical still water bending moment
M_{WV}	Nm	Vertical wave bending moment
s	mm/m	stiffener spacing
S	mm/m	Girder span
T	m	Draught

Greek Symbols

Symbol	**Unit**	**Description**
σ_y	N/m^2	Yield stress
θ	deg	roll angle

1 Introduction

1.1 Background

RO/RO is a common abbreviation for a ship specially arranged for roll-on and roll-of cargo handling. Typical RO/RO cargo is cars, trucks, containers and trailers, and is loaded by the use of the cargo's own machine or special loading and un-loading vehicles. There are various types of RO/RO vessels, such as ferries, cruise ferries and cargo ships, as can be seen in figure 1.1.

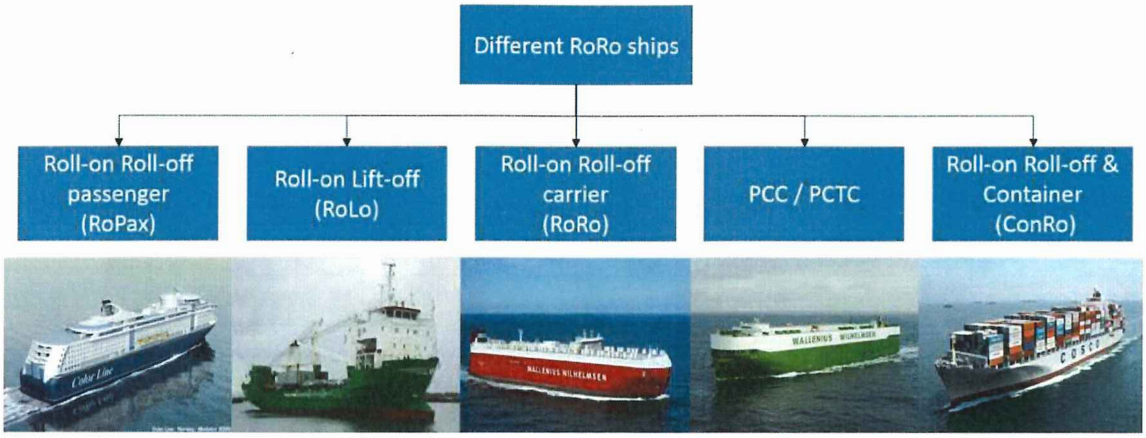


Figure 1-1 Different types of RoRo ships, each with their unique ability and characteristic. Sources (from left to right): Ilsalottodibrera (2018), Horizonship (2018), Wallenius Wilhelmsen Logistics (2018), Wallenius Wilhelmsen Logistics (2018a), and Port Technology (2018).

ROPAX is an acronym for roll on/roll of passenger and the vessel is built for vehicle transportation with passenger accommodation. Vessels that is exclusively used for transporting cars and trailers across the ocean is known as Pure Car Carriers (PCC) and Pure Truck & Car Carriers (PCTC). In general, PCC and PCTC are similar to a RO/RO ship but has more decks. Car Carriers can have one or two side ramps in addition to the stern ramp for unloading of cargo, and the internally ramps are either fixed or hoistable. The load capacity of these ships can be given as lane meters, number of cars or free deck area. To obtain a large load capacity and easy access for the vehicles it is not desirable to have bulkheads, pillars or structure in the cargo hold, as can be seen in figure 1.2.

Figure 1-2 Example of car deck.

Where the transverse bulkheads are widely spaced, or not present at all, deep web frames and beams is introduced to carry the deck load without pillar support. The transverse bulkheads primarily resist the transverse deformation which is caused when a ship is rolling, this is referred to as racking. Racking is considered as one of the main strength problems for Car Carriers as these ships have little or no transversal bulkheads, and it is therefore important to include racking calculations in the early design phase.

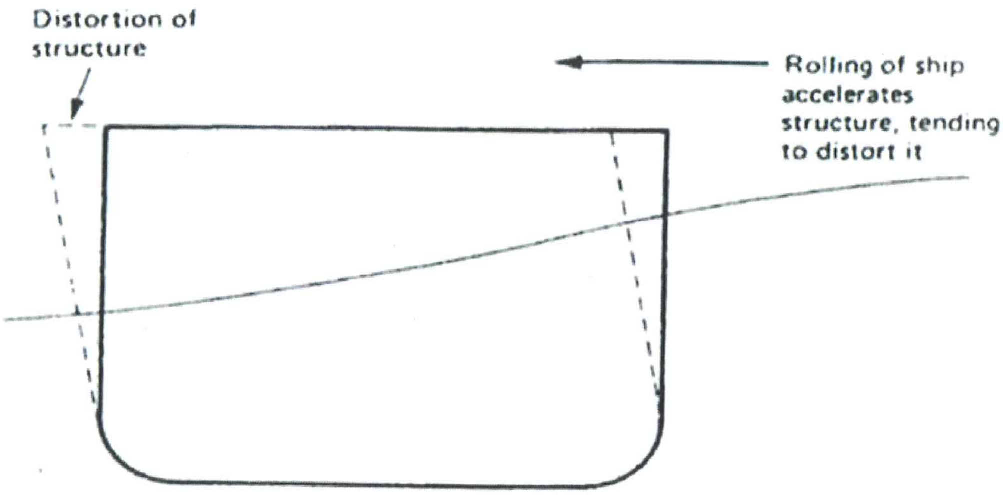


Figure 1-3 Simple explanation of racking

When the ship is rolling, the accelerations on the ship's structure and deck load will create a force tending to distort the structure transversally and may cause deformation at the corners. The deck will move laterally relative to the bottom structure, while the outer shell on one side will move vertically relative to the other side, as seen in figure 1.3 and according to Eyres (2006). The connections between transverse structural members to the bulkhead deck, or the uppermost deck level should therefore be given special attention in a racking strength assessment. The acceleration in the transverse direction depends of the main dimensions, form, load cases and the metacentric height (GM). A high racking moment is achieved when the load is located on the upper decks, but this results in lower GM and thus also lower transverse accelerations which will reduce the racking moment. Experts in the marine industry say that deep vertical web frames in the ship side is the commonly design today, which provide the transverse strength to withstand the racking forces. Multiple incidents where cracks have occurred have been the case, where the racking strength was not evaluated good enough, or because of fatigue. Further on the experts explains that it is wanted to reduce the racking structure as much as possible, and the challenge is to balance the cargo hold capacity contra the issue with racking strengths and cracks.

The deep web frames introduce another problem as it demands a lot of space which could be used for cargo. This must be compensated by increasing the breadth of the ship, or the capacity of vehicles/cargo must be reduced. The main dimensions decide many of the ship's characteristics, e.g. stability, cargo hold capacity, structural arrangement, power requirements and economic efficiency. Determining the main dimensions is therefore a particularly important phase in the overall design. In the conceptual design phase, a preliminary scantling of the construction is made. The selection of an appropriate scantlings is important for an approximate assessment of structural weight and achievable clearances. The achievable clearances are affected by the height of deck beams and girders and may result in a lower deadweight/displacement ratio. If the ratio is to be kept, the main dimensions must be changed, and the ship's characteristics will be changed.

1.2 Racking strength assessment

A more slender structure is beneficial, but the required calculations to determine a typical midship section like this, is not applied in the concept design phase. In an early phase, a simplified racking assessment using beam or FE-model may be carried out. In this case the racking calculations is made to comply with the rules and regulations from DNV GL and RO/RO ships. DNV GL-pt.5.ch.3. (2018) divides the racking strength assessment into two categories; Scope of racking calculations for category I vessels, hereby referred to as the simplified method, and scope of racking calculations for category II vessels, hereby referred to as the advanced method. The methods can be summarized as given in table 1.1.

The advantage of the simplified method is that you early can determine the need for space and thus the dimension required and calculate a provisional weight for a new design. The second approach, the advanced method for racking calculations, is more time demanding and not suitable for use in an early design phase. This approach for a racking strength assessment should give a more slender structure, which is space and weight saving. The methods applied will be evaluated and used to find a new method to efficiently determine a typical midship section without doing the full analysis scope. The midship section should be applicable to use in the concept design phase to determine size and weight of the ship.

Table 1.1 Comparison of methods for racking strength assessment

Simplified method (Category I)	**Advanced method (Category II)**
Simplified racking assessment using beam or FE model	Global FE model representing the global stiffness
PSM shall be modelled with beam elements	Evaluation area: plates and finer mesh (Sub-modelling technique)
Fixed in all freedoms of translation at bulkhead deck	BC: 3 points: two at each side at the transom and one point in the centerline at the bulbous bow
Dynamic loads: transverse and vertical	Static deck loads and selfweight for critical loading condition, with sea pressure

1.3 Approach

1. Investigate the current practice in the industry with respect to design solutions and methods, and relevant regulations.
2. Compare and evaluate the consequences and the opportunities with the advanced method against the simplified method.
3. Investigate the effect of global loads (torsion) vs local loads (sea pressure, deck cargo/vehicles) on racking, to determine the governing impact.
4. Evaluate the strong web frames (commonly design today/prerequisite for a simplified method) against a more slender structure which is beneficial for vehicle lane width and weight for a specific ship.
5. Combine the results to find a method to efficiently/quickly determine a typical midship section (hence size and weight of the vessel) in concept/initial design phase without doing the full analysis scope.

2 Literature review

2.1 Structural Design of Car Carriers at Early Design Stages

Ship design is a complex and iterative process to design the best possible vessel for a customer. The concept design phase is particularly important as the main dimensions of the ship is decided. The main dimensions decide many of the ship's characteristics, e.g. stability, hold capacity, power requirements and economic efficiency.

Schneekluth and Bertram (1998) says that a ship should not be larger than necessary, as the characteristics desired by the shipping company can usually be achieved with various combinations of dimensions. Further they say that an iterative procedure is needed when determining the main dimensions and ratios. The following sequence is appropriate for cargo ships:

1. Estimate the weight of the loaded ship. The first approximation to the weight for cargo ships uses a typical deadweight/displacement ratio for the ship type and size.
2. Choose the length between perpendiculars using the Schneekluth's formula
3. Establish the block coefficient
4. Determine the width, draught, and depth collectively.

The main dimensions are decided in the first step of a ship value chain, figure 2.1. Although many characteristics can be changed during detailing design, the difference is relatively marginal to the prior stage.

Figure 2-1 Ship's Value Chain (Andrade, et al., 2015)

Moreover, according to studies from 1985 by (Kerlen, 1985), the steel price constitutes between 24% to 35% from the total construction costs, thus is a big factor in the vessel's final price. Also, according to (Gaspar, 2013), after the definition of cost in the conceptual design phase, there is only a small margin of changes that can be done in the other phases as 70% of the total costs are assumed committed after the initial design is set. This can be better visualized in figure 2.2.

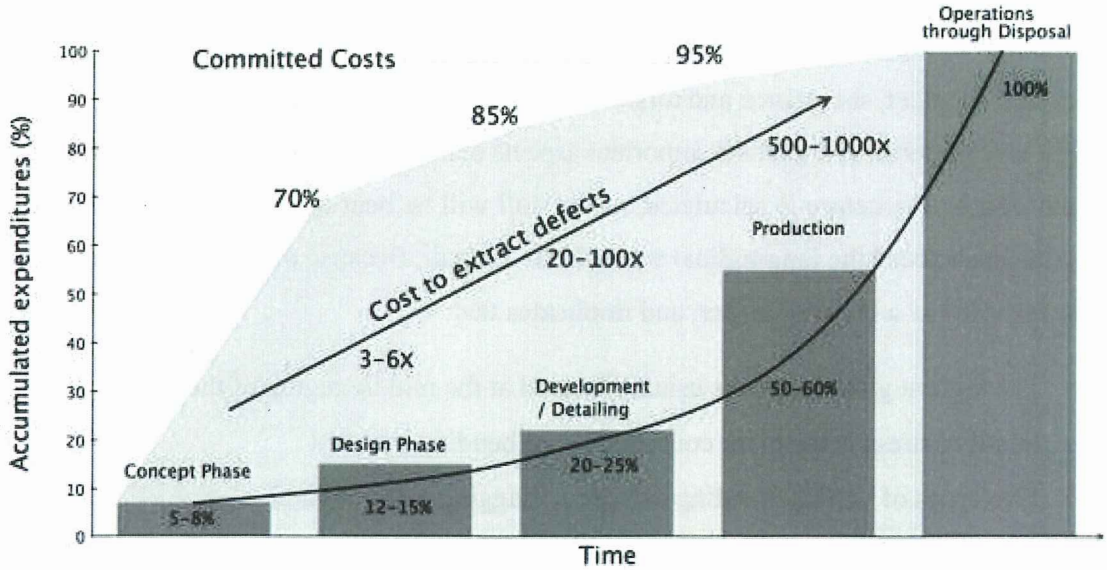


Figure 2-2 Accumulated expenditures and committed costs in the main design phases. (Gaspar, 2013)

Considering the effects of the conceptual design in the total production cost, the steel cost percent and the difficulty to change main dimensions during later design phases, the best practice for structural optimization would be optimizing key features at an early stage, where changes are easier to make and cost less.

2.1.1 Structural design loads

When a ship is sailing at sea, it is subjected to various load patterns with many magnitudes which cause deformation of its structure, as well as stresses. The designer needs to know the hull structure load features, as accurately as possible: direction of the working load, frequency of occurrence, distribution pattern on the hull structure and behavior in the time domain, etc. The loads are normally categorized as follows:

- Longitudinal strength loads
- Transverse strength loads
- Local strength loads

2.1.2 Longitudinal strength loads

Longitudinal strength loads are loads concerning the overall strength of the ship's hull, such as the bending moment, shear force and torsional moment acting on a hull girder. The longitudinal strength is considered as one of the important aspects of structural ship design, when the overall strength of a hull structure is calculated, as the hull will be bent or twisted if the longitudinal strength loads exceed the longitudinal strength for the hull. Because of a ship's slender form, it can be regarded as a beam or girder, and implicates that:

- The highest global stress is usually located at the middle region of the ship
- Bending stress is the main consequence of bending moment
- Two types of vertical bending can occur: sagging and hogging.

The bending moment, M, along the length of the beam can be determined from the moment diagram. The bending moment at any location can then be used to calculate the bending stress over the beam's cross section at that location, as shown in formula 2.1 and illustrated in figure 2.3.

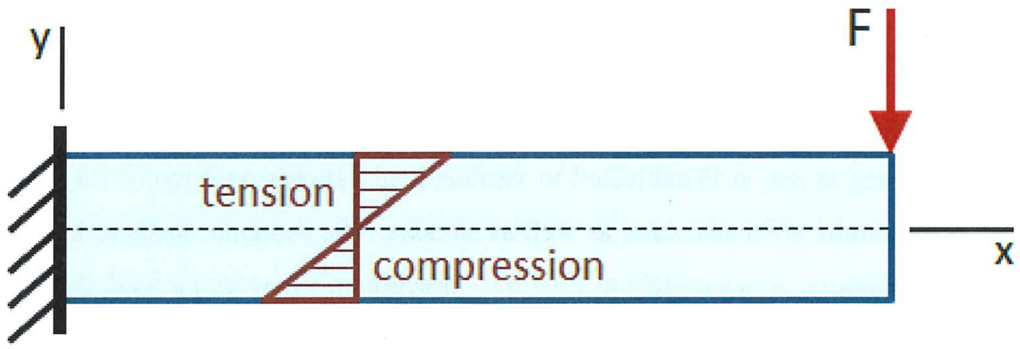


Figure 2-3 Bending stress distribution

$$\sigma_b = \frac{My}{I} \tag{2.1}$$

Where:

σ_b is the bending stress,

M is the bending moment,

Y is the distance from a fiber to the neutral axis plane,

I is the area moment of inertia relative to the axis where the moment is applied.

2.1.3 Transverse strength loads

The transverse strength loads will cause distortion of transverse members due to unbalance of external and internal loads, including structural and cargo weights. According to Y. Okumoto et al. (2009), these loads can be regarded as being independent of longitudinal strength loads, for the longitudinal loads only cause a ship to behave as a beam and they do not cause distortion of the transverse section. The transverse loads can be categorized as follows:

- Structural weight, ballast water weight and cargo weight
- Hydrostatic and hydrodynamic loads
- Inertia force of cargo or ballast due to ship motion
- Impact loads

The 1st point which include structural weight, ballast water and cargo weight are deck loads, are constant loads, but time dependent. The hydrostatic load is the static pressure from the water surrounding the transverse section, which acts on the hull structure as an external load. Another external load is the hydrodynamic load induced by the interaction between waves and the ship motion and subjects the outer shell of the ship to fluctuating water pressure. It is superimposed on the hydrostatic load and creates the total water pressure.

The inertia force is induced by the reaction force of self weight, cargo weight or ballast weight due to the acceleration of the ship motion. Y. Okumoto et al. (2009) gives the following example to explain the inertia force: Assume that a tanker is rolling among waves in a fully loaded condition, then the cargo oil in the hold has a cyclic movement in the transverse direction. This must result in a fluctuating pressure of the hull structure of the tank due to the inertia force of the cargo oil movement. In addition, internal pressure is introduced not only by rolling but also by the ship's other motions, such as heaving, pitching, etc. This inertia force is the transverse load which applied for the racking strength assessment, which is studied in this work.

There are also two types of impact loads which are classified as transverse strength loads: slamming and sloshing. But they are not included in this work.

2.1.4 Local strength loads

The local strength loads include loads which affect the local strength members such as shell panels, stiffeners and connecting constructions between stiffeners.

2.2 Ship Responses relevant for Transverse Strength Loads

The ship responses are not calculated for each equivalent design wave (EDW), but the worst load case for the racking strength assessment is found and the ship responses are calculated as the rule requirement, in chapter 3.2.2. The ship motions, as defined in figure 2.4, is caused by different wave conditions.

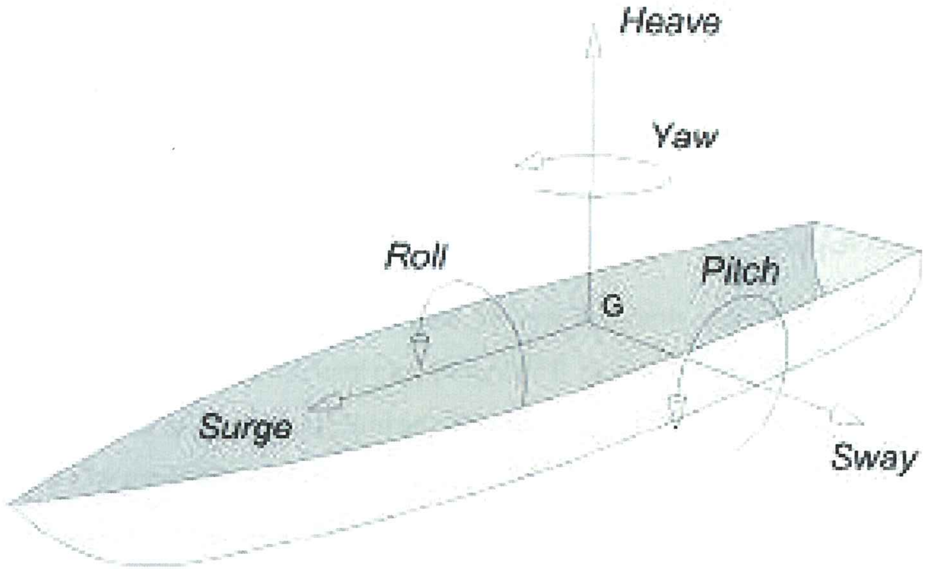


Figure 2-4 Ship motions divided into six components in the six degrees of freedom, Varela, J. (2011)

DNVGL-RU-SHIP-Pt.3-Ch.4 (2018) describes different EDW's, shown in figure 2.5, which shall be used to generate the dynamic load cases for structural assessment.

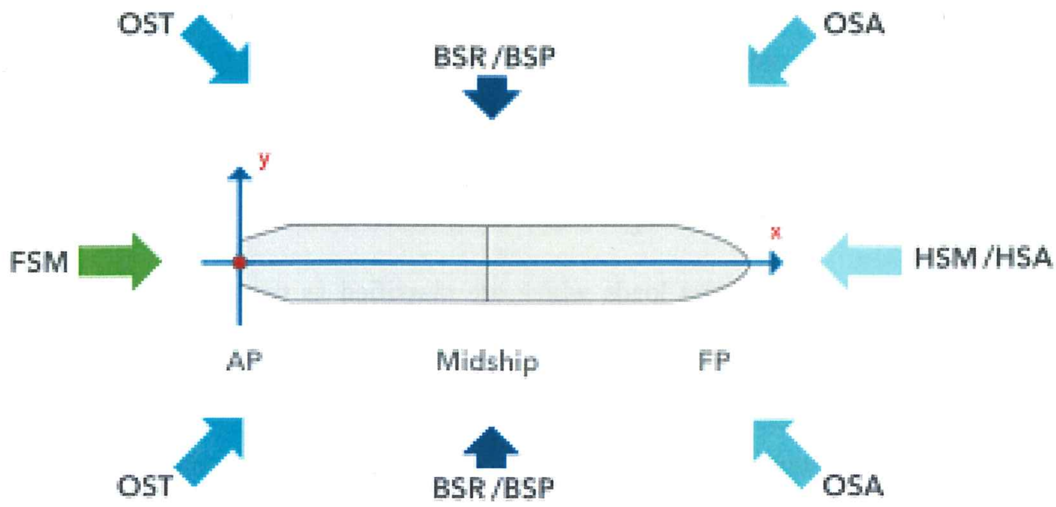


Figure 2-5 Equivalent Design Waves (EDW)

For the racking strength assessment, the transverse strength loads should be maximized and as described, this is caused when the ship is rolling. The wave condition in interest is therefore beam sea, with EDW of either BSR or BSP, to port or starboard side. The BSR load cases are defined as BSR-1P and BSR-2P and are beam sea EDWs that minimize and maximize the roll motion downward and upward on the port side respectively with waves from the port side. BSR-1S and BSR-2S are the same, but for starboard side.

BSP load cases are defined as BSP-1P and BSP-2P and are beam sea EDWs that maximize and minimize the hydrodynamic pressure at the waterline amidships on the port side respectively. BSP-1S and BSP-2S are the same, but for starboard side. A closer description of all ship responses for BSR and BSP load cases is given in table 2.1, by DNVGL-RU-SHIP-Pt.3-Ch.4 (2018).

Table 2.1 Ship responses for BSR and BSP load cases - strength assessment (DNVGL-RU-SHIP-Pt.3-Ch.4 (2018))

Load case	*BSR-1P*	*BSR-2P*	*BSR-1S*	*BSR-2S*	*BSP-1P*	*BSP-2P*	*BSP-1S*	*BSP-2S*
EDW	BSR		BSR		BSP		BSP	
Heading	Beam				Beam			
Effect	Max. roll				Max. pressure at waterline			
VWBM	Sagging	Hogging	Sagging	Hogging	Sagging	Hogging	Sagging	Hogging
VWSF	Negative-aft Positive-fore	Positive-aft Negative-fore	Negative-aft Positive-fore	Positive-aft Negative-fore	Negative-aft Positive-fore	Positive-aft Negative-fore	Negative-aft Positive-fore	Positive-aft Negative-fore
HWBM	Stbd tensile	Port tensile	Port tensile	Stbd tensile	Stbd tensile	Port tensile	Port tensile	Stbd tensile
TM	-	-	-	-	-	-	-	-
Surge	-	-	-	-	-	-	-	-
a_{surge}	-	-	-	-	-	-	-	-
Sway	To starboard	To portside	To portside	To starboard	To portside	To starboard	To starboard	To portside
a_{sway}	W.S ← L.S	W.S → L.S	L.S → W.S	L.S ← W.S	W.S → L.S	W.S ← L.S	L.S ← W.S	L.S → W.S
Heave	Down	Up	Down	Up	Down	Up	Down	Up
a_{heave}	W.S ↑ L.S	W.S ↓ L.S	L.S ↑ W.S	L.S ↓ W.S	W.S ↑ L.S	W.S ↓ L.S	L.S ↑ W.S	L.S ↓ W.S
Roll	Portside down	Portside up	Starboard down	Starboard up	Portside down	Portside up	Starboard down	Starboard up
a_{roll}	W.S ↷ L.S	W.S ↶ L.S	L.S ↶ W.S	L.S ↷ W.S	W.S ↷ L.S	W.S ↶ L.S	L.S ↶ W.S	L.S ↷ W.S
Pitch	-	-	-	-	Bow down	Bow up	Bow down	Bow up

2.3 Finite Element method

Nowadays the finite element method (FEM) is an essential and powerful tool for solving structural problems not only in the field of shipbuilding but also in the design of most industrial products and even in non-structural fields, Y. Okumoto et al.(2009). The conventional method in solving stress and deformation problems is an analytical one using theories of beams, columns and plates, etc. On the other hand, FEM:

1. Divides a structure into small elements
2. Assumes each element to be a mathematical model
3. Assembles the elements and solves the overall

As shown in figure 2.6, presented by Y. Okumoto et al.(2009)

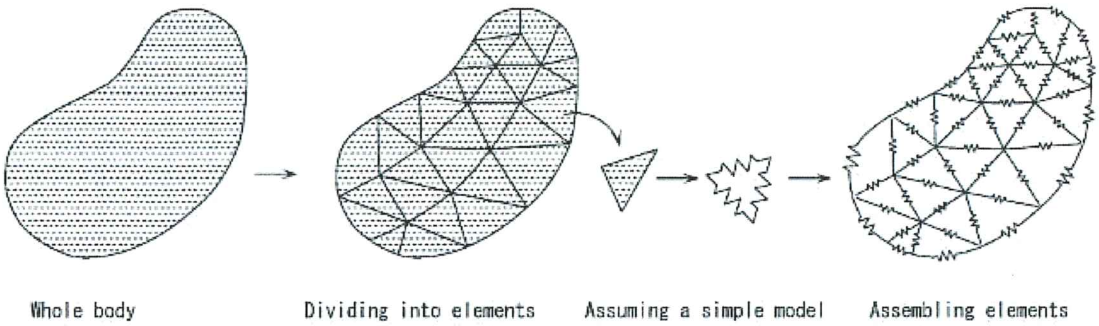


Figure 2-6

The model can be divided into different types of elements, typical elements of FEM is shown in figure 2.7.

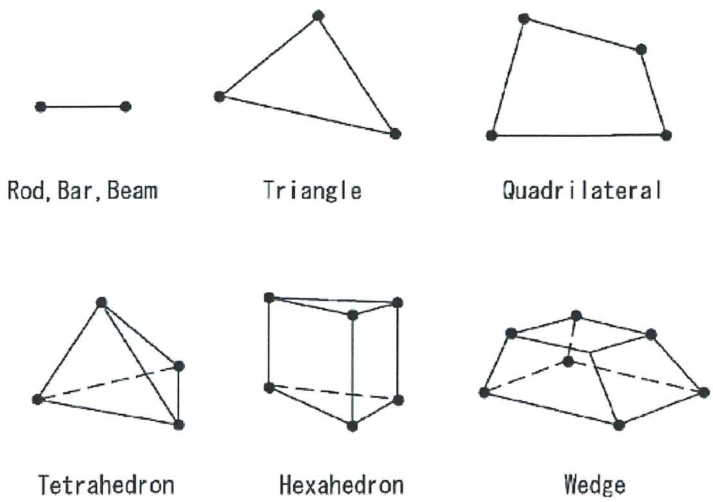


Figure 2-7 Elements of FEM

Each element has its nodes connecting to either the external boundaries or nodes from the adjacent element. The variables measured are the nodes degrees of freedom Y. Okumoto et al. (2009). Since the finite element method is an approximation, it is important to remark that it will not give an exact solution. A solution that is closer to the theoretical one can be achieved by adjusting the finite elements type, properties and size, according to Lande (2016). A reduction in element size will however mean more equations, referring to the stiffness matrix. The individual element nodal equilibrium equations are generated, and the characteristics matrix of finite element is assembled into the global nodal equilibrium equations. Another more direct method of superposition, called the direct stiffness method, whose base is nodal force equilibrium, can be used to obtain the global equations for the whole structure, according to D. Doan et al. (2017). The implication of the direct stiffness method is the concept of continuity, or compatibility, which requires that the structure remains together. The finally assembled global equation for dynamic problems is written in matrix form and presented in equation 2.2.

$$M\ddot{u} + C\dot{u} + Ku = F \tag{2.2}$$

Where:

F = force vector,

K = stiffness matrix,

U = displacement vector,

C = damping matrix,

M = mass matrix.

The complexity of the FE calculations can easily be understood by the simplified equation modified by the boundary conditions (limits of some of the displacements), which is a set of simultaneous algebraic equations that according to D. Doan et al. (2017) can be written in expanded matrix form as equation 2.3.

$$\begin{Bmatrix} F_1 \\ F_2 \\ F_3 \\ F_4 \\ \vdots \\ F_n \end{Bmatrix} = \begin{bmatrix} K_{11} & K_{12} & \cdots & K_{1n} \\ K_{21} & K_{22} & \cdots & K_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ \cdots & \cdots & \cdots & \cdots \\ K_{n1} & K_{n2} & \cdots & K_{nn} \end{bmatrix} \begin{Bmatrix} u_1 \\ u_2 \\ u_3 \\ \vdots \\ u_n \end{Bmatrix} \tag{2.3}$$

In the equation, n is the structure total number of unknown nodal degrees of freedom. Which means that with a fine mesh (structure divided into small elements) the number of unknown nodal degrees of freedom is very large. According to D. Doan et al. (2017), these equations can be solved for the u_i by using an elimination method such as Gauss's method or an iterative method, such as the Gauss-Seidel method. From the displacements determined in equation XX, the secondary quantities of strain and stress (or moment and shear force) can be obtained and used for a structural stress-analysis problem. Therefore, typical relationships between strain and displacement and between stress and strain, must be defined. D. Doan et al. (2017) gives an example of this, with a case of one-dimensional deformation in the x-direction, where strain, ε_x, related to displacement u is described in equation 2.4.

$$\varepsilon_x = \frac{du}{dx} \tag{2.4}$$

In addition, the stresses must be related to the strains through the stress/strain law, generally called the constitutive law. To obtain an acceptable result, we must have the ability to define the material behavior accurately. This is easiest described by Hooke's law, which is often used in stress analysis, and is described as stress(σ) as a function of the strain (ε) and modulus of elasticity E, shown in formula 2.5.

$$\sigma = E\varepsilon \tag{2.5}$$

2.3.1 Finite Elements applied to Ship's Structural Design

Finite Element Analysis (FEA) has been performed from several authors on different subjects. Söder (2008) used a global FE model for the racking strength calculations. A midship model may be sufficient, and a midship section like Amlashi (2008) made for a Bulk carrier may be used. He used a ½ + 1+ ½ cargo hold model, where the longitudinal parts of the middle cargo hold are defined with non-linear material. The other parts are modelled with linear material. Different mesh sized was applied over the length of the model, using a fine mesh for the estimated failure area, and a coarser mesh for the surrounding area.

Further work with a similar model has been performed by Shu (2010) Due to difficulties at the boundaries for the cargo hold model, a three cargo hold model is chosen. This is also what DNV GL recommends for a cargo hold analysis, with the evaluation cargo hold area in the middle, and with an extension on each side, as can be seen in figure 2.8.

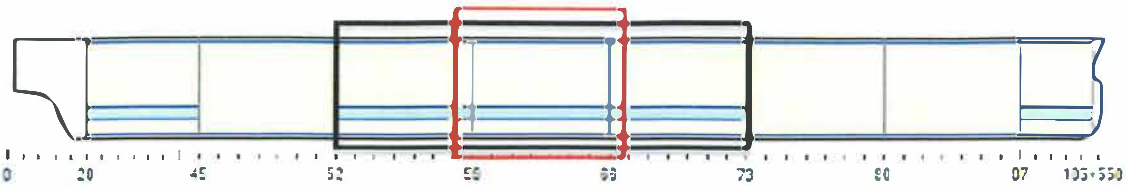


Figure 2-8 Evaluation area and extension for a cargo hold analysis (DNV GL CG 0127)

2.3.2 Hull girder load adjuster

DNVGL-CG-0127 (2015), explains a procedure for hull girder load adjustment. An adjustment of the hull girder loads should be done in case of partial ship FE model. A partial ship FE model only represents a part of the ship, and the local loads applied to the model will induce hull girder loads which represent a semi-global effect. The hull girder load adjuster will ensure that the desired hull girder loads targets are met by applying additional forces and moments on the ends of the model.

2.3.3 Fast generation of design using generic 3D FEM models

A case study was performed by Zanic et al. (2007) where an approach that combines a fast generation of design variants using generic 3D FEM models was made for use in the concept design phase. He states that only the full ship 3D FEM analysis is considered sufficient for the correct assessment of the global structural response, i.e. racking. The main disadvantage of the full-ship 3D FEM model is the large amount of work needed for preparation and evaluation of the model. Therefore, it is not applied in the industry at the concept design stage and is used mostly for the verification purposes of the final configuration in the preliminary and detail design phase. The approach established a simplified way of analyzing these complex effects using simplified 2.5D transverse strip models and/or generic coarse mesh 3D FE models that can ensure rapid generation and comparison of different structural topological concepts. The developed concept design model is seen in figure 2.9

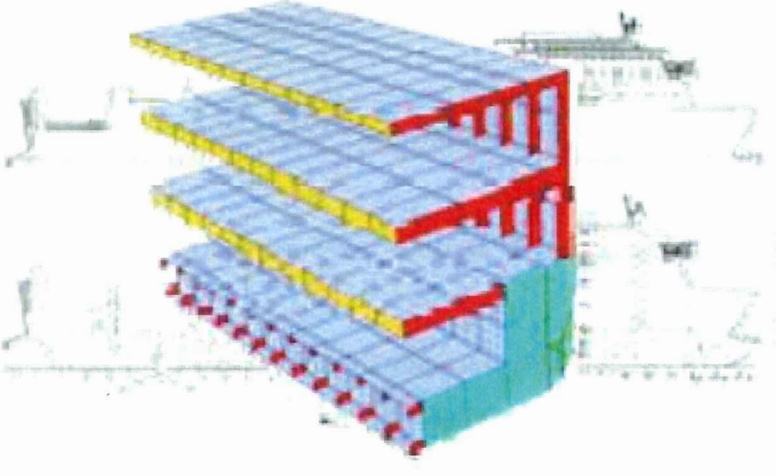


Figure 2-9 Concept design model, Ropax (Zanic 2007)

A transverse strength response, and particularly for racking is provided by use of FEM. The calculation is performed by use of 2D FEM model, as seen in figure 2.9, where eight types of finite elements and macro elements are used, i.e. two bracketed beams, two bars, two quadrilateral stiffened shell elements, triangle and spring element.

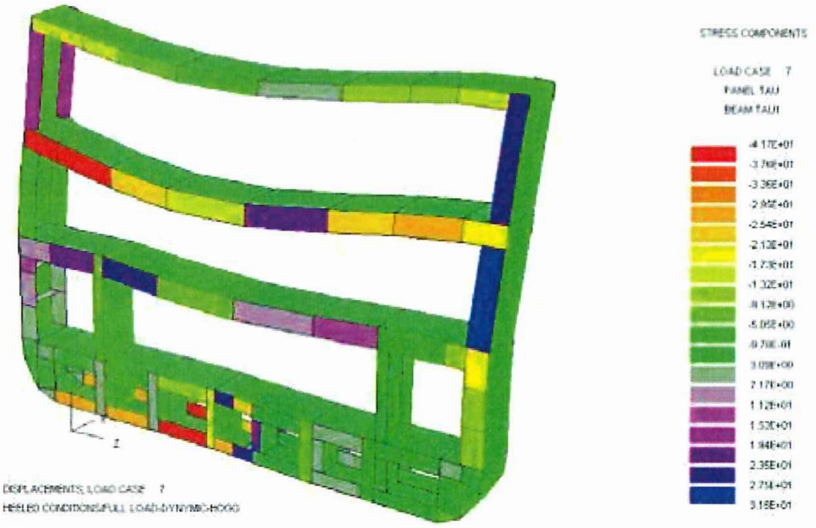


Figure 2-10 RoPax shear stress field and rackling displacment (Zanic 2007)

Zanic have also together with Andric J. (2010) made an attempt to contribute to the improvement of an analysis model within overall structural synthesis procedure for multi-deck ships. The paper gives recommendations to modeling principles and model validation. Based on the findings from Zanic et al. (2007) the generic 3D FE model was further tested on a global level. The generic ship model is used in the decision support problem formulation in concept design phase. He states that the most demanding modeling task in the concept design phase is to generate a structural model with equivalent global stiffness so that the overall hull girder bending, and racking modes can be simulated as accurately as possible. Two generic models are developed for a comparison of vertical deflection with the full ship as the reference model. The generic models comprise one basic generation and one additionally refined model to better investigate the influence the underwater hull form. The results are found in figure 2.11 and show that the difference in the two developed models are little. Additionally, the figure shows that the vertical deflection is most critically at the midship area.

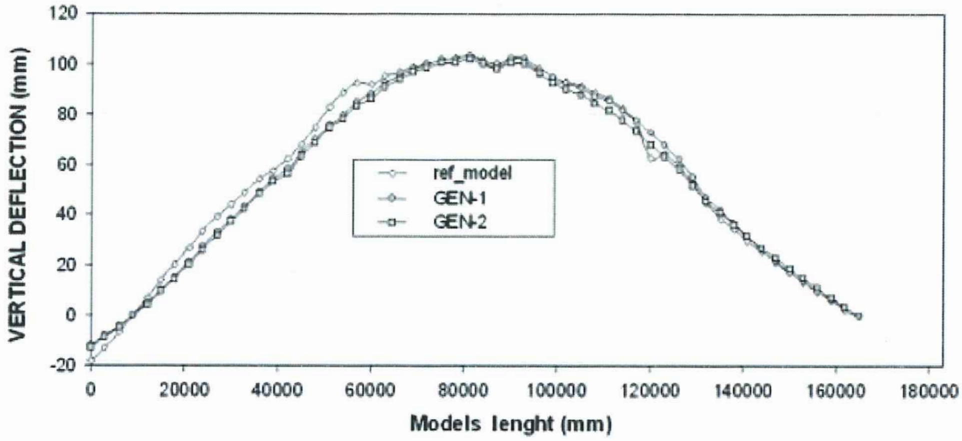


Figure 2-11 Comparison of vertical deflection between full ship the two generic models. (Zanic et al. 2010)

A more detailed validation of the generic model concept for transverse strength calculations (racking) was left as further work.

2.4 Structural design of Car Carriers

DNV GL CG 0137 (2016) explains that there exist two different structural concepts for car carriers; the conventional rigid deck design and the hinged deck design, often referred to as the flexible design. The conventional car carrier design means that the vertical side webs are in line with the transverse deck girders. With this design, transverse forces on the decks will induce bending of the deck transverses, as the vertical side and transverse deck girder is rigid when exposed to transverse forces. For the hinged design it is opposite, where no bending moment is induced in the transverse deck girder when the deck is exposed to transverse forces. This is because the vertical side is not in line with the deck transverse girder. A comparison of the conventional rigid deck design and the hinged deck design is seen in figure 2.12.

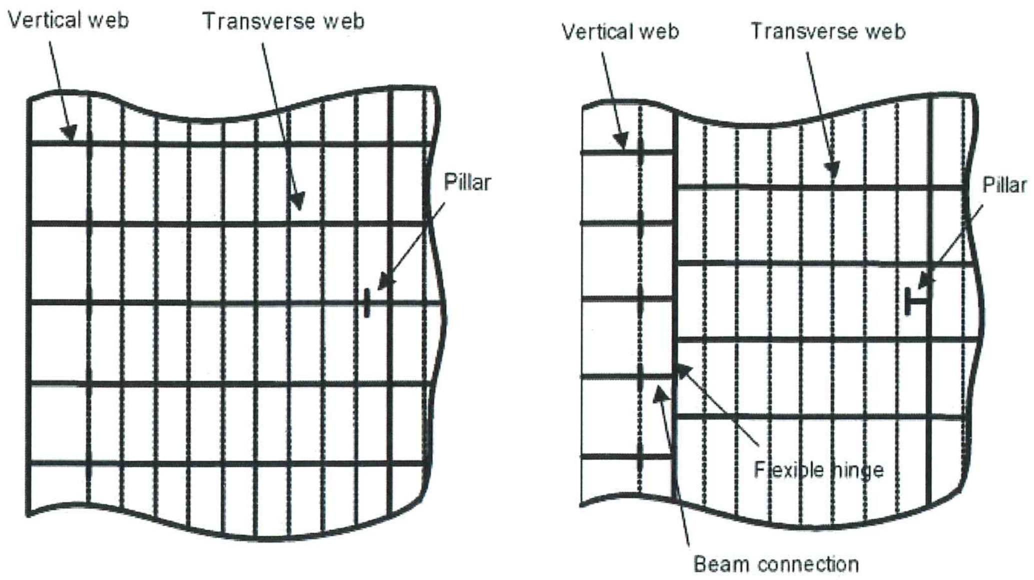


Figure 2-12 Comparison between conventional (left) and hinged deck design (right)

The two designs also differ in relation to how the racking moment is carried by the frame. For the conventional design, a considerable fraction of the racking moment created above the bulkhead deck is mainly to be carried by the frame section itself. The hinged design is only able to carry a reduced portion of the racking force on the frame. The main reason for this is the design, as the vertical – and transverse web is not in line, the vertical side frame will deform as a cantilever beam supported at the bulkhead deck. To carry the racking forces, the bow region and the stern must be "activated" and contribute as racking constraining structure.

2.4.1 Racking Strength Assessment

DNV GL CG 0137 (2016) explains how the racking response may be carried out for different sizes of a car carrier:

- Smaller car carriers: the racking moment on each frame may be carried by the frame alone
- Smaller car carriers may also be designed assuming that the racking moment over a broader area (i.e. several web frame spacings) of the cargo space should be carried by the same broad area
- Larger car carriers: the structure may be designed so that the racking moment for each frame section is not fully carried by the frame itself.

When the racking moment is not fully carried by the frame itself, the racking moment is transferred through the decks to stronger racking constraining structure, such as the bow, stern, engine casings, bulkheads, deep webs and strengthened ventilation trunks.

A racking strength assessment is done by Söder (2008) for pure car and truck carriers (PCTC). He compared the guidelines regarding racking calculations given by the two classification societies Lloyd's Register and DNV GL. In order to do so FE models was designed and analyzed with properties of typical PCTC vessels. The analysis does also include an assessment of racking strength for the Wallenius Marine vessel Mignon. The analysis concludes that determination of which boundary conditions that are appropriate for a global FE racking analysis do depend of which parts of the vessel that are of interest. He uses the advanced method, given by DNV GL for calculation of racking strength for one selected transverse bulkhead. And explains that the DNV GL approach is to analyze a global FE model, where the racking forces should be balanced with a distributed pressure and moment on the submerged hull. If only the upper parts of the vessel are of interest a limited model (LR approach) extending from the main deck could be a neat and time efficient alternative to a full FE model. A limited model is possible du to that these vessels generally are much stiffer in athwart directions below main deck. For further work, he urges to continue inspections of hot spot locations in the racking frame, as the stresses on these places where higher than allowed for classification approval according to Lloyd's Regulations, on the Mignon ship.

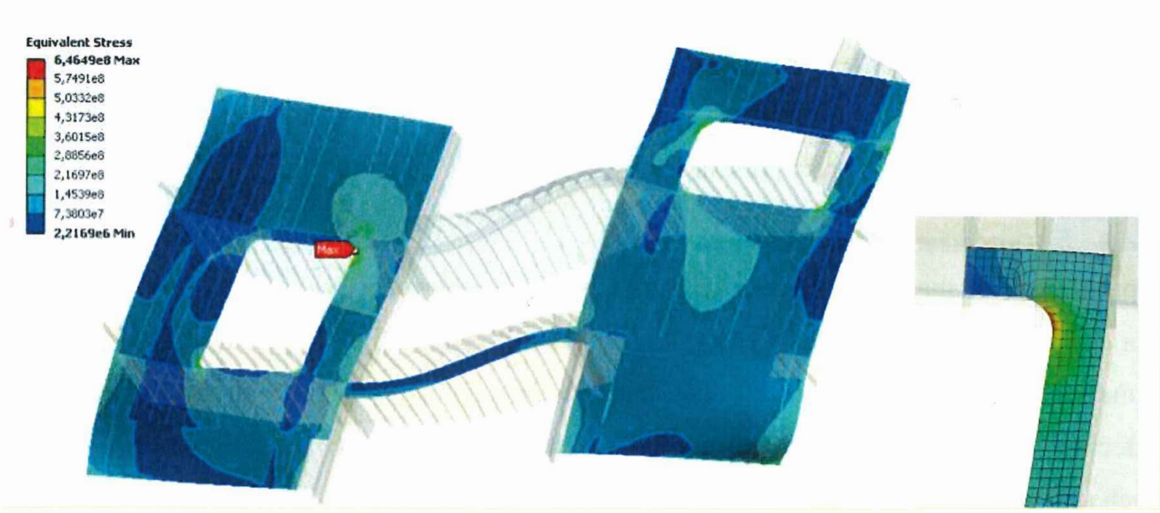


Figure 2-13 Local FE model of the racking frame, showing equivalent stresses. (Söder 2008)

Figure 2-14 Global FE model, (Söder 2008)

Söder's analysis of the Mignon ship is later used by Amundin (2012) to calculate fatigue life on the ship.

Söder et al (2011) presents a method for monitoring of racking-induced stresses in ro-ro ships. The approach is built on the assumption that the racking stresses are mainly induced by the roll and sway motions and therewith related inertia and gravity forces. The full-scale measurements shows that racking is a relevant problem for ro-ro ships, and they provide data which can be applicable for structural condition reports.

Naar et al. (2004) utilizes a coupled beam method, which estimates elastic response in the longitudinal bending of a ship with a large multi-deck superstructure. The method described can be applied during an early project stage, but they do not include any racking calculations.

2.4.2 Structural Optimization

As it is wanted to do a structural optimization of the current design, we should be familiar with three ways of structural optimization: optimization of shape, topology and dimensioning. These ways of optimizations are also presented by Lande (2016).

2.4.3 Optimization of Shape

Optimization of shape is related to the ship's main dimensions. If a ship's structural strength is not adequate, with demands of very large PSM dimensions, a change of the ship's main dimensions should be considered. The beam/depth ratio is considered as one of the most effective ways of increasing the structural strength. However, it may create other problems, such as ship efficiency, seakeeping and stability abilities.

2.4.4 Optimization of Topology

Optimization of the topology is related to the framing style, the spacing between PSM and stiffeners. The optimization of topology can vary from what is beneficial regarded cost. For instance, in high labor countries, steel price may not be as important as labor hours, a simple design with larger topology demanding fewer working hours may be beneficial. In low labor countries, the steel weight is more important than working hours, a smaller spacing between elements will therefore be beneficial as this minimizes the panel thickness and therefore weight. The consequence is that the design will demand more welding meters and paint.

2.4.5 Optimization of Dimensioning

Optimization of dimensioning aims to increase performance of the section by changing its cross-sectional properties in relation to acting stresses. Because of the bending stress distribution on a beam, the most effective way of increasing the beam strength to bending stress is to increase the amount of material at the extremities.

2.5 Software

2.5.1 Nauticus 3D Beam

3D Beam is used as the software for the simplified beam analysis, as this software is intended for linear static analysis of 2D and 3D frame structures. It is designed with ship and offshore structures and -equipment in mind but it is also very well suited for analysis of other types of typical frame and truss structures. The program is based on the matrix displacement method, as described in 2.4, and the structural frame is idealized by nodes, beams and supports. The stiffness matrix is formed for each beam, giving the relationship between forces and displacement at the beam ends. The stiffness contribution from each beam is added into the final stiffness matrix, and the equations is finally solved for the desired displacements corresponding to a set of external forces.

The advantage of 3D Beam is that it offers simple modelling of a ship cross section. It is easy to apply loads, boundary conditions and beam properties. The beam stresses are easily accessed, and you get an indication of where the highest stresses for the beam model are, and a response plot can be activated for more detailed information of a selected beam. Bending moments and shear capacity diagrams will also give a good indication of the model's behavior. All this is accessed with a relatively low computational time, included the modelling time and the time for the analysis to run.

3D Beam is not appropriate for more local analysis and local connections are hard to model. Plates, such as decks, must also be included in the profile properties, since 3D Beam only utilize 1D FEM elements such as beams. As the specification for the ship studied in this case, uses different grades of steel for deck plates and girders, this can not be taken into consideration for the beam analysis.

2.5.2 GeniE

GeniE is a program used for modelling of structures, such as ships, and can be modelled using beam and plate elements. It is therefore suitable for more complex structures. As there is demands for a global FE model for the advanced racking strength assessment, GeniE was chosen as the computational program for the FE analysis of the full global model with both beam and shell elements. The program is well suited for this global analysis, with an interface and modelling opportunities well suited for structural ship models. However, modelling the evaluation area after the structural drawings demanded a lot of modelling time, even though some structural members could be copied. As the evaluation area is modelled on such a detailed level, errors mainly regarding gaps, element size and other model errors such as sliver edges will occur. With a global model with a refined mesh for some parts of the model, you can expect a large number of elements. Compared to the beam model in 3D Beam, the stiffness matrix will be much larger, and the computational time will be much longer.

GeniE provides basic results presentation of beam force/moment diagrams and plate/shell stresses. Xtract may be started for more advanced postprocessing capabilities, as these are connected through the Sesam interface, shown in figure 2.15. Sestra is a program used for running linear structural analysis of FE-models.

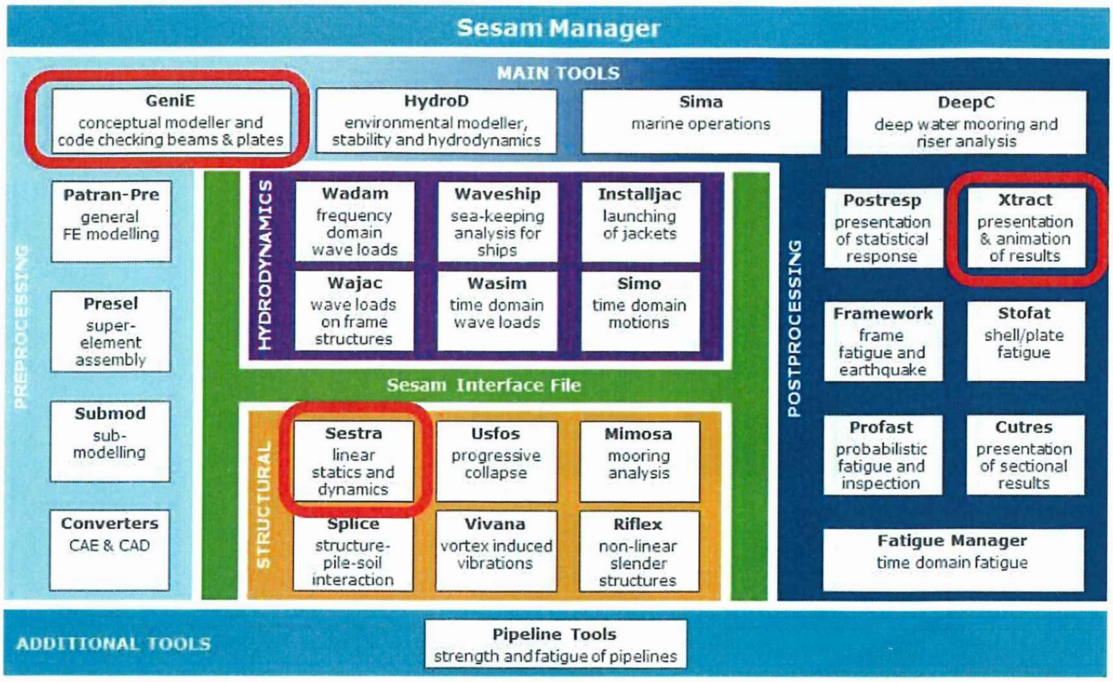


Figure 2-15 Sesam software, programs used marked in red.

Xtract is the model and results visualization program of Sesam and presents results for truss, beam, membrane, plate, shell and solid models in alternative ways: deformed model, contour curves, numeric data on display. Based on stresses computed by the analysis program Sestra, Xtract computes and presents derived stresses: stresses decomposed into membrane and bending parts, principal stresses and von Mises stress.

2.5.3 Nauticus Hull

Nauticus Hull is also a DNV GL, and is a software used to generate reports containing hull cross sectional properties for specific ships. It can also perform rulechecks, which in this case is used to calculate the critical load case for racking and envelope transverse acceleration. Nauticus Hull should also be used for the new developed method, if this includes a local model with hull girder adjustment.

3 Methodology

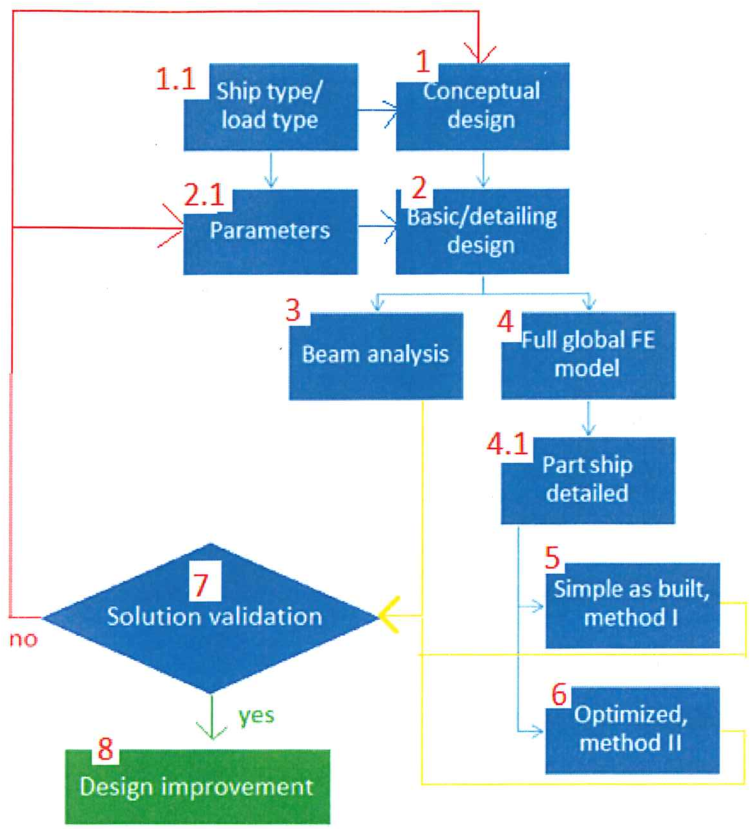


Figure 3-1 Methodology chart

Following the figure's logic of figure 3-1, the first step of the procedure is to select ship type, loads to be applied and responses to study (step 1.1). This creates the conceptual design of the ship (step 1), which the analysis is based on and is described in chapter 4.1. The load type defines the forces acting on the vessel that are studies as: global loads, local loads, bending moments, shear forces, torsional forces etc. In this case the transverse strength of a car carrier is checked with two calculations scopes for racking.

The ship type and load type feeds information to the parameters (step 2.1) which is used for basic and detailed design (step 2). This step is further divided into the beam analysis (step 3) and the full global model (step 4). For the beam analysis (step 3) the methodology is described in chapter 3.3, and following the logical numbering of the figure step 4, the full global FE model is described in chapter 3.4. The full global model is further divided into a detailed part ship, as this is modelled. The detailed part ship is first modelled as the conceptual design (step 1) with the procedure given for step 4. Later an optimized method should be developed and is therefore given as step 6. Due to time limitations, this is however not done, and the methodology for step 6 is not described later. When the analysis of 3, 5 and 6 is done, respectively, all solutions should go through step 7, the solution validation. The solution may either be sufficient or not. If the solution if sufficient it may either be regarded as a design improvement, or just as an acceptable design. If the solution is not acceptable, one should return 2.1 or 1 and investigate changes which can lead to a successful design.

3.1 Racking strength assessment

For the racking strength assessment special attention shall be given to the connections between transverse structural members to the bulkhead deck, or the uppermost deck level with high racking rigidity. Intersections between horizontal and transverse members shall be assessed in areas subjected to high racking deformations, i.e. response caused by roll motion acting on the cargo at multiple decks combined with self-weight or structure and equipment.

The transverse strength shall be checked against the ultimate limit state (ULS) under extreme loading and the fatigue limit state (FLS) under variable cyclic loading. The extent of the calculation depends on the vessel's arrangement and complexity. DNVGL-RU-SHIPS Pt.5 Ch.3(2018) defines two categories, based on structural configuration, are used to determine the scope and calculation requirements for ULS and FLS.

3.1.1 Scope of racking calculations for category I vessels

A category I vessel is defined as:

- designs with not more than two RO/RO decks above bulkhead deck
- designs with evenly distributed self-supporting side web frames, e.g. frames able to restrain the racking response from all decks based on given frame spacing

For category I vessels the transverse strength is provided by deep vertical web frames in the ship's side and/ or transverse bulkheads in the accommodation area. A simplified racking assessment model using beam elements is accepted for the evaluation of the transverse strength for the ULS scope. A simplified FLS assessment for racking will be required on a case by case basis depending on the nominal stress.

3.1.2 Scope of racking calculations for category II vessels

A category II vessel is defined as:

- designs with multiple decks and few effective transverse strength members such as an engine casing box, stair casing box and deep racking frames/ bulkheads.

For category II vessels a global FE strength analysis is required to document the racking response and to demonstrate that the stresses are acceptable under ULS load conditions. A separate FLS analysis shall be carried out.

3.2 Loads and load cases

3.2.1 Loads for global racking strength assessment

The loading condition, which in combination with relevant dynamic load cases results in the maximum racking moment about the bulkhead deck, shall be chosen for the ULS transverse strength analysis. The racking moment is calculated according to 3.2.2. For the simplified racking analysis, using beam elements, the dynamic loads which is applied, shall be taken as

$$Transverse = (UDL + selfweight) \times a_{y-env} \tag{3.1}$$

$$Vertical = (UDL + selfweight) \times g \tag{3.2}$$

3.2.2 Racking moment calculation

The racking moment is calculated using both cargo weight and the self-weight to obtain the total mass. For unloaded weather decks it is sufficient to include only the load corresponding to the self-weight. The transverse force on each deck which is created under rolling is obtained as the total mass times the transverse envelope acceleration. The transverse envelope acceleration is based on the GM value for the actual loading condition but shall not be taken less than 0.05B for ULS and 0.035B for FLS. The racking moment, M_R, is calculated as

$$M_R = \sum_i (m_{c,i} + m_{s,i)} \times a_{y-env} \times (z_i + z_{main}) \tag{3.3}$$

Where $m_{c,I}$=mass on deck number *i*

$m_{s,i}$ = self weight on deck number *i*

$a_{y,I}$ = transverse acceleration at deck number *I* for the dynamic load cases specified in formula 3.4

z_i = vertical distance above base line for deck number *i*

z_{main} = vertical position above base line for bulkhead deck

Where the transverse envelope acceleration, at any position, is calculated as

$$a_{y-env} = \left(1 - e^{-\frac{B \times L}{215 \times GM}}\right) \sqrt{a_{sway}^2 + (g sin\theta + a_{roll-y})^2} \tag{3.4}$$

To calculate the transverse envelope acceleration, ship motions and accelerations relevant for roll is needed. These are calculated according to DNV GL RU Ship Pt3 Ch4 (2018)

Roll period, in s, is taken as

$$T_\theta = \frac{2.3\pi k_r}{\sqrt{gGM}} \tag{3.5}$$

The roll angle, in deg, is taken as

$$\theta = \frac{9000(1.4-0.035T_\theta)f_p f_{BK}}{(1.15B+55)\pi} \tag{3.6}$$

Where

$f_p = f_{ps} = 1.0\, for\ extreme\ sea\ loads\ design\ load\ scenario$

$f_{BK} = 1.2\, for\ ships\ without\ bilge\ keel$

$f_{BK} = 1.0\, for\ ships\ with\ bilge\ keel$

$k_r = 0.39B\ in\ general$

In cases where the metacentric height has not been calculated, it can be taken as

$GM = 0.07B\ in\ general$, and minimum 0.05B for cases where GM is calculated.

The roll acceleration, in rad/s^2 is taken as

$$a_{roll} = f_p\theta\frac{\pi}{180}\left(\frac{2\pi}{T_\theta}\right)^2 \tag{3.7}$$

3.2.3 Racking load cases without direct hydrodynamic analysis

Inertia loads for cargo load and self weight on all decks above bulkhead deck based on:

$$a_y = a_{y-env} \tag{3.8}$$

$$a_z = g \tag{3.9}$$

Where $a_{y\text{-}env}$ is calculated according to the formula 3.4 given above. For FLS analysis, f_p factor must be included, but it is not applicable when FLS assessment is based on ULS screening.

In addition, the hydrostatic sea pressure based on roll angle, θ, must be applied.

$$P = \rho g h \quad (3.10)$$

3.3 Methodology for beam analysis

As described in 3.1.1 a simplified racking strength assessment model using beam element is accepted for the evaluation of the transverse strength for the ULS scope. The software 3D Beam is chosen for the beam analysis, where all primary structural members above bulkhead deck are modelled. The effective breadth, b_{eff}, for the PSM of attached plating should be calculated according to DNVGL-RU-SHIP Pt.3 Ch.3 (2018) and is taken as:

$$b_{eff} = S \times \min\left[\frac{1.12}{1+\frac{1.75}{\left(\frac{\ell_{bdg}}{S\sqrt{3}}\right)^{1.6}}}; 1.0\right] for \frac{\ell_{bdg}}{S\sqrt{3}} \geq 1.0 \quad (3.11)$$

$$b_{eff} = 0.407\left(\frac{\ell_{bdg}}{S\sqrt{3}}\right) for \frac{\ell_{bdg}}{S\sqrt{3}} < 1.0 \quad (3.12)$$

For the plate- and the free flanges of transverse deck girders and vertical side girders in way of deck- and side girder cross joints, the effective breadths, b_e, shall not be taken larger than:

$$b_{eff} = 1.15h_s + kh_d \, for \, deck \, girders \quad (3.13)$$

$$b_{eff} = 1.15h_d + kh_s \, for \, side \, girders \quad (3.14)$$

Where:

$h_s = web \ height \ of \ side \ girder \ in \ mm$

$h_d = web \ height \ of \ deck \ girder \ in \ mm$

$k = 0.25 \ for \ plate \ flanges$

According to the rules for RO/RO ships, DNVGL-RU-SHIP Pt.5 Ch.3 (2018) the boundary conditions applied should be fixed in all freedoms of translation at bulkhead deck. And the dynamic load which shall be applied was given in chapter 3.2.1.

3.3.1 Acceptance criteria beam analysis

The ultimate limit state acceptance criteria are given in table 3.1.

Table 3.1 Permissible stresses for racking ULS

Normal membrane stress(1)	Shear stress	Von Mises stress
200/k	120/k	220/k
(1)Axial stress for face plates of PSM's modelled with beam elements		

Where *k* is the material factor and is specified for normal steel and high tensile steel (NV36) in table 3.2.

Table 3.2 Material factor, k.

Specified minimum yield stress R_{eH} in N/mm^2	k
235	1,0
355	0,72

3.4 Methodology for Global FE Analysis

3.4.1 Global FE Model

For the global FE analysis, the complete ship should be modelled, this is because the model should represent the global stiffness. Therefore, all transverse and longitudinal structure should be modelled, and both port and starboard side needs to be included in the global model. The model is used to calculate nominal global stresses in primary members away from areas with stress concentrations. The global model is used to provide deformations used as boundary conditions for a local area, which in this case is referred to as the evaluation area. This is called a sub-modelling technique, and the global analysis is carried out with finer mesh for selected areas. These areas can be included as a part of the global model or be made as separate models with boundary deformations or boundary forces from the global model.

For a global analysis, DNVGL-CG-0127 (2015) recommends the following coordinate system; right hand coordinate system, as shown in figure 3.2. With the x-axis positive forward, y-axis positive to port and z-axis positive vertically from baseline to deck.

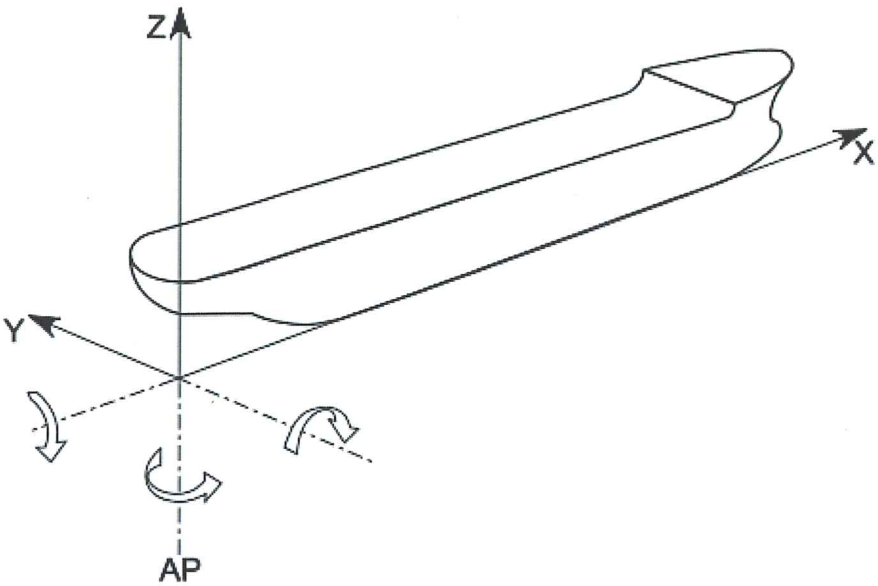


Figure 3-2 Global coordinate system

3.4.2 Mesh size

The mesh is normally to be arranged such as the grid points are located at the intersection of primary members. This means the element size should be set as one element between longitudinal girders, transverse webs and between stringers and decks.

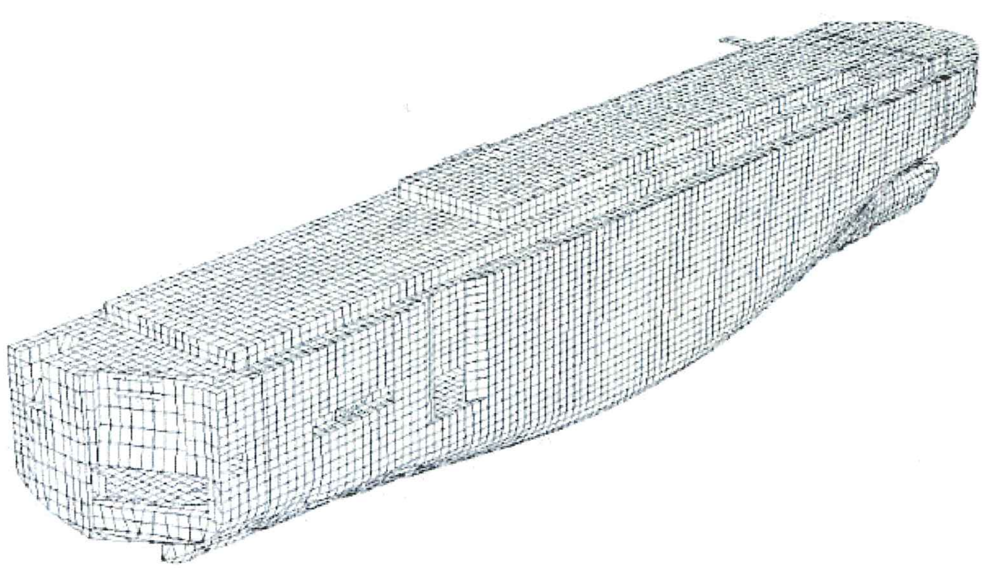


Figure 3-3 Mesh shize for RO/RO

3.4.3 Model idealization

In general, all primary longitudinal and transverse structural members, i.e. deck plates, bulkhead plates, stringers and girders and transverse webs should be modelled by shell or membrane elements. However, some deviations of this is made outside the evaluation area. Girders shall be modelled as membrane or shell plates but can also consist of a combination with flanges modelled as beam or truss elements. Outside the evaluation area the girders are modelled as beam elements, along with some sections of transversal deck girders which are without interest for the racking strength assessment.

Stiffeners are to be lumped together, to match the mesh size. The cross-section area of the lumped elements must be the same as the sum of the areas of the lumped stiffeners, the bending properties are irrelevant. An example is given in figure 3.4, where the area of 1.5 stiffeners in each direction is lumped together, creating a stiffener with 3 times the area of one stiffener.

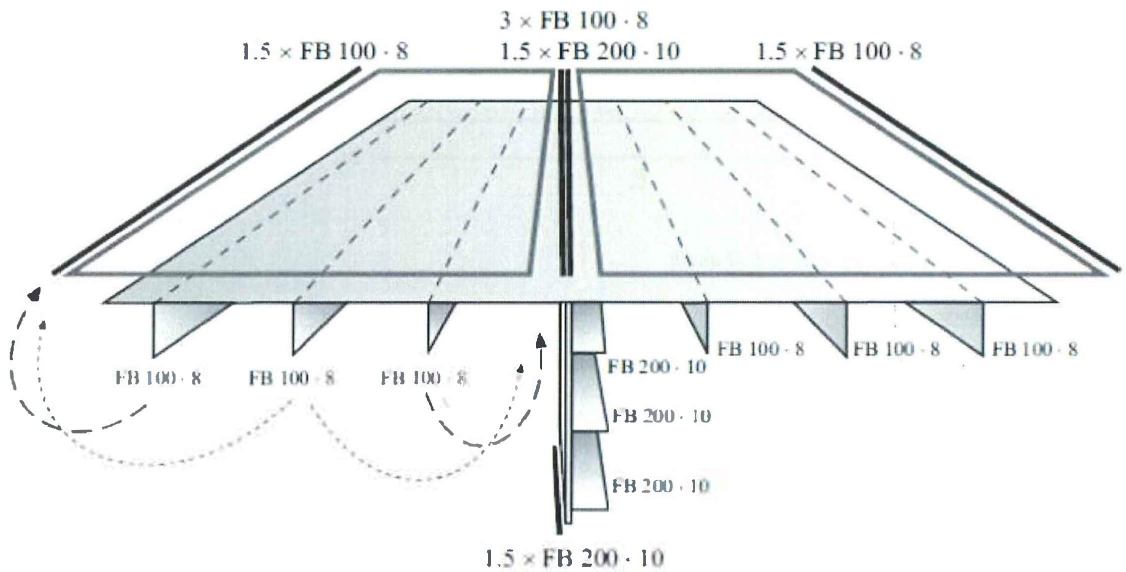


Figure 3-4 Lumped stiffeners

All openings such as deck or door openings and cut outs are to be represented in a way such that the deformation is adequately represented. This is done by calculating a reduction in element thickness, shown in formula 3.15-3.17.

$$t_{red}(y) = \frac{H-h}{H} t_0 \tag{3.15}$$

$$t_{red}(x) = \frac{L-l}{L} t_0 \tag{3.16}$$

$$t_{red} = \min(t_{red}(x), t_{red}(y)) \tag{3.17}$$

Where the definition of t_0, L, l, H and h can be seen in figure 3.5.

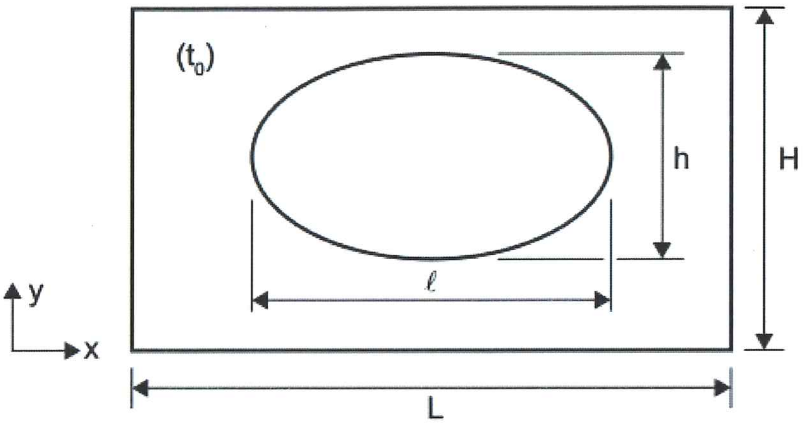


Figure 3-5 Definitions of t_0, L, l, H and h

3.4.4 Boundary condition

The boundary conditions applied should prevent rigid body motions. Therefore, fixation points are applied where the transom intersects the main deck, close to where the stern is "rectangular" and a forward fixed point in the centerline, as shown in figure 3.6.

	Location	Direction of support
Transom	SB	*Y, Z*
	PS	*Z*
Forward End	CL	*X, Y, Z*

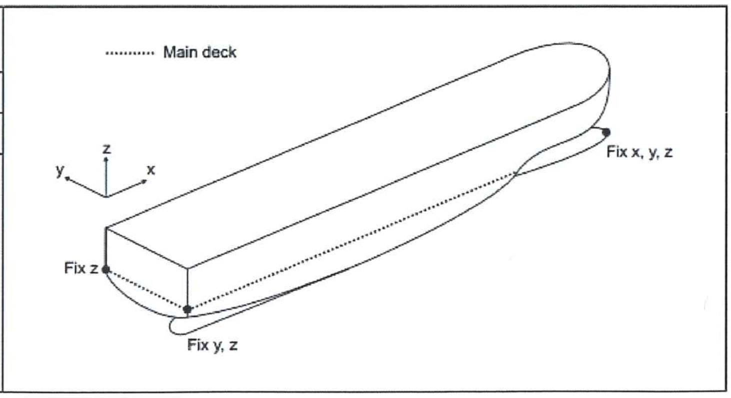


Figure 3-6 Boundary conditions for global RO/RO model

3.4.5 Loads and load application without hydrodynamic analysis

When the critical loading condition with respect to racking has been established based on 3.2.1 the loads for the global analysis may be applied as follows, and shown in figure 3.7:

1. A transverse line load (deck load and selfweight) is applied on all decks above bulkhead based on rule envelope transverse acceleration. The transverse line load is found from the formula:

   $$transverse\ line\ load = (UDL_i + sw_i) \times a_{y-env,i} \quad (3.18)$$

   Where UDL_i = Uniformly distributed load on deck number *i*

   sw_i = self weight of deck number *i*

   $a_{y\text{-}env,i}$ = transverse envelope acceleration for deck number *i*

2. Apply hydrostatic sea pressure based on rule roll angle, θ.
3. Vertical inertia load based on one *g*.

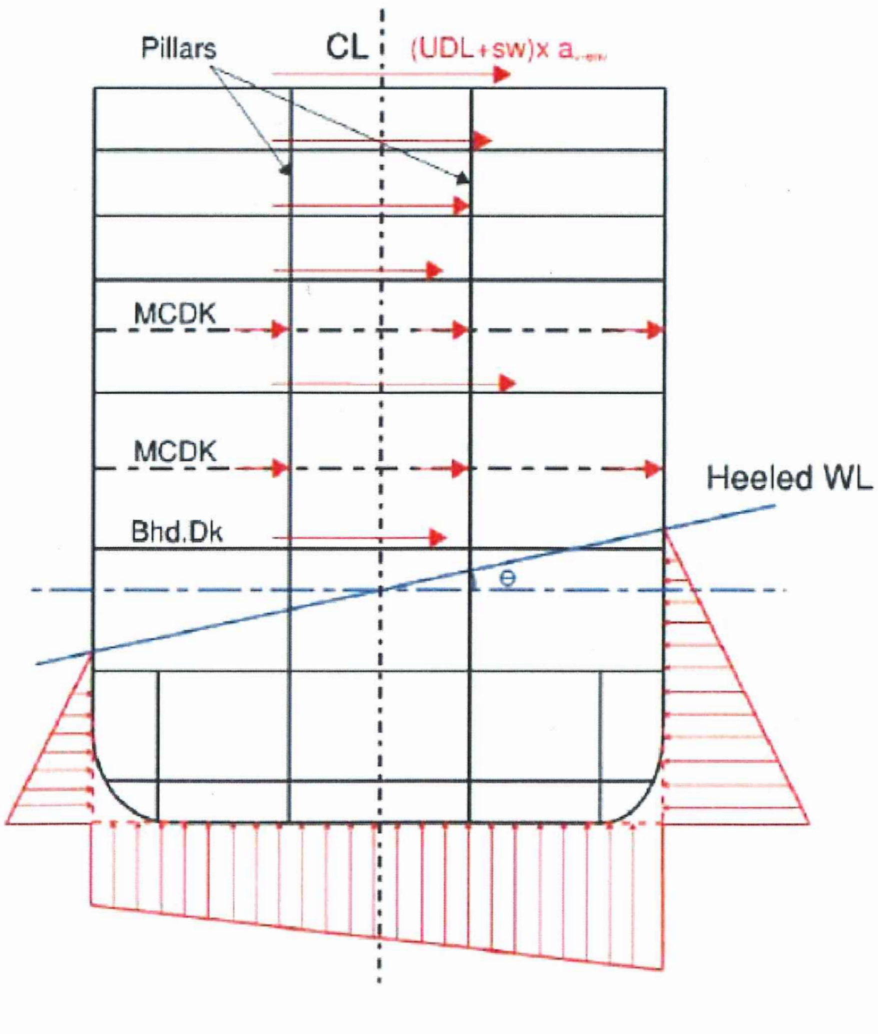


Figure 3-7 Load application without hydrodynamic analysis

3.4.6 Balancing of Global FE Model

After the loads are applied according to 3.4.2, it is important to check the balance of the global FE model. For cases were a direct wave load analysis is carried out and were these loads are directly transferred to the model, the reaction forces will be small DNVGL-CG-0137(2018). For all other cases, the FE will not automatically be in balance with minimum reaction forces. An adjustment to the racking moment is not acceptable for achieving force and moment balance of the FE model. Therefore, the load balancing for cases without hydrodynamic analysis should be done by adjusting the dynamic sea pressure with the following method DNVGL-CG-0137(2018)

1. Adjust the FE model vertically to achieve buoyancy force equal to vertical loads (deck loads, self weight and tank content).
2. Rotate the model until balance of transverse forces is achieved or use the fraction of the sea pressure in heeled condition.
3. Re-check vertical force balance and adjust the pressure if necessary.
4. Re-check transverse force balance and adjust by rotation (roll) if necessary.
5. Balance the racking moment Mxx by a force pair distribution (i.e. line load expressed in N/m) along the intersection line between the freeboard deck and the ship side. The racking moment Mxx is then calculated about the axis defined as the intersection line between the freeboard deck and the centre line. The force pair distribution can either be constant or have a proper variation in the longitudinal direction. One option is to scale the force pair distribution with the height of the parallel ship side below the freeboard deck. Another option is to scale the force pair with the width of the hull in the waterline.

3.4.7 Acceptance criteria FE Analysis

Stresses in plating of transverse racking constraining structure shall not exceed the permissible values given in table 3.1.

4 Methodology Application – Case

4.1 Case definition (step 1,1)

The analysis with the two calculations scopes for racking is based on the design of MS Autosky, shown in figure 4.1

Figure 4-1 MS Autosky, Marine traffic (2018)

The car carrier has the following specification:

Length Overall	140 m
Breadth	22.7 m
Maximum Draft	7.35 m
Vessel speed	20 kn
Car capacity (RT 43)	2080
Car Decks	7 – Tank Top
Deck Area	16,870 m^2

The racking strength assessment is further based on the structural design of MS Autosky, in figure 4.2, frame number 116 is shown. This frame number is a typical midship section, with the exception of deck 5 and 6 which has reinforcements with respect to the deck and side girder because of the ramp opening in the deck.

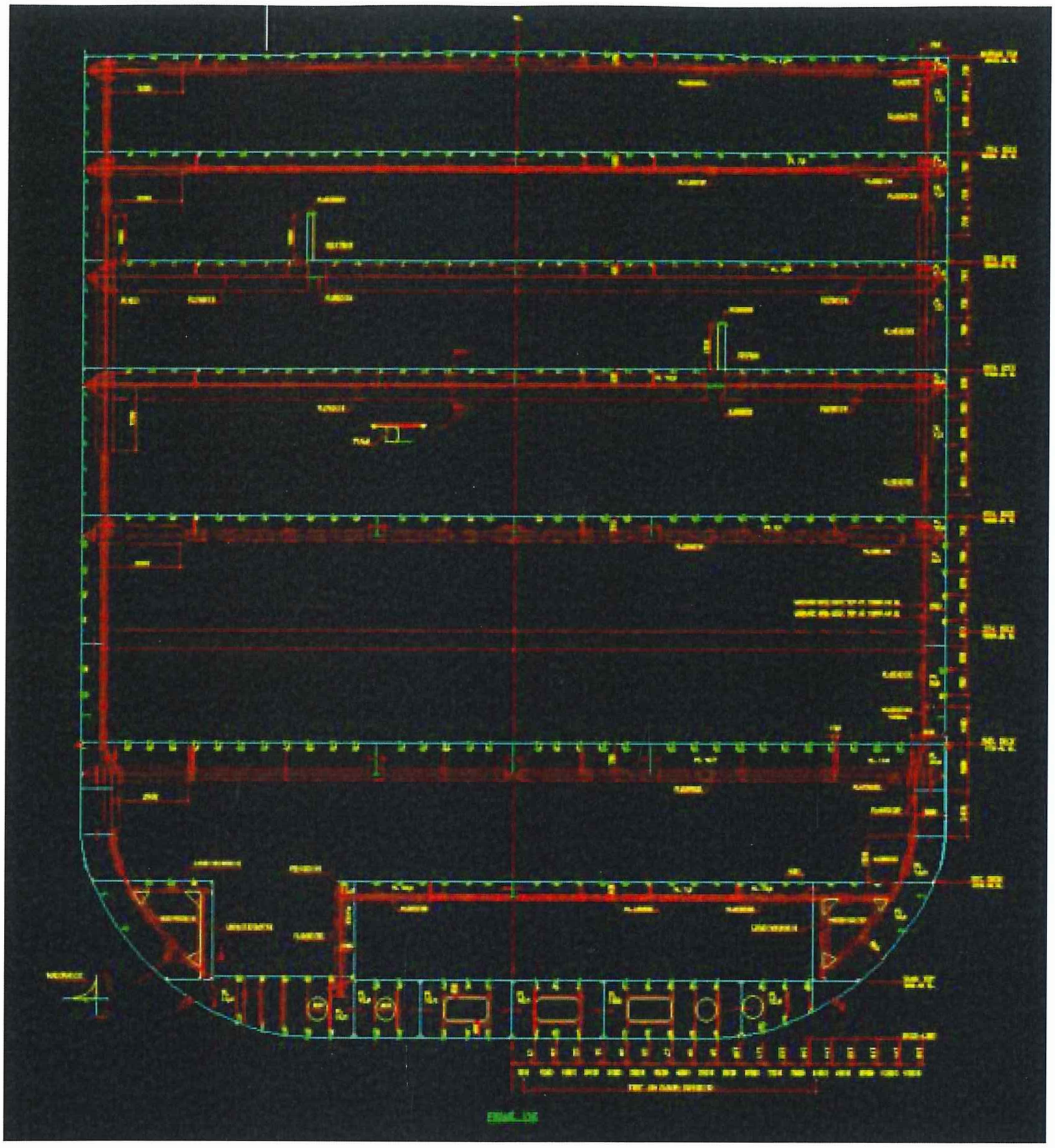


Figure 4-2 Structural drawing of frame 116

The side frames have the following dimensions, in mm, from tank top to 2nd deck:

T: W:800x12 F200x32

Above 2nd deck:

T W: 550x8 F200x22

In addition, the side girders have reinforced flanges above 2nd deck, with a length of 1000 mm, with thickness 32 mm. At the end of ramp openings, the transversal deck girder is reinforced with a larger flange of either 700x19 mm (deck 5 and 6) or 550x19 mm (deck 7). Where there are reinforced transverse deck girders, the side girders flange dimensions are increased to 400x22 mm, as can be seen in figure 4.2.

Structural arrangement on 2nd deck:

Deck plate: 12,5 mm NV36

Longitudinal deck beams: L150x150x9 with s=0,6m

Transverse girder, strans=1,3 m:

W:795x10/14 FL:250/400x32

Longitudinal girder in center line: W795x10 FL:300x32

Longitudinal side Girders: W:795x10 FL:800x10

Other structural profiles can also be found in the appendix, "Profiles used in 3D Beam", which include all profiles above 2nd deck.

The uniform load for each deck is given in table 4.1, these are the load capacities for each deck as given in the structural drawings. In table 4.2 a load case which is more normal for each deck is applied, the reasoning for this is later described.

Table 4.1 Load capacity

Deck no. \ Load	Wheel load [tonnes]		Uniform load [kg/m^2]
	Max. axle load		
		Single wheel load	
7th deck		1,6	200
6th deck		1,6	200
5th deck		1,6	200
4th deck		8,0	500
3rd deck (hoistable)		1,1	170
2nd deck	Translifter	23,7	
	Mafi truck	24,9	
	Wheel loader	36,6	2500
1st deck		4,0	750
Tanktop		5,0	4000

Table 4.2 Normal load case for UDL for each deck

Position	Uniformly distributed load [kg/m^2]
Deck 2	350
Deck 4	350
Deck 5	120
Deck 6	120
Deck 7	120
Top of Garage	0

Figure 4.3 shows the profile plan of the ship, as it can be seen, the ship has very little transverse bulkheads which is effective as racking strength members. The decks are sloped athwart of the midship (at frame 102). The evaluation area is also shown on this figure and is later explained in chapter 4.1.1.

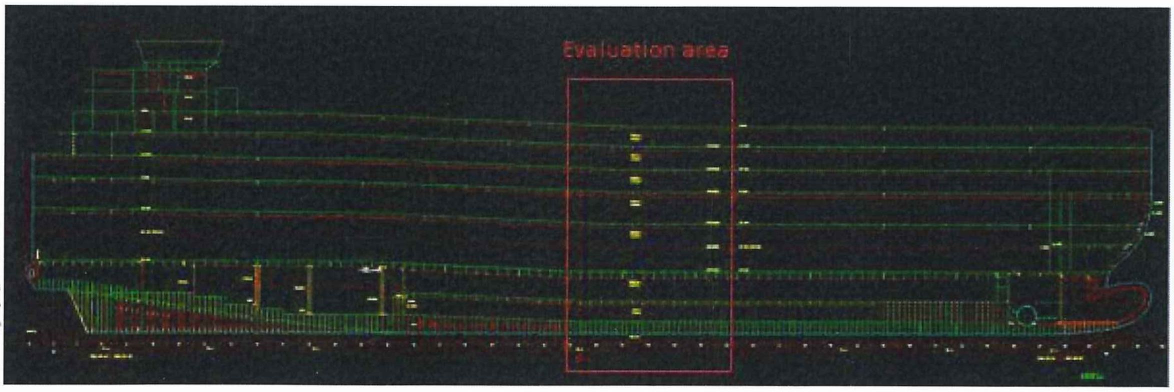


Figure 4-3 Profile plan

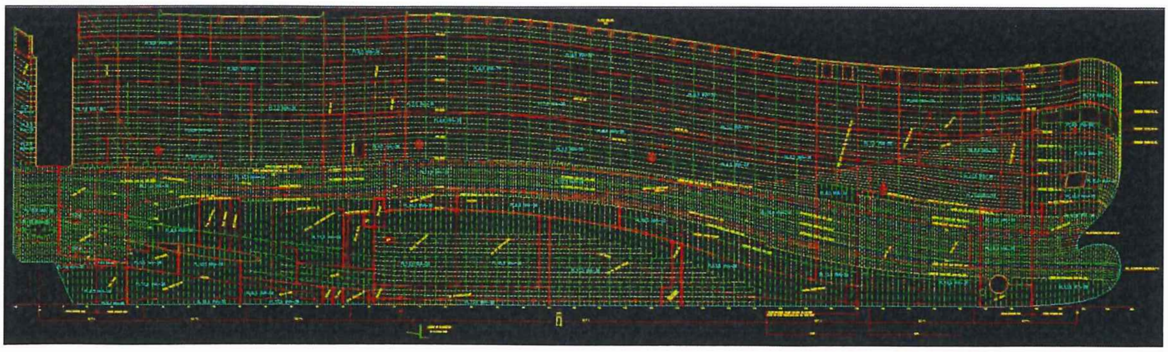


Figure 4-4 Shell expansion

Figure 4.4 shows the shell expansion, as well as including the plate thickness of the outer shell, it shows some more structural members which is included in the global FE model, which should be included for the racking strength evaluation. This is the ventilation duct between frame #50 and #70, as well as some transverse bulkheads in the fore ship that may contribute to the racking strength. Further on, it can be seen that the spacing between the side girders is equivalent of 4 times the frame spacing of 650 mm, equal to 2300 mm, above the 2nd deck. Below the 2nd deck, which also are defined as the bulkhead deck, the spacing is 1300 mm, as it also located in the ice belt.

4.1.1 Evaluation area

As described in 2.1.2 the longitudinal strength is considered as one of the most important aspects of structural ship design. The highest global stresses are usually located at the middle region of the ship, which is confirmed by rule based bending moment in waves, calculated in Nauticus Hull, as seen in figure 4.5. The critical section is often defined within the area of maximum bending moment.

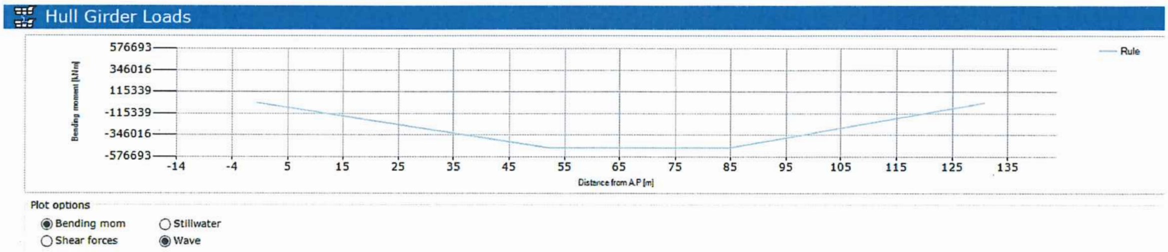


Figure 4-5 Rule bending moment in waves

The evaluation area is defined from frame number 100 to 132, equivalent of 64,4 to 85,2 meters. By defining this area as the evaluation area, we are within the area where the highest bending moment occur. Also, critical areas like ramp openings, sloped decks and fixed ramps are included, which can be analyzed in the global FE model. On figure 4.6 the deck plan of deck 6 and 7 can be seen, with the red box as the evaluation area.

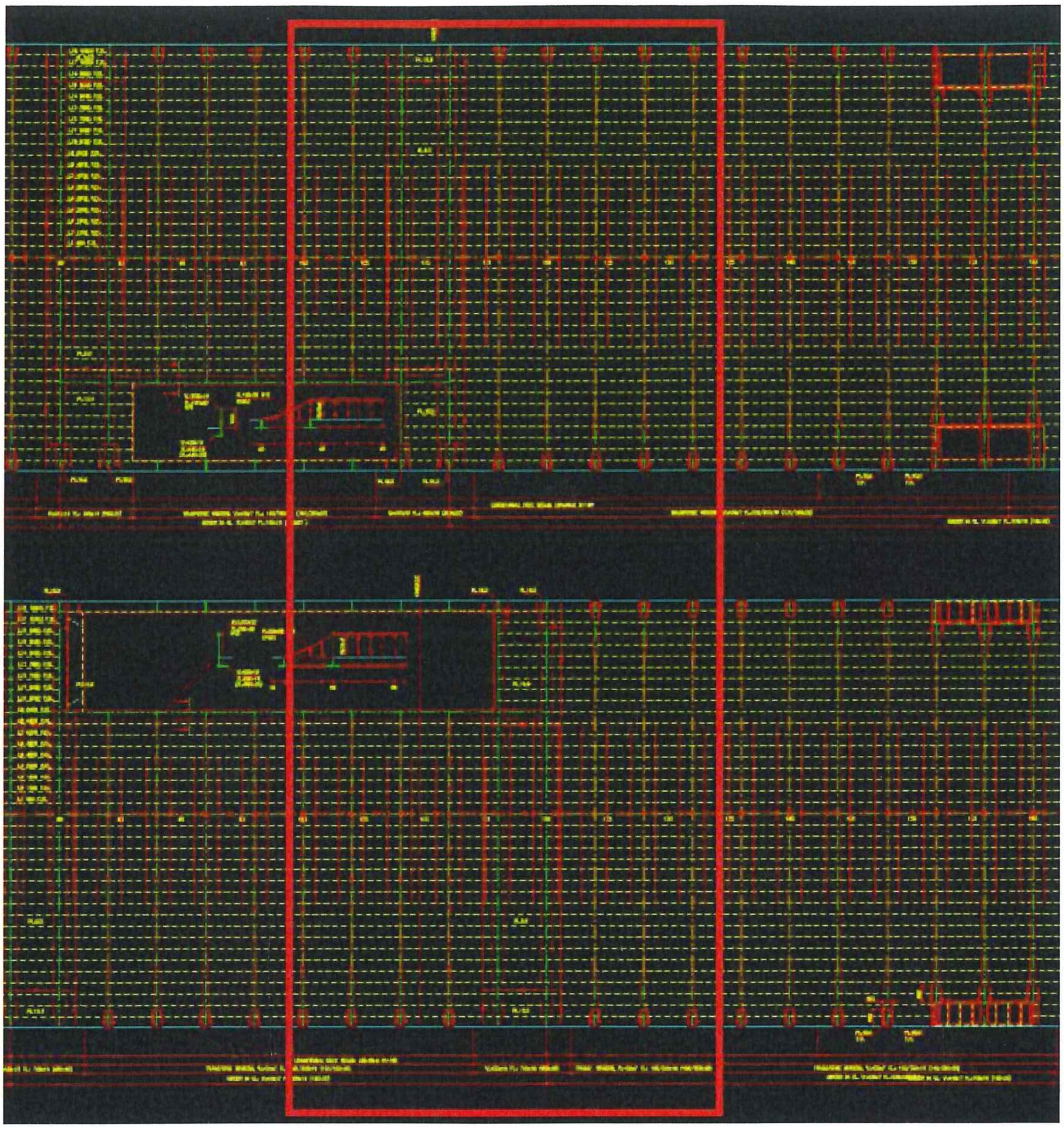


Figure 4-6 Plan of deck 6 and 7

4.2 Initial conditions

To find the loading condition, which in combination with relevant dynamic load cases results in the maximum racking moment about the bulkhead deck, the envelope transverse acceleration needs to be calculated. This is done by using the rulecalculator in Nauticus Hull, where the calculations are based on the formulas presented in 3.2.2. Along with the maximum envelope transverse acceleration, the RuleCalculator will give the critical loadcase, roll period and roll angle for the given position.

With this method, there are however some preparations that must be done in order to use the RuleCalculator. First of all, the ship data must be assigned, as shown in figure 4.7, where the main dimensions are assigned.

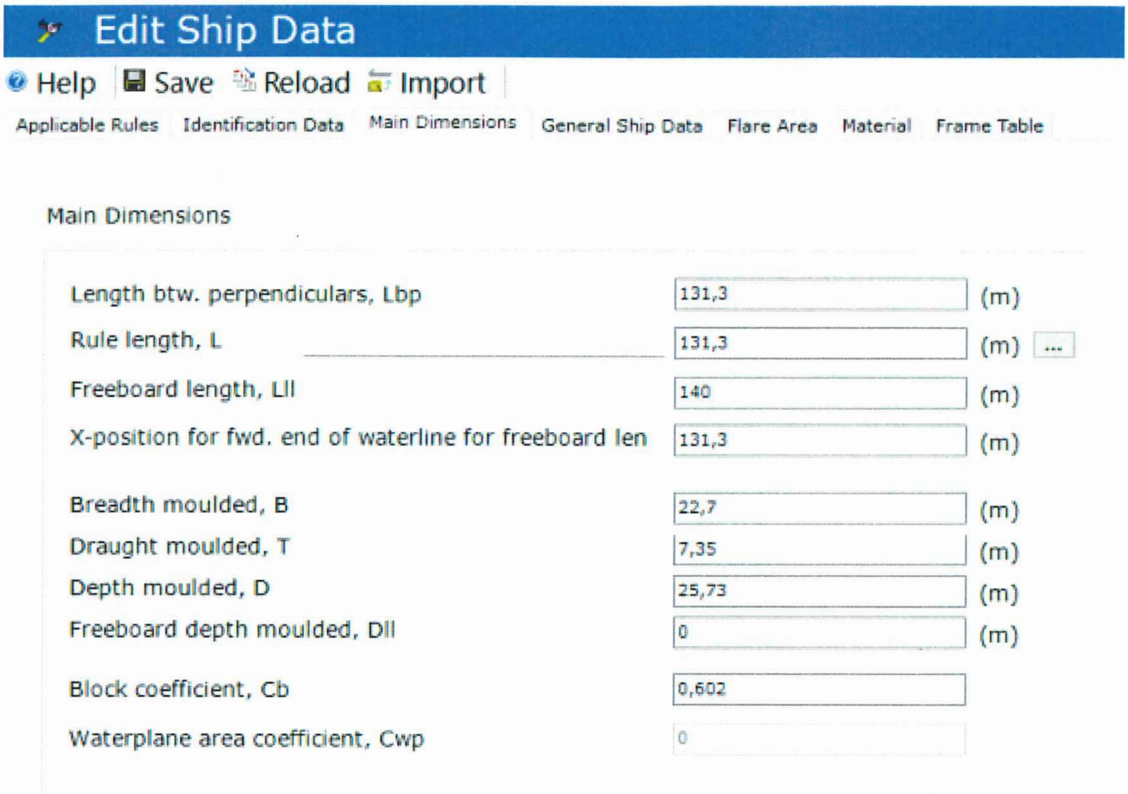


Figure 4-7 Ship data assigned in Nauticus hull

In order to be able to assign the prescriptive loading condition, as given in the specifications, a cross section must be added, in order to make a compartmentation and create compartments loads in Nauticus Hull. Prescriptive loading conditions, as full load and ballast, can be assigned, as shown in figure 4.8.

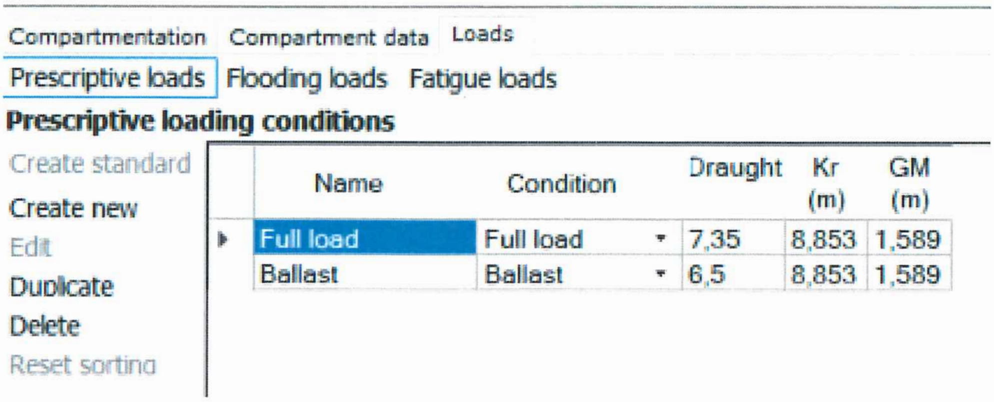


Figure 4-8 Prescriptive loading condition

This must be done as the RuleCalculator collects information about roll radius of gyration, kr, and the metacentric height, GM, from the prescriptive loading conditions. But in the design phase where the racking strength assessment is done, these values are normally not calculated and are based on a rule description of a factor times the breadth of the ship.

The envelope transverse acceleration can now be calculated for the different positions.

The input parameters are:

- x-position, calc.point [Frame No.]
- y-position, calc.point [mm]
- z-position, calc.point [mm]
- Load Scenario
- Maximize acceleration component

We keep in mind that the transverse dynamic load which shall be applied is the uniformly distributed load and the self-weight, based on the envelope transverse acceleration, therefore the highest racking moment will need to be a full load condition. To find the critical load condition, the acceleration is calculated for all positions (all decks above bulkhead deck) and the input parameter "maximize acceleration component" is varied from aX, aY and aZ.

Table 4.3 Results from Rulecalculator, maximised for different directions

Maximize	aX	aY	aZ
Critical loadcase	ExtremeSea_SD, Ballast, OSA_1P	BWExchange_SD, Ballast, BSR_1P	ExtremeSea_SD, Full load, BSP_1P
Max ay_env	5,543-6,673	5,415-6,644	5,415-6,644
Roll angle	29,4	23,5	29,4

For calculations of loads for the beam analysis (step 3) and the full global FE model (step 4) the envelope transverse acceleration for each deck is given in table 4.4.

Table 4.4 Envelope transverse acceleration

Position	max a_{y_env}
Deck 2	5,415
Deck 3	5,576
Deck 4	5,814
Deck 5	6,076
Deck 6	6,272
Deck 7	6,469
Top of Garage	6,644

The rule roll angle which is used for application of the hydrostatic pressure is found to be 29,4 degrees.

4.3 Methodology application -Simple beam analysis

4.3.1 Limitations and assumptions

As the beam analysis is used for basic design, it is chosen to simplify the structure and only replicate one frame several times. Because of this, it is assumed more than enough to copy the frame 5 times, as it expected that the stresses will be similar for the side girders. The model is further simplified by not including any deck openings or sloped decks. Reinforcements in webs for the connections between deck girder and side girder is not included. Some reinforced flanges are however included in the model, as these are considered as important areas with respect to the bending stress. Deck 3 is also completely excluded from the analysis, meaning that this deck has no contribution with respects to loads.

It is assumed that the beam analysis will give a conservatively result, mainly because of the application of effective breadth of plate flanges.

Further on, after the first analysis, it is assumed that the load capacities regarded decks intended for trucks is too high and cannot be considered as a normal loading condition.

4.3.2 Modelling

A cross section of one frame is first modelled, and beam properties, shown in table 4.5 and 4.6 for the side girders and transverse deck girder is assigned. Profiles of the side girder from deck 1 to 2 and profiles for deck 2 is also included in the tables below, as it is used in a beam analysis on a later stage. For the first model, only PSM above bulkhead deck (deck 2) is included in the model.

Table 4.5 Profiles of side girder

	Effective plate width	Plate thickness	Web height	Web thickness	Flange width	Flange thickness
Deck 1 to 2	797,4	12,5	795	12	400	32
Deck 2, thick flange	1376,1	10	550	8	200	32
Deck 2 to 4	1376,1	10	550	8	200	22
Deck 4 to 5	904,7	10	550	8	200	220
Deck 5 to 6	668,5	10	550	8	200	22
Deck 6 to 7	668,5	10	550	8	200	22
Deck 7 to ToG	588,6	6	550	8	200	22

Table 4.6 Deck profiles

	Transverse girder	Stiffener type	Longitudinal Center Girder	Longitudinal side girder
Deck 2	T W795x10 F250x32	L150x90x10x10	T W795x10 F300x30	T W795x10 F200x30
Deck 4	T W510x8 F250x19	L100x75x10x10	T W510x7 F100x19	T W510x7 F100x19
Deck 5	T W430x7 F120x20	L65x65x6x6	T W430x7 F120x20	
Deck 6	T W430x7 F120x20	L65x65x6x6	T W430x7 F120x20	
Deck 7	T W430x7 F120x20	L65x65x6x6	T W430x7 F120x20	
Top of Garage	T W360x7 F250x22	L65x65x6x6	T W360x7 F100x22	

The effective breadth of the attached plating is calculated according to equation 3.3, by assigning PSM spacing, S, and bending length of PSM, ^{l}bdg in 3D Beam, as shown in figure 4.9.

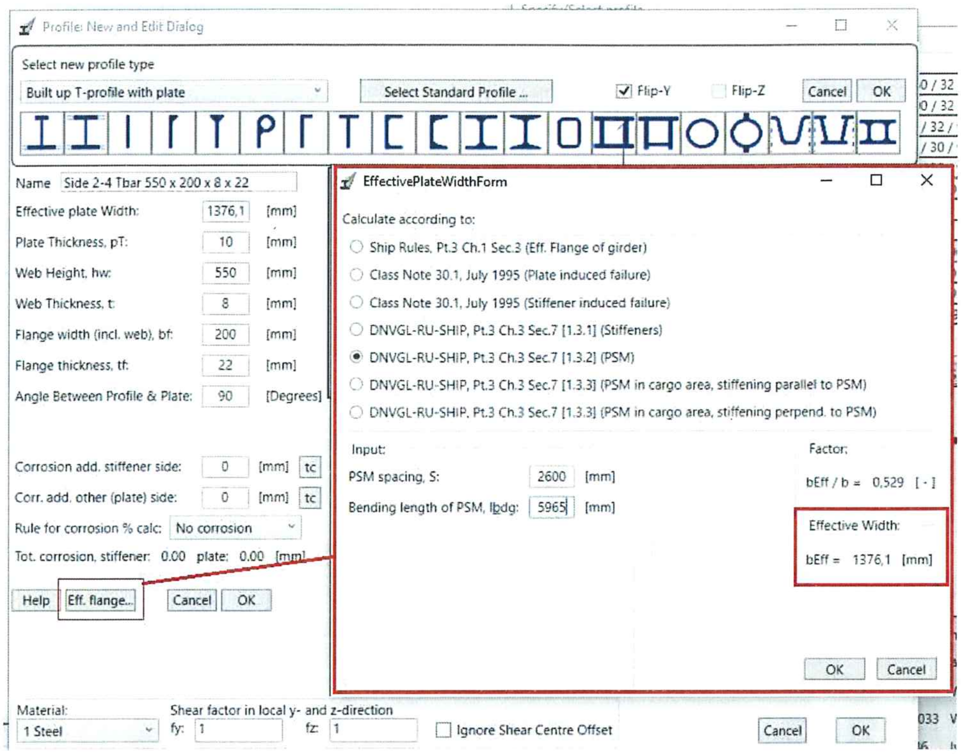


Figure 4-9 Effective plate width

The local axes are also changed for the beams with the wrong rotation, so the local y- and z-axis is aligned in the right direction with respect to the orientation of the profile's cross section and the direction of distributed loads. Longitudinal stiffeners are added on each deck, with the length of the distance between primary structural members, S, equal of 2600 mm.

The cross section can now be copied to replicate the evaluation area, as shown in figures 4.10 and 4.11.

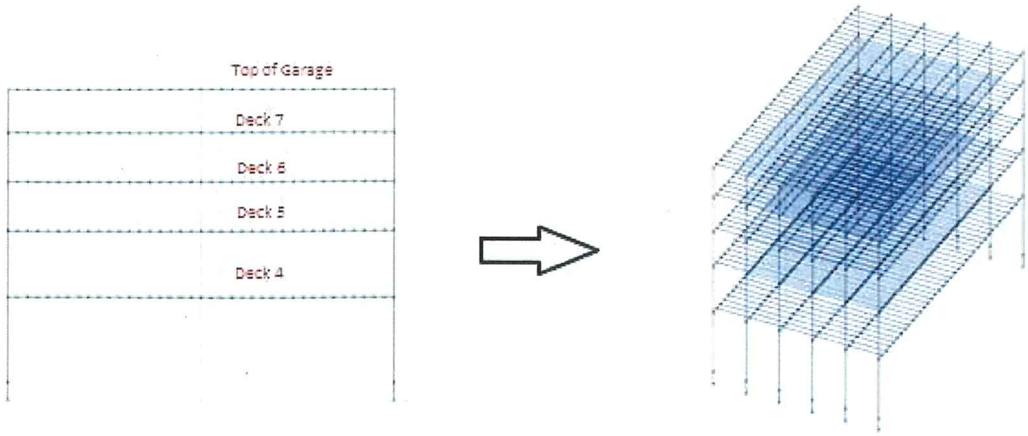


Figure 4-10 Developed model in 3D Beam

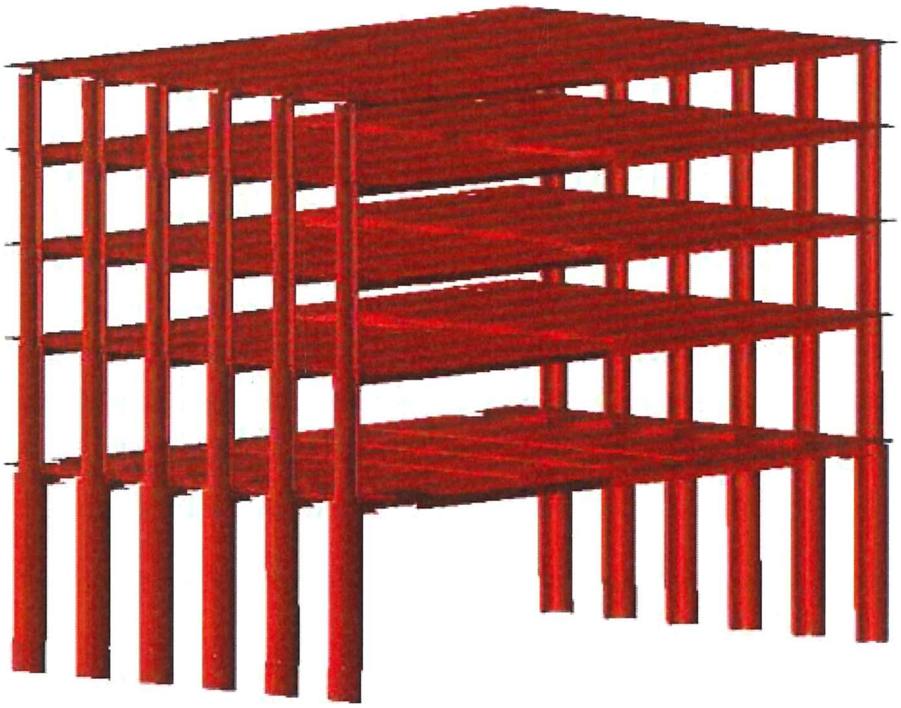


Figure 4-11 Solid model view in 3D Beam

4.3.3 Load application

From DNVGL-RU-SHIP Pt.5 Ch.3 (2018) the loads to applied for the racking case is the uniformly distributed load and the selfweight of the deck, respectively multiplied with the transverse envelope acceleration for the transverse load and with gravity for the vertical load.

As the profiles are modelled with beam elements with the effective flange assigned for both transverse girder and longitudinal stiffener, the mass of each deck calculated in 3D Beam may not be correct. Compared to the weight calculations for the full global model in GeniE, the selfweight of decks was calculated without the plate for the longitudinal stiffeners.

Table 4.7 Load calculations for beam analysis

Position	Uniformly distributed load [kg/m^2]	Selfweight distribution [kg/m^2]	Load deck (UDL+SW) [kg/m^2]	Load stiffener (UDL+SW)*S [kg/m]
Deck 2	2500	235	2735	3556
Deck 4	500	147	647	1682
Deck 5	200	82	282	733
Deck 6	200	82	282	733
Deck 7	200	82	282	733
Top of Garage	0	75	75	195

Table 4.8 Applied transverse and vertical force in beam analysis

Position	Transverse inertia line load [N/mm]	Vertical force [N/mm]
Deck 2	19,3	34,9
Deck 4	9,8	16,5
Deck 5	4,5	7,2
Deck 6	4,6	7,2
Deck 7	4,7	7,2
Top of Garage	1,3	1,9

As there is no requirements or recommendation from the DNVGL-rules, the transverse load is applied as distributed load in the local x-direction. In figure 4.12 the transverse load and local axes are shown for two selected beams. The two selected beams share the same start node, equal of y=0, meaning that the direction of the beam is opposite. Beams on the positive side of the global coordinate system in y-direction have a local coordinate system with positive x-direction equal to the positive y-direction in the global coordinate system. Beams on the negative side of the global coordinate system in y-direction, have a local coordinate system with the x-direction facing the other way. This means that the transverse line load must be assigned with a positive value for beams on positive side of global y-direction and with a negative value for beams on the negative side of the global coordinate system. The distributed load assigned in the local x-direction is working in the positive y-direction of the global coordinate system.

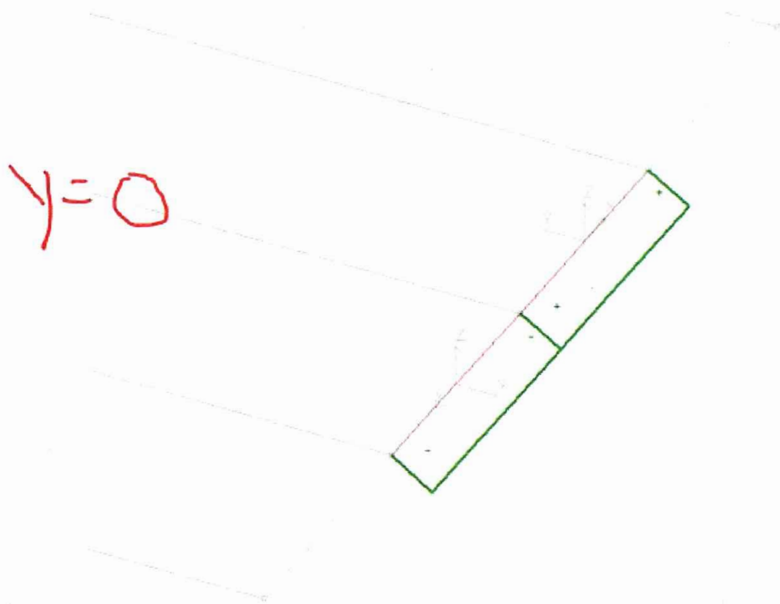


Figure 4-12 Applied transverse line load, as distributed load in local x-direction

Figure 4.13 shows the applied loads for racking load case, with values from table 4.8.

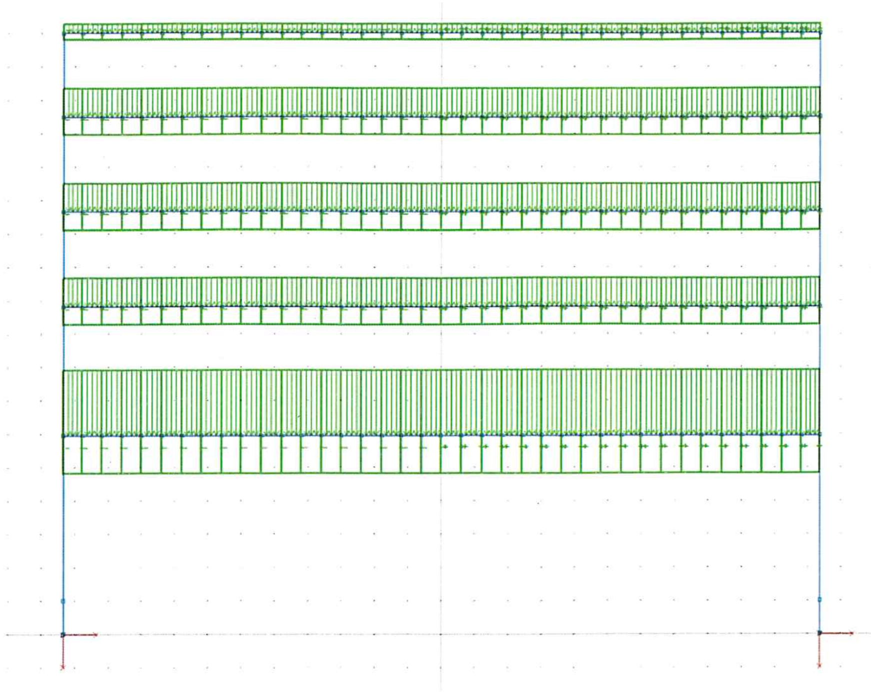


Figure 4-13 Applied loads to model

4.3.4 Boundary conditions

Boundary condition is applied as by rule requirement with fixed in translation for the nodes located at bulkhead deck, shown in figure 4.14.

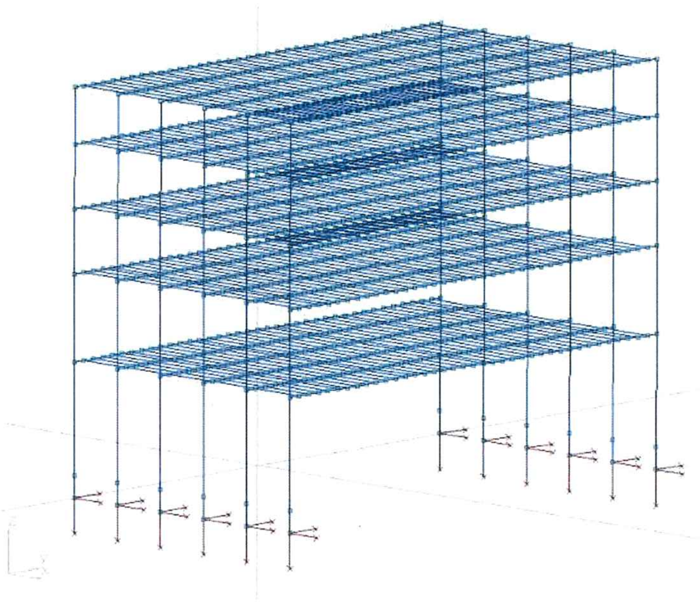


Figure 4-14 Model with boundary conditions displayed

4.4 Methodology application - Global FE Model

4.4.1 Limitations and assumptions

For the global model, the superstructure is excluded, due to simplifications for modelling. The weight should however be included, which it is not in this case. Tank content is also excluded and should be included if relevant for the load condition. There are also some inaccuracies in the fore ship, as it is missing some structure in the bow section and bulbous bow. It should also be included by the means of lumped stiffening, but as it is far away from the evaluation area, it is assumed that it does not affect the results significantly.

4.4.2 Modelling

From DNVGL-CG-0127 (2016) we have that the global model is to represent the global stiffness satisfactorily with respect to the objective for the analysis. This means that all transverse and longitudinal structure outside the evaluation area, which is marked in red on figure 4.15, must be modelled so the ship has sufficient global strength.

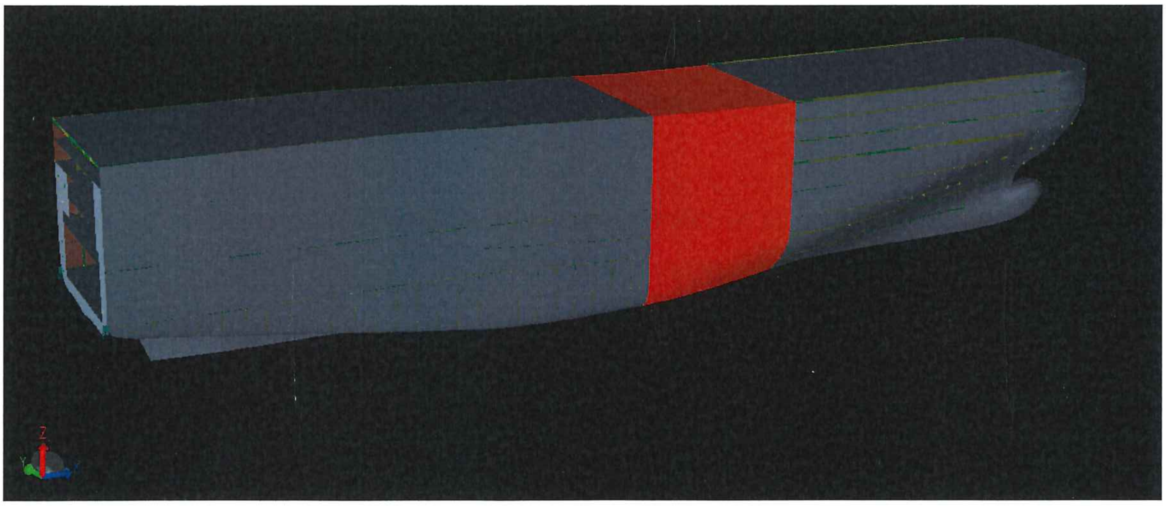


Figure 4-15 Developed full global model

For the global model, the hull lines are exported from NAPA and a xml-file is created in GeniE. First, the upper section is extruded as the export did not have sufficient height to the upper deck, top of garage. The skeg is not included in the export from NAPA and is manually added as plates. The outer shell is displayed in figure 4.16.

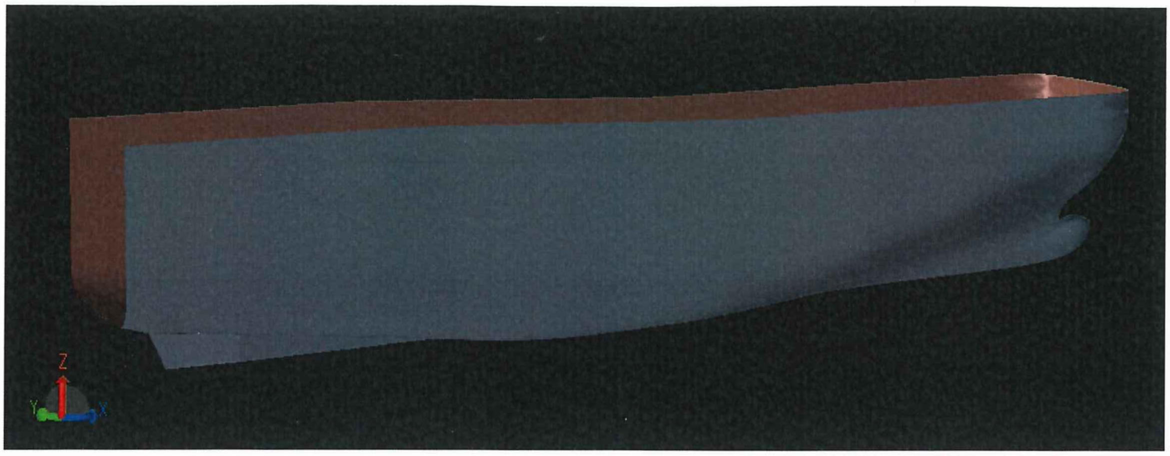


Figure 4-16 Hull shell imported from NAPA

All decks and bulkheads are modelled as plates and assigned properties as from the class drawings. In addition, the side girders which extends the full ship height in the evaluation area are modelled as plates, (recommendation from DNVGL rules XXXX). Side girders extending only to 2nd deck is modelled as beams. All plate elements are shown in figure 4.17, while all beam elements in the global model are shown in figure 4.18.

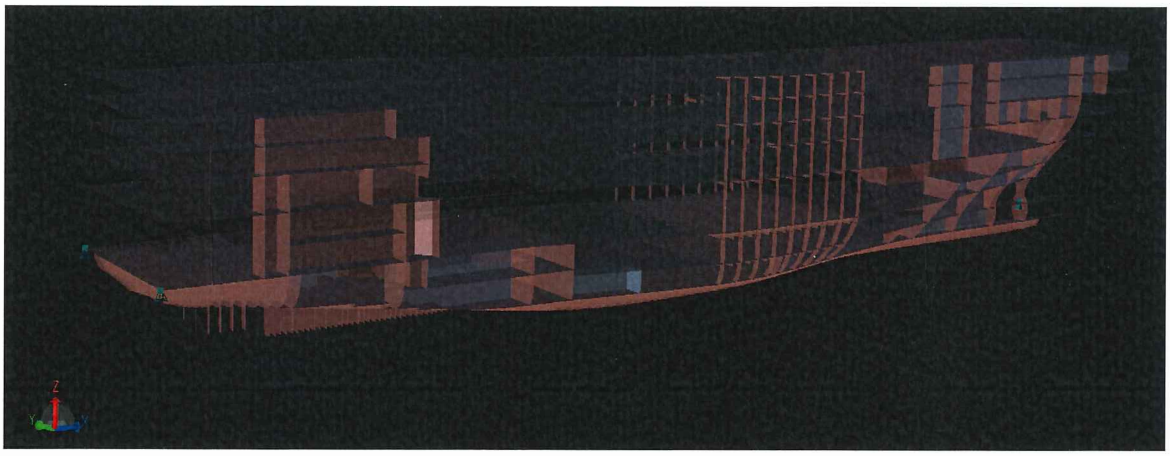


Figure 4-17 All shell plate elements in the global model

All beams and stiffeners outside the evaluation area is modelled after the methodology presented in 3.4.3. The lumped stiffeners, where possible, are placed with a grid of 2600 mm in the longitudinal direction and 3600 mm transversely.

In table 4.9 the calculation for the lumped center stiffener for deck 1 in the aft area is shown. The rest of the lumped stiffener calculations is included in appendix and include in total 59 lumped stiffener calculations.

Table 4.9 Lumped stiffener calculation

Position/Area	Type	Area	No of Lumped Stiff	Additional area	Type of stiff in pos	Area of stiffener in pos	New area	New profile
Deck 1, Center	L65x65x6	0,000744	5	0,00372	T_W400x7_F150x25	0,006375	0,010095	Lumped_Deck1_Center

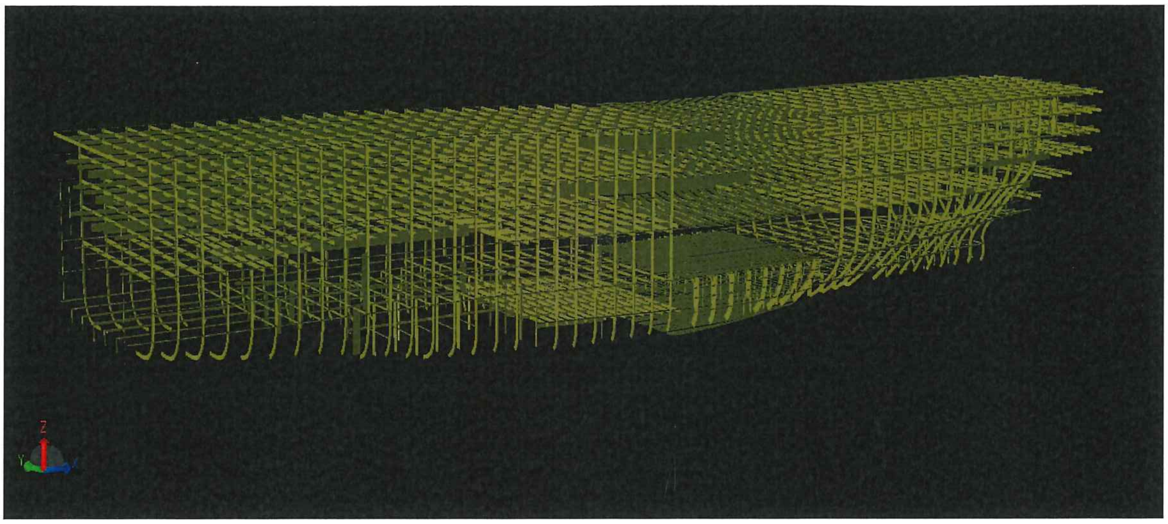


Figure 4-18 All beam elements included in the global model

By DNVGL-CG-0127 (2015) girder webs shall be modelled by means of membrane or shell elements. However, flanges may be modelled using beam and truss elements. As the connections between side girder and deck girder is considered to be an important area, the deck girder is modelled as shell element for the section with larger flange and the rest is modelled as beam element. This can be seen in figure 4.19 where the orange lines present the free plate edges.

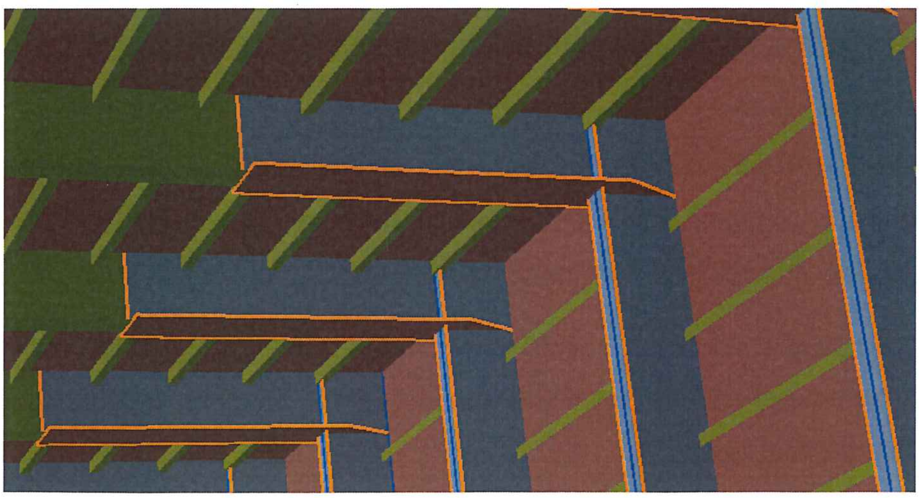


Figure 4-19 Modelling of transverse girders

However, as the deck loads first specified for deck 1 and 2 very large, these decks were assumed important, and the transverse girders was modelled as plate elements. The longitudinal members are in general always modelled as beam elements, as they are not that interesting to investigate for the racking strength assessment. The complete evaluation area is shown in figure 4.20.

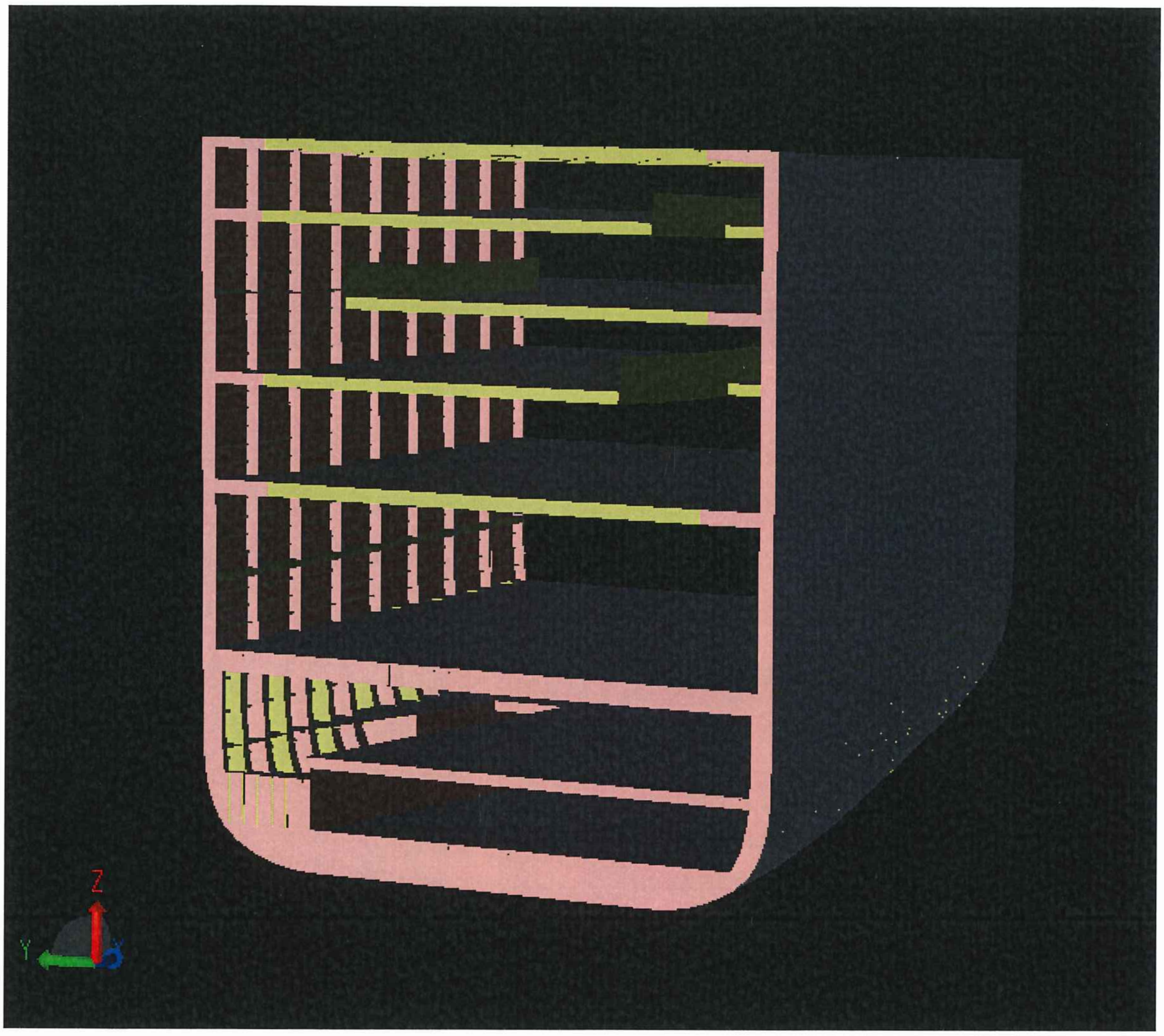


Figure 4-20 Evaluation area, modelled with plate and beam elements

From DNVGL-CG-0127 and chapter 3.4.2 the mesh arrangement is to be taken as one element between longitudinal girders, one element between transverse webs, and one element between stringers and decks. The mesh size was mainly decided by the distance between the transversely primary supporting members of 2600 mm and as some decks are sloped, the plate length will therefore exceed 2600 mm. The mesh size outside the evaluation area was therefore selected to be 2700 mm. For the evaluation area, finer mesh is wanted and as all structural members is modelled the mesh size will automatically be smaller as the mesh size is decided by the distance between structural members (600 mm between longitudinal stiffeners), but it is selected as 700 mm.

As the difference between the mesh size for the evaluation area and outside the evaluation area is fairly large, a section of 2600mm on each side of the evaluation area is assigned the mesh property of 1300 mm element length, as seen in figure 4.21.

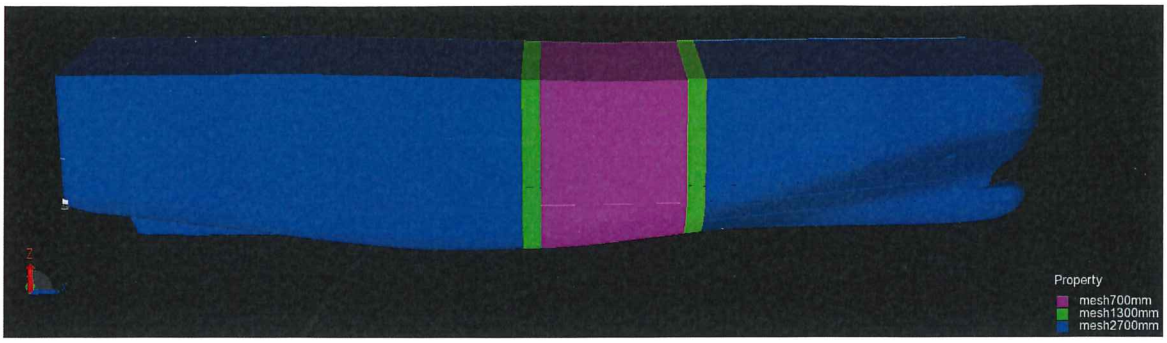


Figure 4-21 Mesh properties

This will give a better transition for the mesh between the finer mesh in the global model and the standard mesh size outside the evaluation area. In addition to the "transfer" zone, the growth rate for all mesh properties is set to be 1,3, as shown in figure 4.22. The growth rate specifies the rate of growth from an element to the neighbour element.

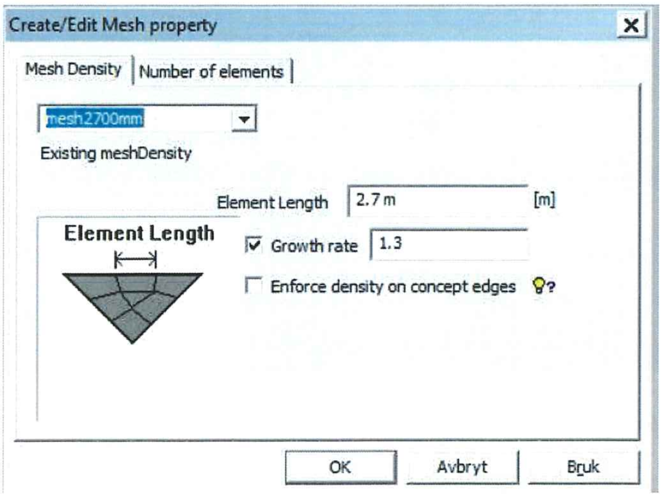


Figure 4-22 Specified growth rate for mesh property 2700 mm

The generated mesh for the full global model is shown in figure 4.23, with a finer mesh for the evaluation area.

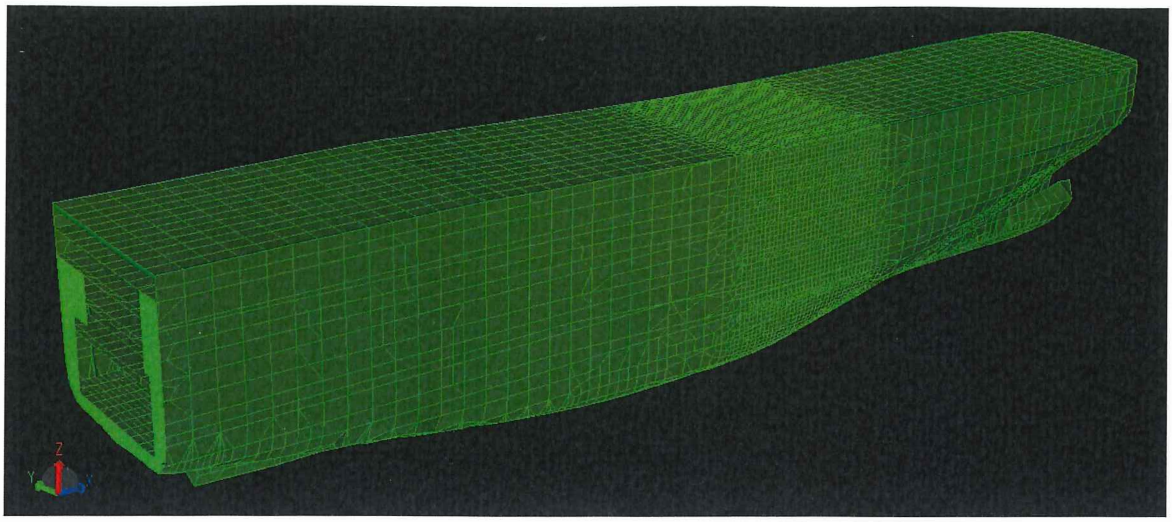


Figure 4-23 Generated mesh of global model

4.4.3 Boundary condition

The boundary condition is applied as three support points, with the location and direction of support given in table 4.10 From the methodology described in 3.4.4 the direction of support is changed for the support points at the transom, due to the direction of the transverse load is applied.

Table 4.10 Applied boundary conditions for the global model

	Location, name	Direction of support
Transom	Starboard, Sp1	Z
	Portside, Sp2	Y,Z
Forward end	Centerline, Sp3	X,Y,Z

The forward point is also moved from the centerline at the bulbous bow to the centerline at a transverse bulkhead in the fore ship, because of limitations in structure for the bulbous bow, as seen in figure 4.24. Otherwise large local deformations could be expected, also influencing the global deformation as the point will be less constrained.

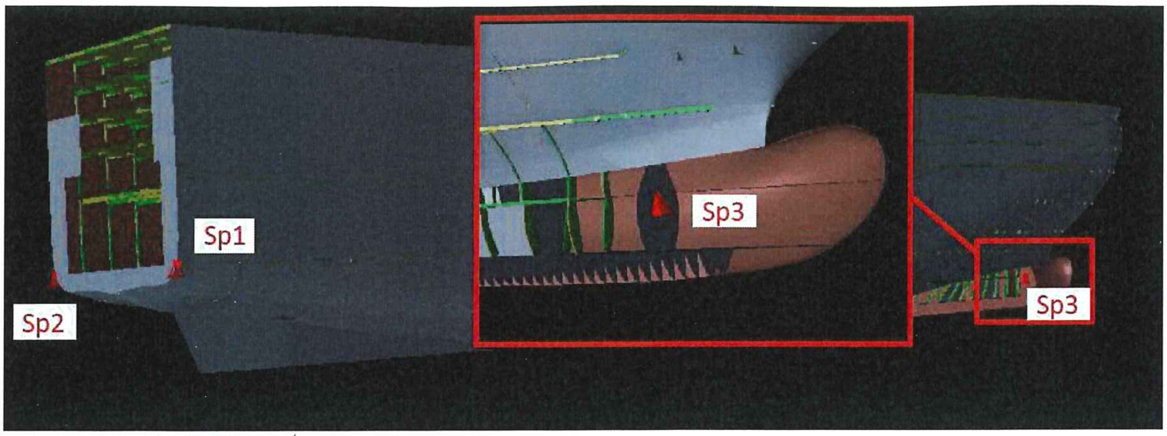


Figure 4-24 Applied boundary condition, shown in global model

4.4.4 Load cases

The load cases are divided into 16 different load cases and is later combined to create the racking load case. The division is made to make it easier to verify each load case and for balancing of the model. The load cases are divided into deck loads for each deck, the transverse inertia line load for each deck and sea pressure. In figure 4.25 the applied load cases for a racking strength assessment is shown.

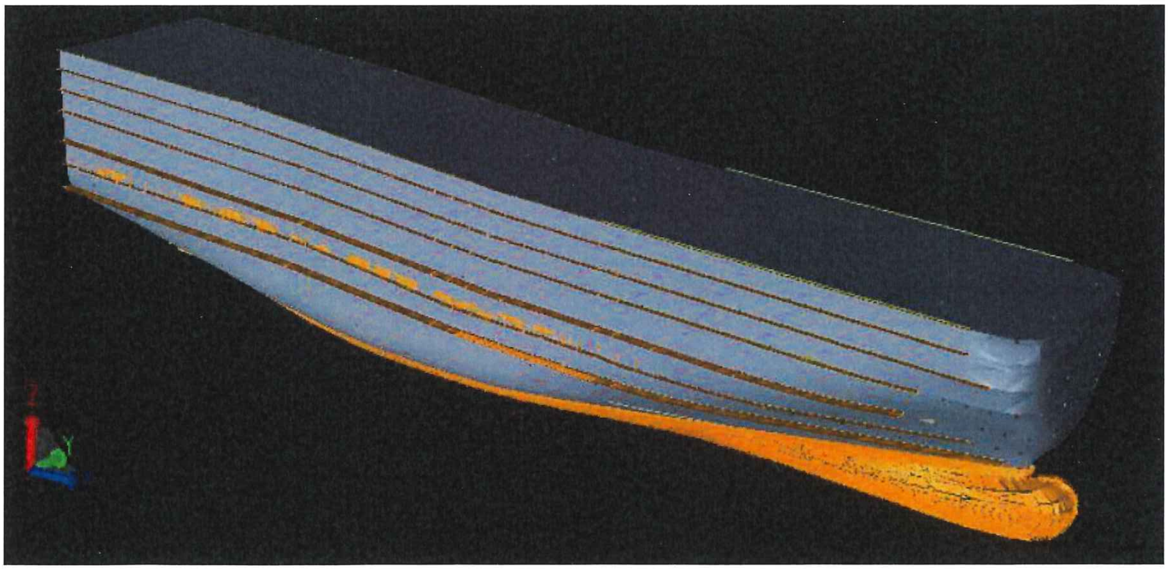


Figure 4-25 Applied racking load case to global model

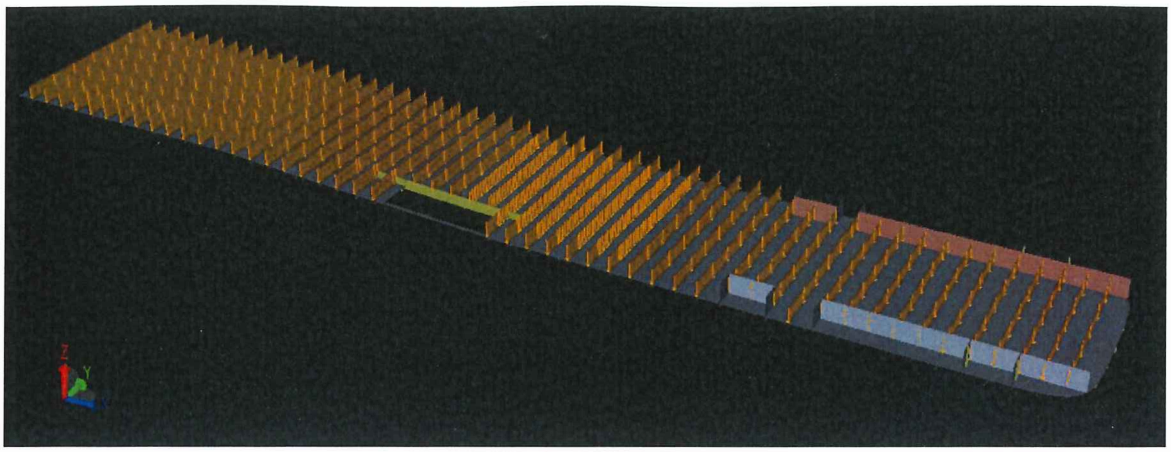


Figure 4-26 Deck load applied on deck 7

The deck load is applied as a line load on the transverse girders, to not cause a buckling problem as would be the case outside the evaluation area, if it was applied as surface load. The vertical loads applied is shown in table 4.11.

Table 4.11 Vertical load for global analysis

	Uniformly distributed load [kg/m^2]	Spacing [m]	Gravity [m/s^2]	Vertical load [N/m]
Tank top	1800 / 4000	2,6	9,80665	38246 / 101989
Deck 1	350	2,6	9,80665	8924
Deck 2	350	2,6	9,80665	8924
Deck 3	120	2,6	9,80665	3060
Deck 4	350	2,6	9,80665	8924
Deck 5	120	2,6	9,80665	3060
Deck 6	120	2,6	9,80665	3060
Deck 7	120	2,6	9,80665	3060
Top of Garage	0	2,6	9,80665	0

The transverse inertia line load is applied as a longitudinal line load along each deck, the load applied is shown in table 4.12.

Table 4.12 Transverse inertia line load

	max ay_env	Uniformly distributed load [kg/m²]	Distributed selfweight load [kg/m²]	Transverse inertia line load [N/m]
Deck 2	5,415	350	230	71268
Deck 3	5,576	120	121	30509
Deck 4	5,814	350	146	65473
Deck 5	6,076	120	105	30966
Deck 6	6,272	120	87	29485
Deck 7	6,469	120	80	29381
Top of Garage	6,644	0	75	11380

As the inertia vertical line load, based on one g, also should be applied, this is done by selecting one load case and change the load case property to include the structure self-weight in structural analysis, as can be seen in figure 4.27.

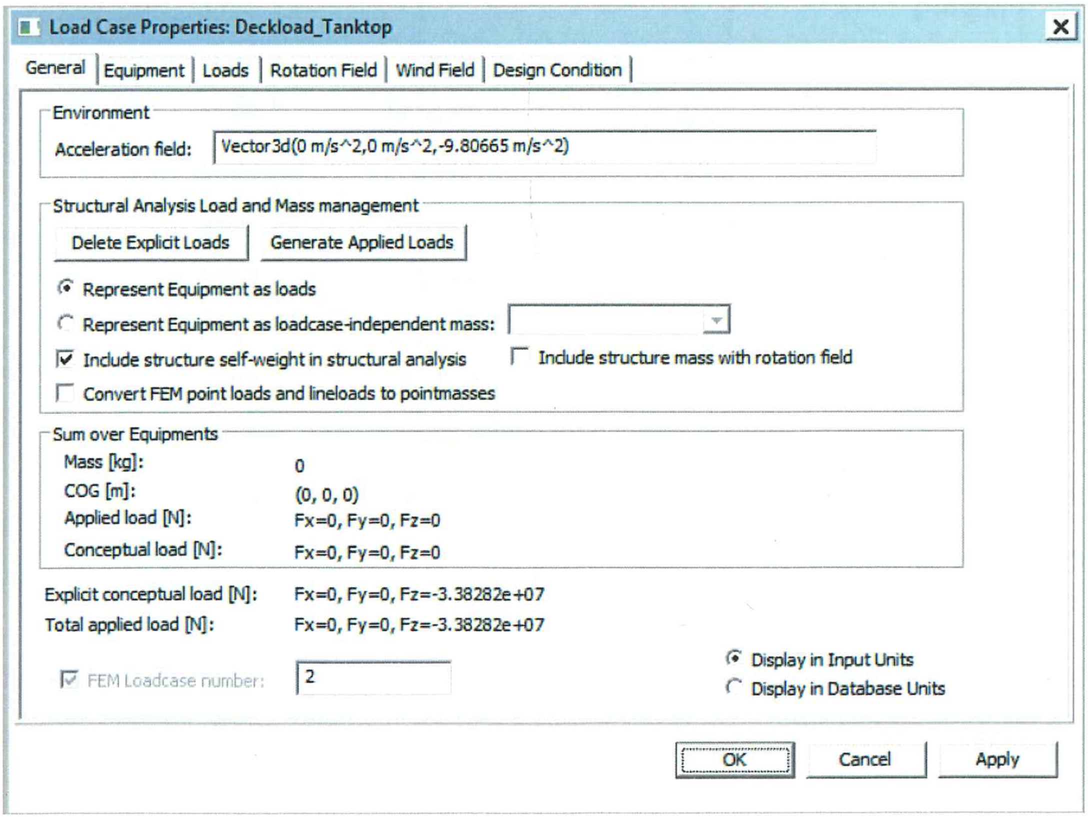


Figure 4-27 Load case property to include structure self-weight

4.4.5 Balancing of global model

After the load cases are applied (deck loads, the transverse inertia line load, hydrostatic sea pressure based on rule roll angle and the vertical inertia load based on one g), the global model must be checked so it is in balance with minimum reaction forces, as shown in table 4.13.

Table 4.13 Balancing of the sea pressure

	X-load [N]	Y-load [N]	Z-load [N]
Sea Pressure	12314	-34791000	115610000
Loads	-9,40853E-11	34781800	-115617000
Difference [N]	12314	-9200	-7000
Fraction [%]	100	0,03	-0,01

5 Results

5.1 Beam Analysis- as by rules

5.1.1 Results of Beam Analysis- as by rules

Table 5.1 Output from analysis

Total number of nodes	1194
Total number of beams	2137
Number of specified (fixed) degrees of freedom	36
Computational time	5 seconds

When the beam analysis is calculated as by the rule description with the deck loads first specified for this case, 294 beams does not meet the stress requirement. The highest bending stresses is 655 N/mm^2, giving a usage factor of 3,28. However, the stresses with regards to shear stress is below the allowable stress for shear. Figure 5.1 shows the stresses for 30 beams, sorted on the stress level, and figure 5.2 show where these beams are located.

	Beam	Name	SigmaHg [N/m	Sig-My [N/mm	Allowed [N/mm	Tau-Qz [N/mm	Allowed [N/mm	Usage, Norm	Ok / Not ok
1	813		0	-655	200	-79	115	3,28	Not ok
2	814		0	-655	200	-79	115	3,28	Not ok
3	815		0	-655	200	-79	115	3,28	Not ok
4	816		0	-655	200	-79	115	3,28	Not ok
5	817		0	-655	200	-79	115	3,28	Not ok
6	818		0	-655	200	-79	115	3,28	Not ok
7	716		0	-497	200	-75	115	2,49	Not ok
8	719		0	-497	200	-75	115	2,49	Not ok
9	727		0	-497	200	-75	115	2,49	Not ok
10	730		0	-497	200	-75	115	2,49	Not ok
11	734		0	-497	200	-75	115	2,49	Not ok
12	738		0	-497	200	-75	115	2,49	Not ok
13	807		0	466	200	56	115	2,33	Not ok
14	808		0	466	200	56	115	2,33	Not ok
15	809		0	466	200	56	115	2,33	Not ok
16	810		0	466	200	56	115	2,33	Not ok
17	811		0	466	200	56	115	2,33	Not ok
18	812		0	466	200	56	115	2,33	Not ok
19	746		0	-440	200	-72	115	2,20	Not ok
20	751		0	-440	200	-72	115	2,20	Not ok
21	760		0	-440	200	-72	115	2,20	Not ok
22	767		0	-440	200	-72	115	2,20	Not ok
23	780		0	-440	200	-72	115	2,20	Not ok
24	787		0	-440	200	-72	115	2,20	Not ok
25	842		0	-424	200	-32	115	2,12	Not ok
26	843		0	-424	200	-32	115	2,12	Not ok
27	845		0	-424	200	-32	115	2,12	Not ok
28	847		0	-424	200	-32	115	2,12	Not ok
29	849		0	-424	200	-32	115	2,12	Not ok
30	851		0	-424	200	-32	115	2,12	Not ok

Figure 5-1 Stresses for beam analysis

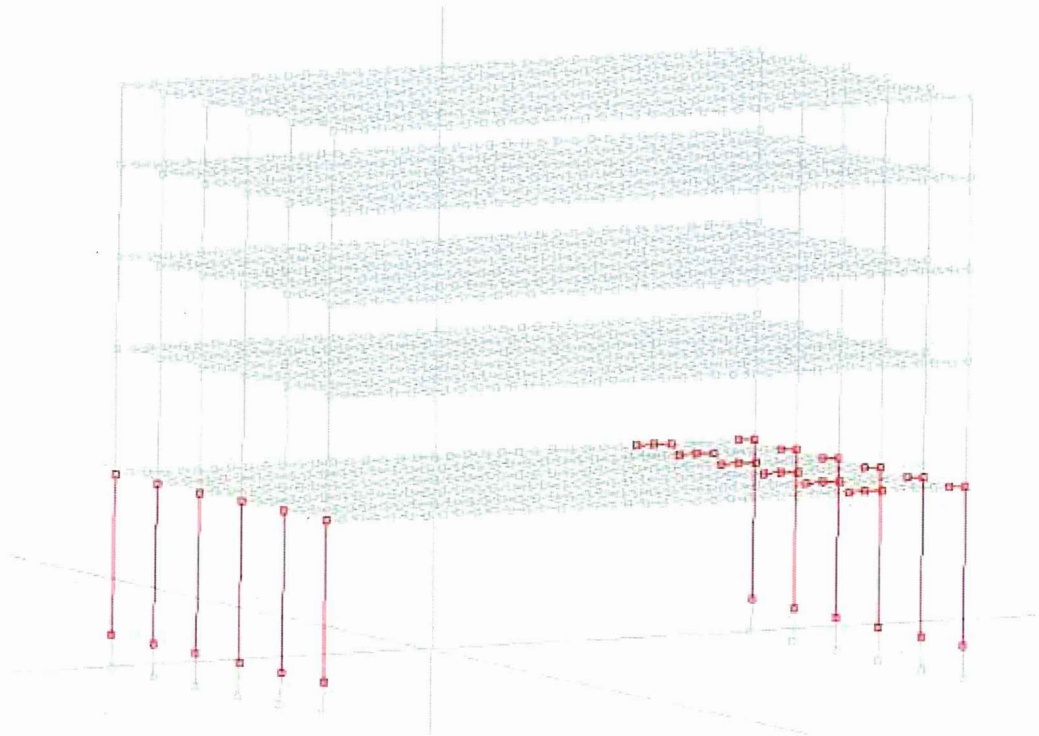


Figure 5-2 Selected beams with highest stresses

From the analysis we can see that the highest stresses occur on the side girders, to the side that we have the distortion created by the racking load case. The distortion can be seen in figure 5.3, which shows the displacement of the model.

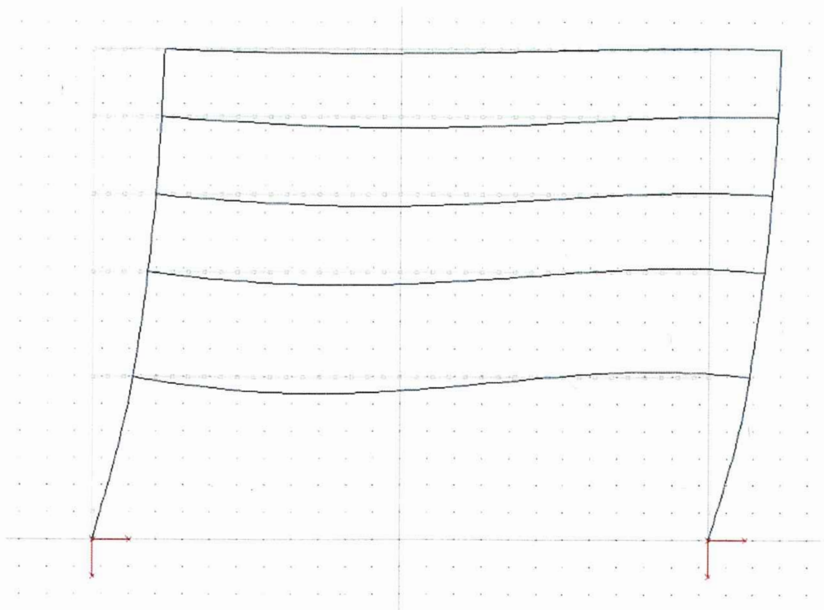


Figure 5-3 Displacements

5.1.2 Discussion of results of beam analysis- as by rules

The beam analysis was expected to be a conservative calculation method, but the values presented in 5.1.1, indicates that the method is not only conservative, but that something is incorrect. The loads are first investigated, and as mentioned, it was found that the deck loads are too high, as it is unlikely that the number of mafi-trucks will be this large at the same time. The deck loads are change to what can be considered as the actual maximum load condition.

The effective breadth which is assigned for each profile will also lead to conservative result, as this decreases the section modulus for the beam. However, when the fully plate breadth is assigned, it only results in a small increase in the section modulus and will not affect the high stresses.

As the boundary conditions is decided by rule, they are hard to argue with. However, as the side girder below bulkhead deck has a web height of 800 mm, and the transverse deck girder has a web height of 795 mm, the connection could be assumed as a fixed point. This is later shown in two other beam analyses.

As the boundary condition which is applied is only fixed in translation, it will have no bending moment in this node, leading to bending moment shown in figure 5.4. The response is also shown in figure 5.5, but only the side girder is selected. From the response plot we can also see the different bending stress about the local y-axis, where the plate is the complete line and the dashed line shows the bending stress response for the flange.

The results presented cannot be used for a racking strength assessment, and we must apply some changes.

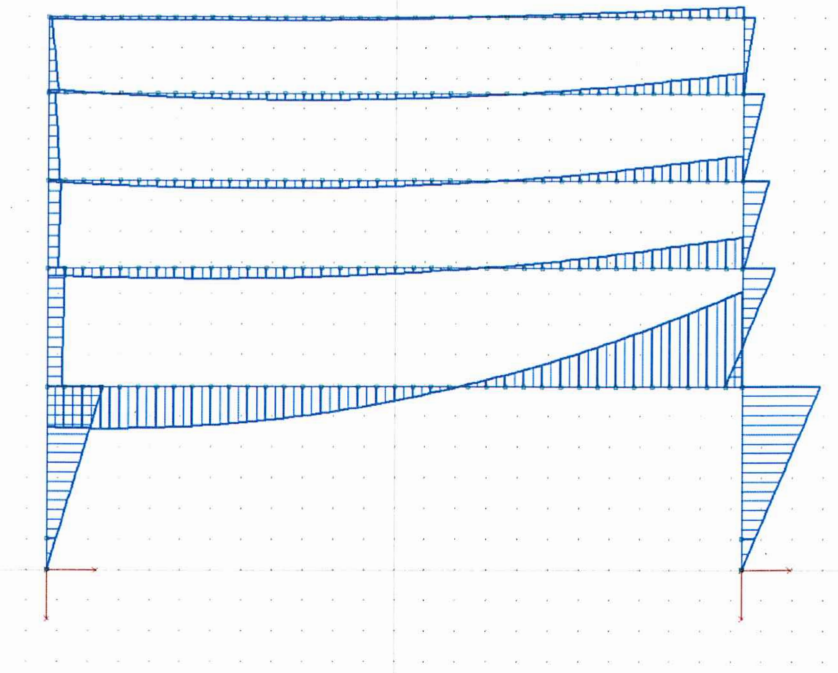


Figure 5-4 Bending moment

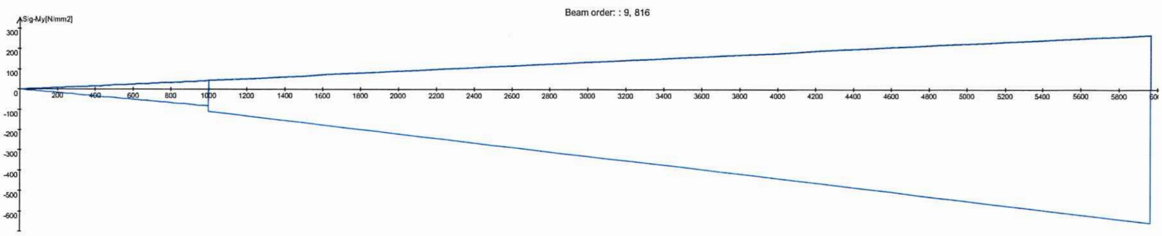


Figure 5-5 Response plot of side girder from bulkhead deck to deck 4

5.2 Beam Analysis- with deck 2

As the results from the first beam analysis was not sufficient for a racking strength assessment, a new analysis is made, based on the old model. First of all, it includes the bulkhead deck and the deck loads are changed to a more realistic and actual case. Hence of these changes the output from the analysis changes and are shown in table 5.2.

5.2.1 Results Beam Analysis- with deck 2

Table 5.2 Output from analysis

Total number of nodes	1633
Total number of beams	2947
Number of specified (fixed) degrees of freedom	66
Computational time	6 seconds

As the deck load is changed, the new forces which is applied transversely and vertically is shown in table 5.3.

Table 5.3 New transverse and vertical forces applied

Position	Transverse inertia line load [N/mm]	Vertical force [N/mm]
Deck 2	4,1	7,5
Deck 4	7,5	12,7
Deck 5	3,2	5,2
Deck 6	3,3	5,2
Deck 7	3,4	5,2
Top of Garage	1,3	1,9

In figure 5.6, the new model which are developed is shown. Since the bulkhead deck now is included in the beam analysis, the transverse and vertical force is also applied to this deck. On the figure it visually looks like the forces applied on the bulkhead deck (deck 2) is lower than the decks applied to deck 4. This is however not the case as the spacing between the transverse girders are 1300 mm for deck 2, while the spacing is 2600 mm for deck 4. You can also see that the same boundary condition is applied to node at the position of deck 1, with only fixed in translation.

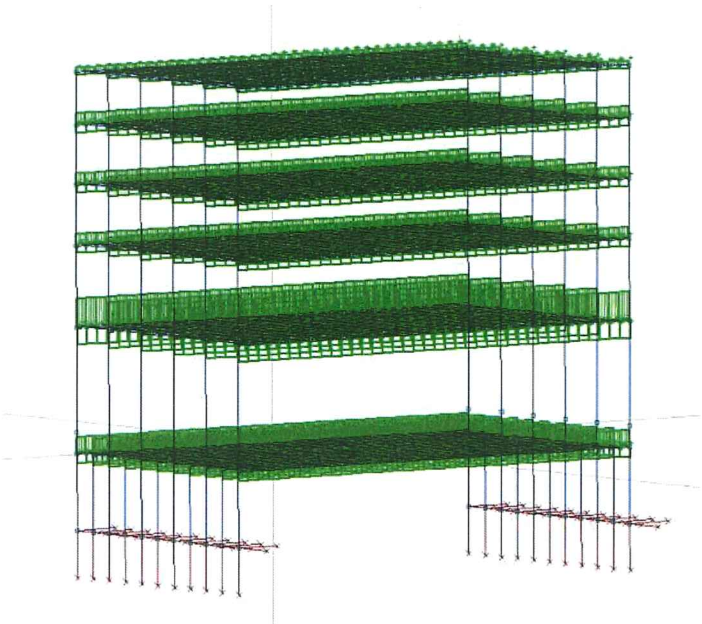
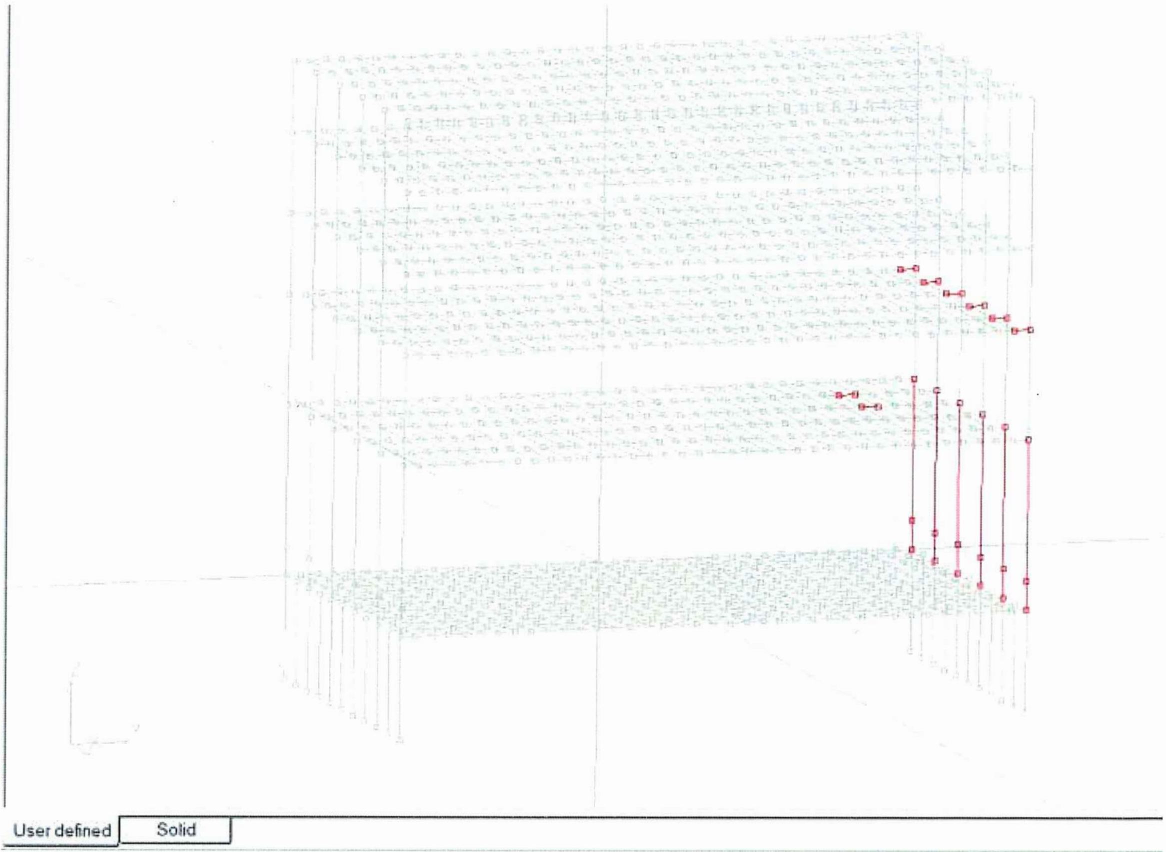


Figure 5-6 The new developed model



	Beam	Name	SigmaHg [N/m	Sig-My [N/mm	Allowed [N/mm	Tau-Qz [N/mm	Allowed [N/mm	**Usage, Norm**	Ok / Not ok
1	777		0	247	200	-65	115	1,24	Not ok
2	778		0	247	200	-65	115	1,24	Not ok
3	776		0	246	200	-65	115	1,23	Not ok
4	779		0	246	200	-65	115	1,23	Not ok
5	775		0	243	200	-64	115	1,22	Not ok
6	780		0	243	200	-64	115	1,22	Not ok
7	1582		0	236	200	-67	115	1,18	Not ok
8	1583		0	236	200	-67	115	1,18	Not ok
9	1584		0	236	200	-67	115	1,18	Not ok
10	1585		0	236	200	-67	115	1,18	Not ok
11	1642		0	-236	200	-28	115	1,18	Not ok
12	1643		0	-236	200	-28	115	1,18	Not ok
13	1645		0	-236	200	-28	115	1,18	Not ok
14	1647		0	-236	200	-28	115	1,18	Not ok
15	1649		0	-236	200	-28	115	1,18	Not ok
16	1651		0	-236	200	-28	115	1,18	Not ok
17	1581		0	232	200	-66	115	1,16	Not ok
18	1586		0	232	200	-66	115	1,16	Not ok
19	1487		0	-221	200	-43	115	1,11	Not ok
20	1495		0	-221	200	-43	115	1,11	Not ok

Figure 5-7 Stresses

Figure 5.7 shows the bending stress for 20 beams, with the highest bending stress of 247 N/mm^2. This gives the usage factor of 1,24 for this beam, in total there are now 48 beams with usage factor above 1.

5.2.2 Discussion of results of beam analysis with deck 2

As we can see from the result, the reduction of the deck loads for all decks is of great contribution to the reduced bending stresses. Deck 2 is also included in the model, mainly because of two things: for comparison to full global model in GeniE and to see how the beam responses for the side girder from bulkhead deck to deck 4 changes. Instead of assigning the boundary condition for the node at deck 2, this is now defined by the stiffness matrix, and we can see a change of the bending moment for the model, as displayed in figure 5.8.

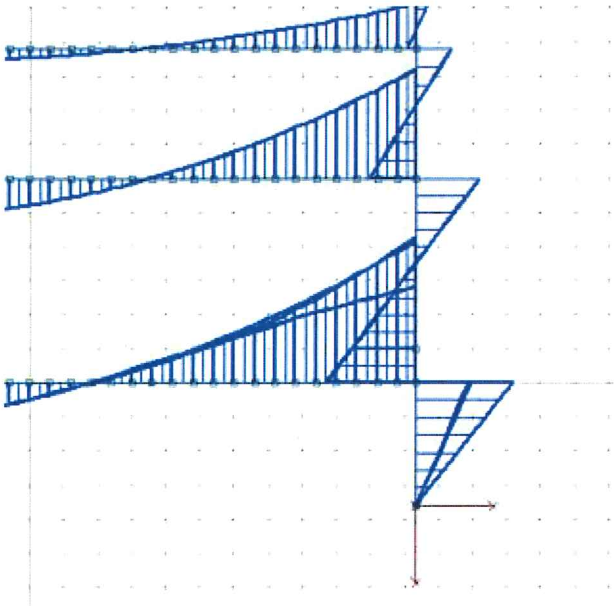


Figure 5-8 Bending moment about local y

As the boundary condition changes for the node at deck 2, it can have bending moment. And as the stiffness matrix calculates, it reduces the side girder's bending stress between bulkhead deck and deck 4, as we can see in the response plot in figure 5.9. The responses we saw for the side girder in the first analysis has now moved to the side girder below bulkhead deck. The section modulus for this side girder is however so big that it has bending stress below the allowable value of 200 N/mm^2.

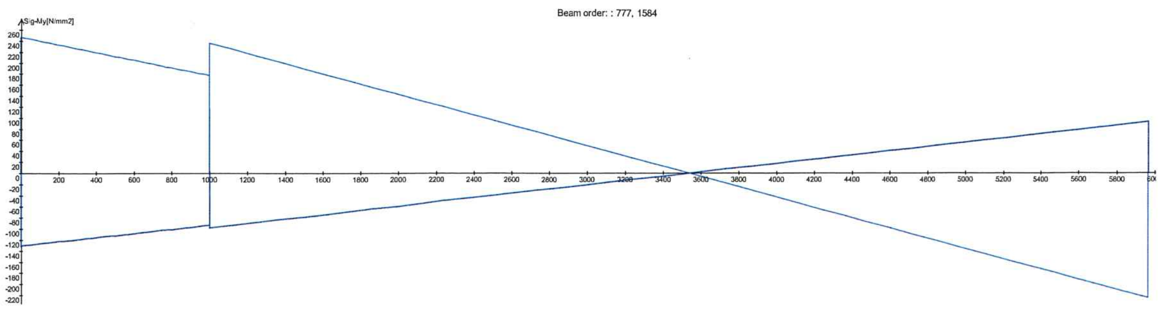


Figure 5-9 Response plot of bending stress for side girder between bulkhead deck and deck 4

5.3 Beam Analysis- developed model

From what we have learned from the two previous beam analyses, a third analysis is developed. The developed model utilizes what we learned from the previous analysis regarding the boundary condition for deck 2, which we now can assume as stiff connection and assigned fixed boundary conditions in all directions of freedom. The deck loads applied are also the more normal maximum loading condition. As the model only have modelled structure above the bulkhead deck, it is more similar to the first beam analysis done by the description of the rules.

5.3.1 Results Beam Analysis- developed model

Table 5.4 Output from analysis

Total number of nodes	1194
Total number of beams	2137
Number of specified (fixed) degrees of freedom	72
Computational time	5 seconds

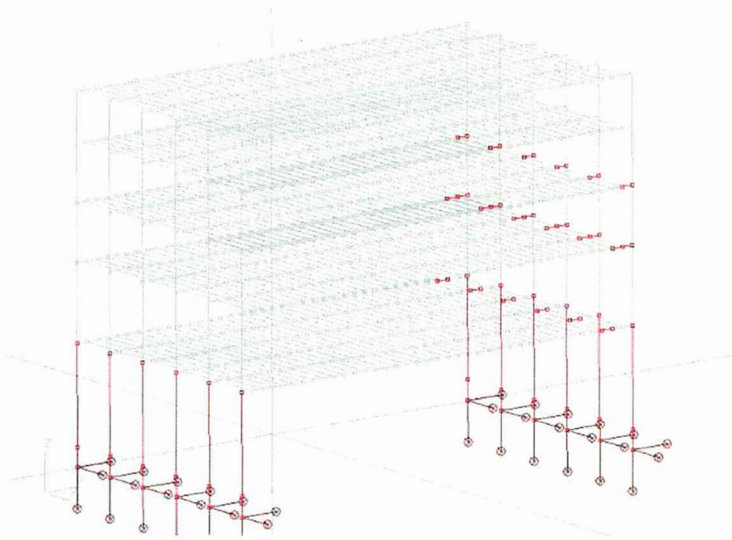


Figure 5-10 Selected beams with high stresses

Figure 5.10 shows the beam analysis model, with the red selected beams as the beams with highest stresses. The boundary condition which is applied can also be seen, with fixed in every degree of freedom.

Figure 5.11 shows the bending stress for 20 beams, with the highest bending stress of 269 N/mm^2. This gives the usage factor of 1,35 for this beam, in total there are now 48 beams with usage factor above 1.

User defined | Solid

	Beam	Name	SigmaHg [N/m	Sig-My [N/mm	Allowed [N/mm	Tau-Qz [N/mm	Allowed [N/mm	Usage, Norm	Ok / Not ok
1	7		0	269	200	-62	115	1,35	Not ok
2	8		0	269	200	-62	115	1,35	Not ok
3	9		0	269	200	-62	115	1,35	Not ok
4	10		0	269	200	-62	115	1,35	Not ok
5	11		0	269	200	-62	115	1,35	Not ok
6	12		0	269	200	-62	115	1,35	Not ok
7	813		0	270	200	-64	115	1,35	Not ok
8	814		0	270	200	-64	115	1,35	Not ok
9	815		0	270	200	-64	115	1,35	Not ok
10	816		0	270	200	-64	115	1,35	Not ok
11	817		0	270	200	-64	115	1,35	Not ok
12	818		0	270	200	-64	115	1,35	Not ok
13	807		0	-238	200	37	115	1,19	Not ok
14	808		0	-238	200	37	115	1,19	Not ok
15	809		0	-238	200	37	115	1,19	Not ok
16	810		0	-238	200	37	115	1,19	Not ok
17	811		0	-238	200	37	115	1,19	Not ok
18	812		0	-238	200	37	115	1,19	Not ok
19	853		0	-232	200	-28	115	1,16	Not ok
20	854		0	-232	200	-28	115	1,16	Not ok

Figure 5-11 Stresses

5.3.2 Discussion of beam analysis – developed model

As figure 5.12 show, we have the same bending moment response for the port (right side in the figure) side girder between bulkhead deck and deck 4, which we had from the results of chapter 5.2. The change in boundary condition may therefore be seen as valid for this model.

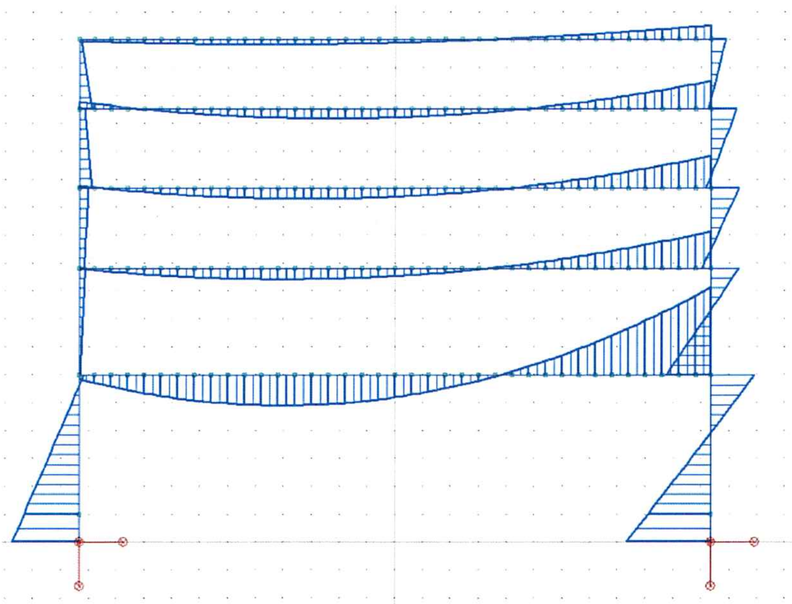


Figure 5-12 Bending moment about local y

5.4 Full Global FE model

5.4.1 General Full Global FE Model Results

Table 5.5 Output from analysis

Total number of nodes	32096
Total number of elements	59692
Number of triangle elements	5006
Number of quad elements	33958
Number of beam elements	20728
Number of specified (fixed) degrees of freedom	6
Number of internal (free) degrees of freedom	192264
Computational time	1317 seconds

All figures presenting the results of the global FE model have the permissible stress value set for the maximum and minimum value of the contour plot. In figure 5.13, these values are set to 200 and -200 respectively, as this is the acceptance criteria for normal membrane stresses.

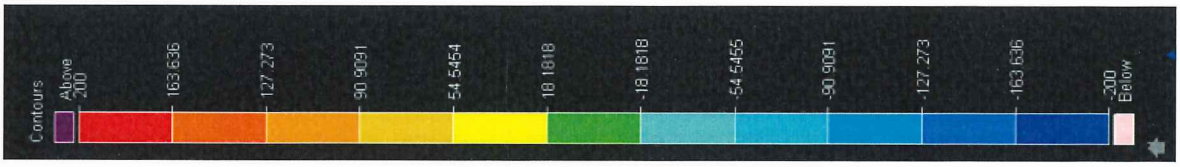


Figure 5-13 Levels of contour plot

All result attributes studied are the nodal decomposed stresses (D-stress) which are general stresses decomposed into membrane and bending parts. This attribute is only relevant for shell elements. From 3.4.7 we have that Stresses in plating of transverse racking constraining structure shall not exceed the permissible values for normal membrane stress, shear stress and the von Mises stress.

5.4.2 Normal membrane stress

Sig-my (σ_{MY}) is the membrane part of stress in the direction of the local y-axis and is in interest when the web frames are studied. In figure 5.14, a set from GeniE is selected to display the bending stress on the side girders web and flange.

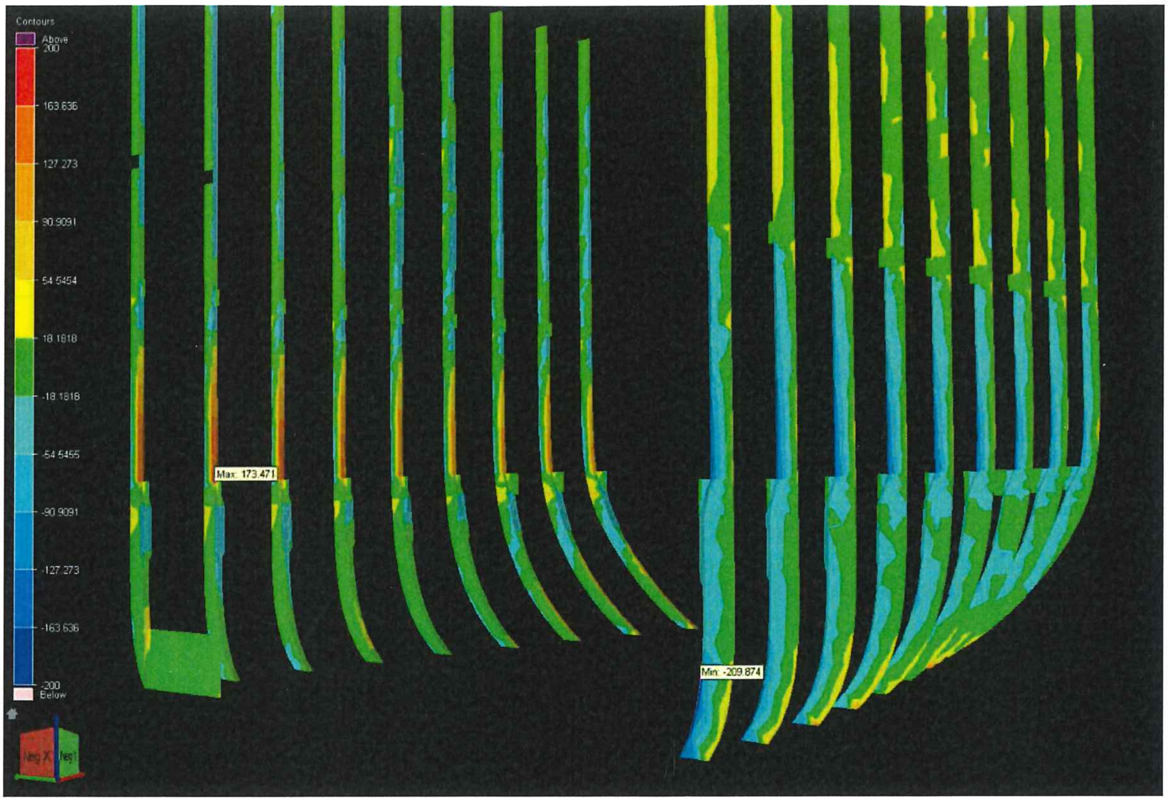


Figure 5-14 Set with only sidegirders

The girders to the left in the figure are the port side girders, and since the racking load case which is applied is rolling to the port and a transverse load applied to starboard side, the result is expected with tension in the flanges on the port side, and compression in the starboard flanges. The minimum and maximum stress for the set shown in figure 5.15 is respectively -209 N/mm^2 and 173 N/mm^2. Which means that the permissible stress is exceeded for the transverse racking constraining structure. However, this will be discussed in chapter 5.4.5.

As easily can be seen in figure 5.15, the highest stress concentration occur between the 2nd and 4th deck. The figure displays frame number 108 as the middle girder.

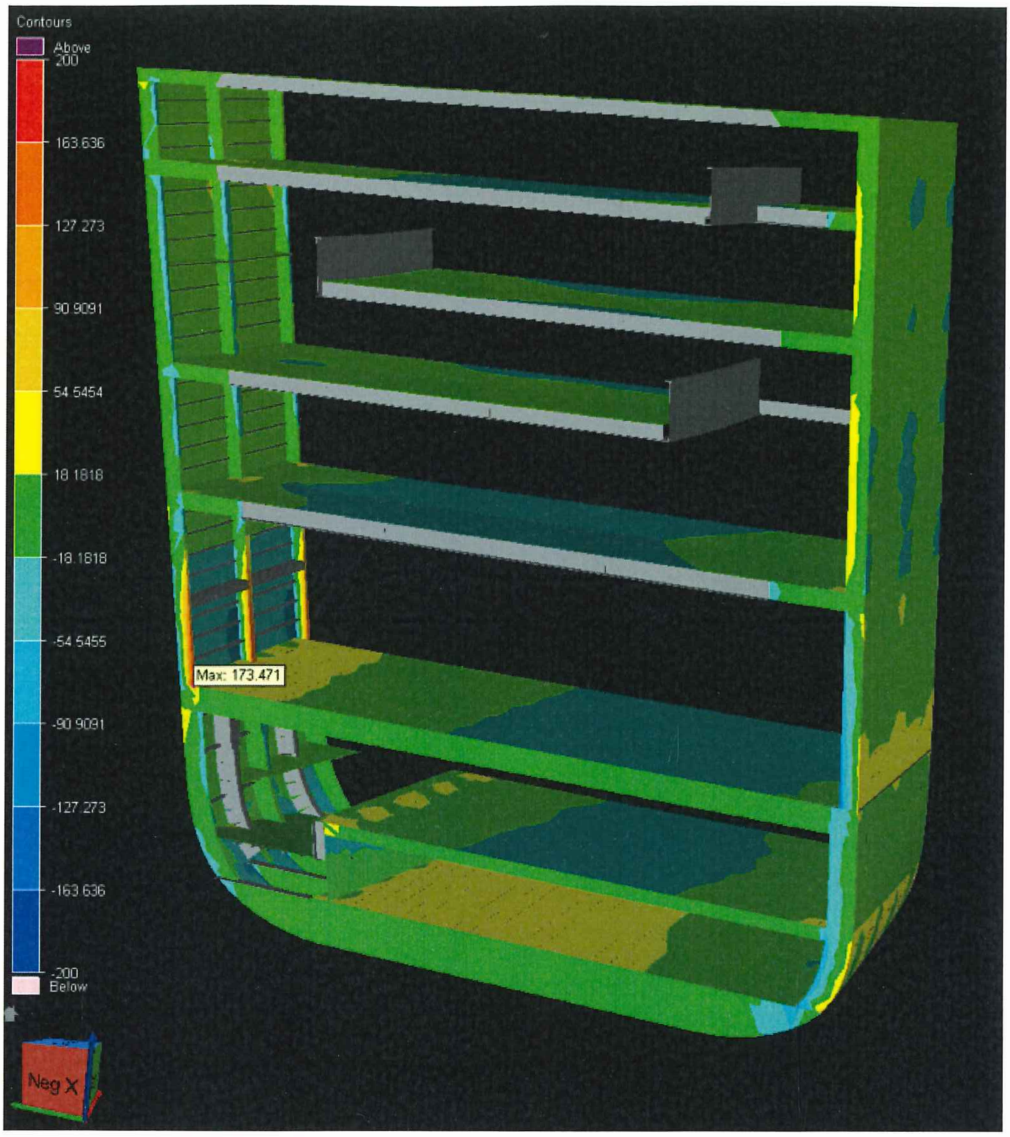


Figure 5-15 Frame #108

It is chosen to investigate the results at this frame closer, due to the peak stresses shown in figure 5.14, which occurred relatively close to the edge of the evaluation area. Although the global model is made to represent the overall global strength, the loads may be inaccurate transferred to the girders at the edges of the evaluation area.

The results from figure 5.16 and 5.17, showing the stress for port and starboard side, are presented in table 5.6.

Table 5.6 Normale membrane stress

Position	Highest normal membrane stress [N/mm^2]	Permissible stresses [N/mm^2]
Port, above 2nd deck	147	200
Starboard, above 2nd deck	114	200

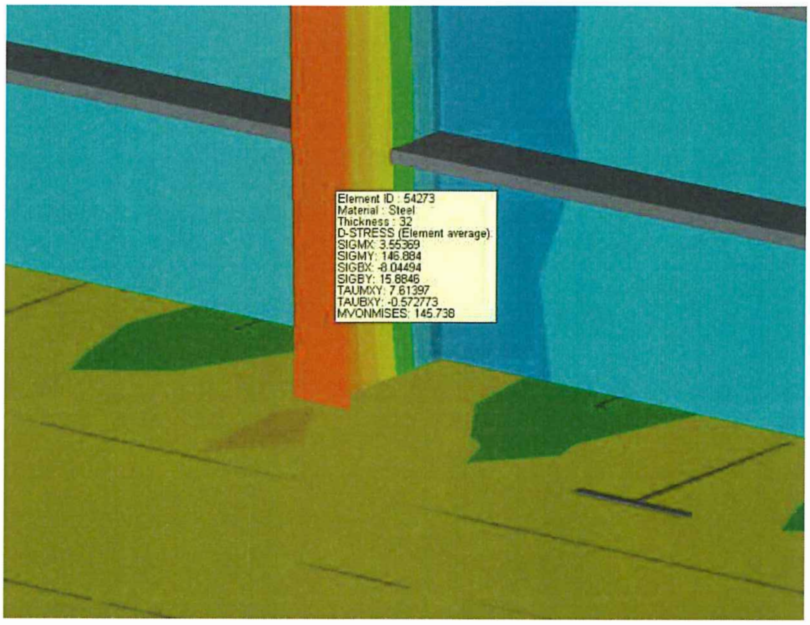


Figure 5-16 Port side, #108 Above 2nd deck

Figure 5-17 Starboard side, #108 above 2nd deck

5.4.3 Shear stress

The shear stress in interest is the TAUMXY (τ_{Mxy}) which is the membrane part of shear stress in the direction of the local x/y-axes.

Figure 5.18 shows the shear stress for the evaluation area. This is generally OK, except for some areas such as the connection between the transverse deck girder and side girder at 2nd deck. The stresses are however only exceeding the value at det deck girder at the end of the evaluation area, as can be seen in figure 5.19 below.

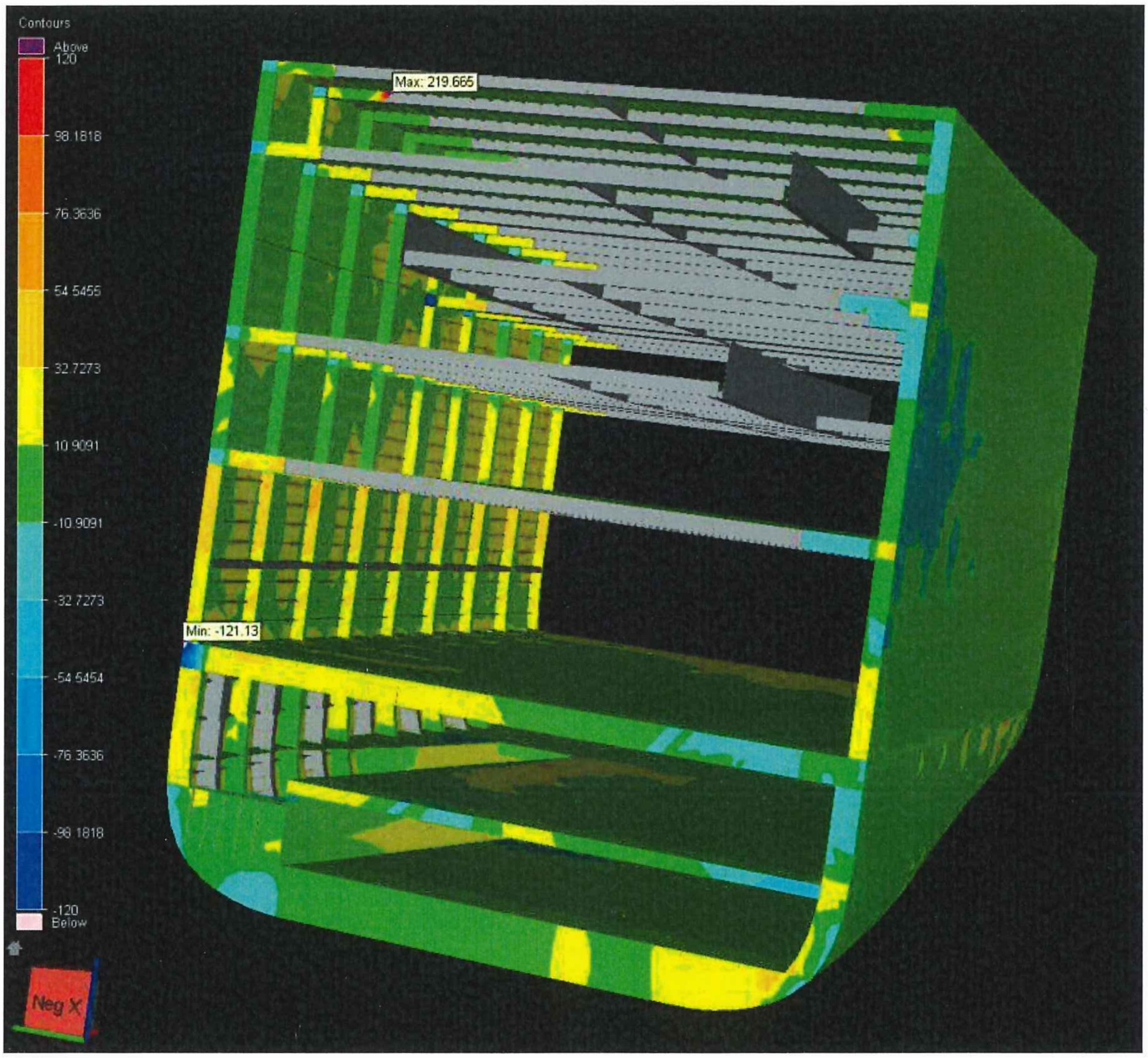


Figure 5-18 Shear stress, evaluation area

As the stress peaks may be explained, the highest shear stress is regarded as 60 N/mm^2 and is positioned at frame 108, just below the 4th deck. This gives a usage factor of 0,5, with the permissible shear stress value as 120 N/mm^2.

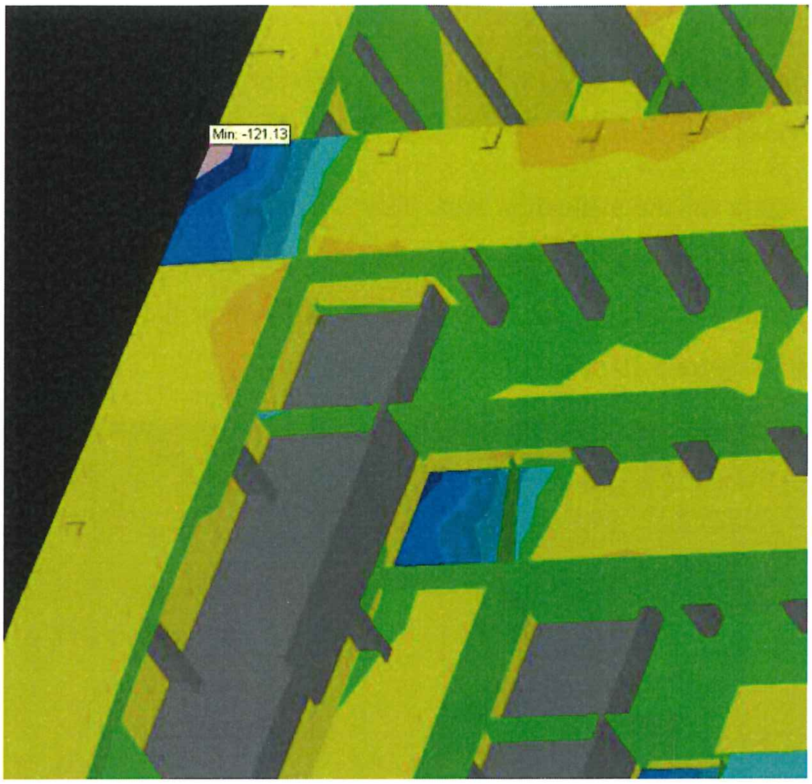


Figure 5-19 Shear stress for connection between deck and side girder

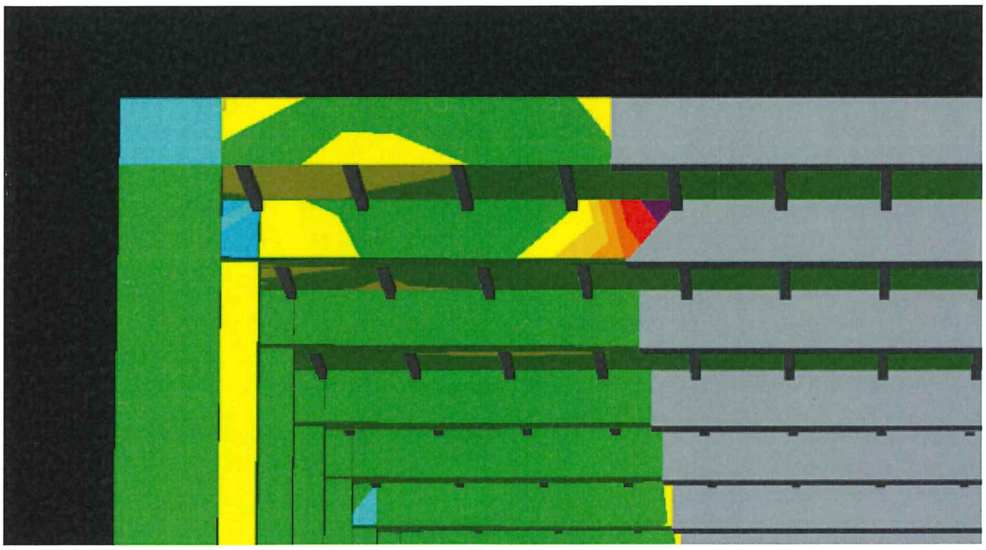


Figure 5-20 Shear stress for top of Garage

Figure 5.20 shows the stress at top of garage, where one transverse deck girder is exceeding the acceptance criteria. As can be seen, this deck girder is not the same the others, and the stress may be caused by a modelling error.

5.4.4 Von Mises stresses

MvonMises – von Mises stress based on membrane stresses.

$$\sigma_{MvonMises} = \sqrt{\sigma_{Mx}^2 + \sigma_{My}^2 - \sigma_{Mx}\sigma_{My} + 3\tau_{Mxy}^2}$$

The von Mises stresses based on membrane stress are generally low, due to that the stresses can also be said to be general low for the other membrane stresses. The stress peaks for von Mises is located where stress peaks already presented is positioned. Some of the stress peaks can be explained. However, the stress location in interest (the side girders) have a maximum von Mises stress of 140 N/mm^2 at the side girder above 2nd deck on port side in frame 108. Which is below the permissible von Mises stress of 220 N/mm^2.

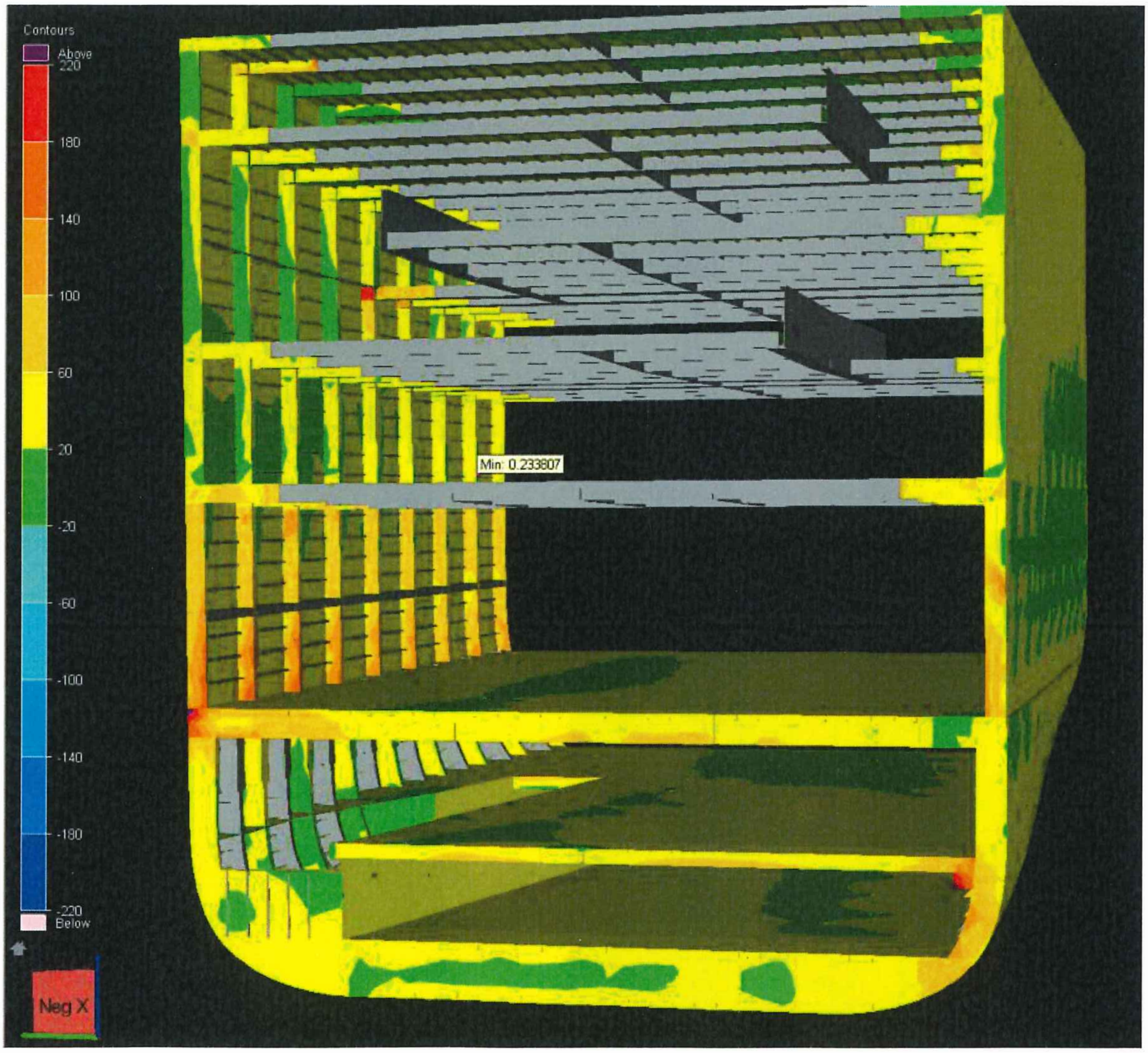


Figure 5-21 von Mises stress, evaluation area

5.4.5 Discussion of Full Global FE Model results

Validation of global model

The results from the global FE model generally seems to be valid. Although, some areas with high stress peaks can be caused by modelling errors, such as the figure 5.20 of top of garage. Although connections between structural members is in general considered to be important, the peaks shown in figure 5.22 and 5.23 below may not be counted as valid, as the structure is not modelled 100% correctly here, as the deep web frame intersects with the stiffeners on the bulkhead. In addition, the peaks are located on the edge of the evaluation area and the load distribution to this area may not be the same as if the structure outside the evaluation area was not lumped and simplified.

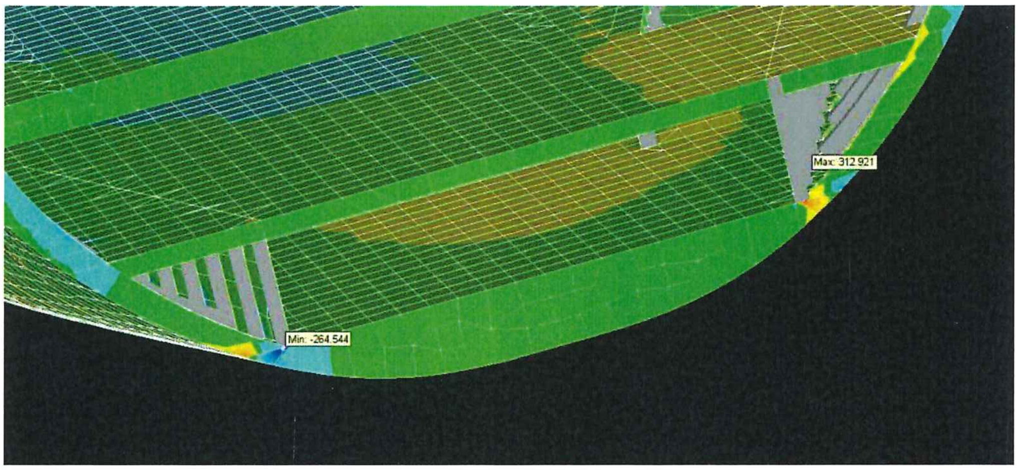


Figure 5-22 Normal membrane stress, peaks for evaluation area

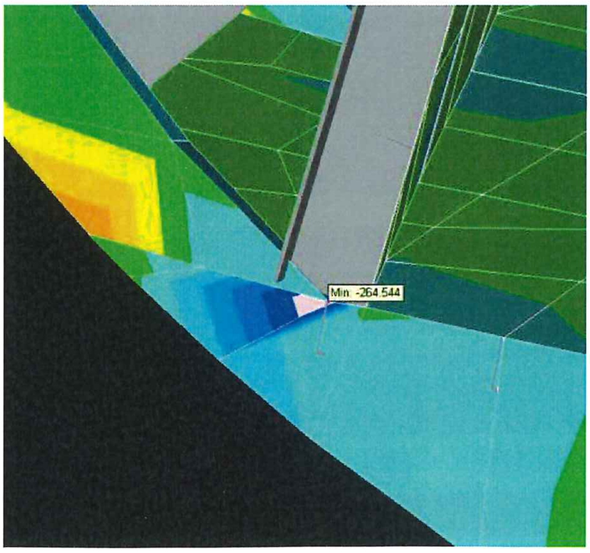


Figure 5-23 Close up of figure 5.22

Some results may also be incorrect as the global model have several bad elements. When the analysis is running, a warning that 38 plates have missing, incomplete or illegal mesh arises. The warning is however not that critical, so the analysis can continue. More specific, the summary of warning from data check of elements show that there is:

- 4307 warped 4-noded shell or membrane elements in this superelement
- 772 4-noded shell or membrane elements with Jacobian Ratio exceeding the limit for warning (equal of 4)
- 1433 3-noded shell or membrane elements with bad element shape

The warped 4-noded shell elements mean that the distance of the forth node to the element plane exceeds 0,0001 times the length of the diagonal connected to the forth node. The Jacobian ratio is the ratio of the maximum to the minimum of the determinants of the Jacobian in the element nodes. A ratio above 4 can cause the factorization of the stiffness matrix to fail. A ratio equal of one is desirable (but not sufficient for an element to be a good element). The warning for 3-noded shell or membrane elements with bad element shape means that the ratio of the largest edge to the smallest height is 4.0 or larger, an element with this warning is shown in figure 5.24.

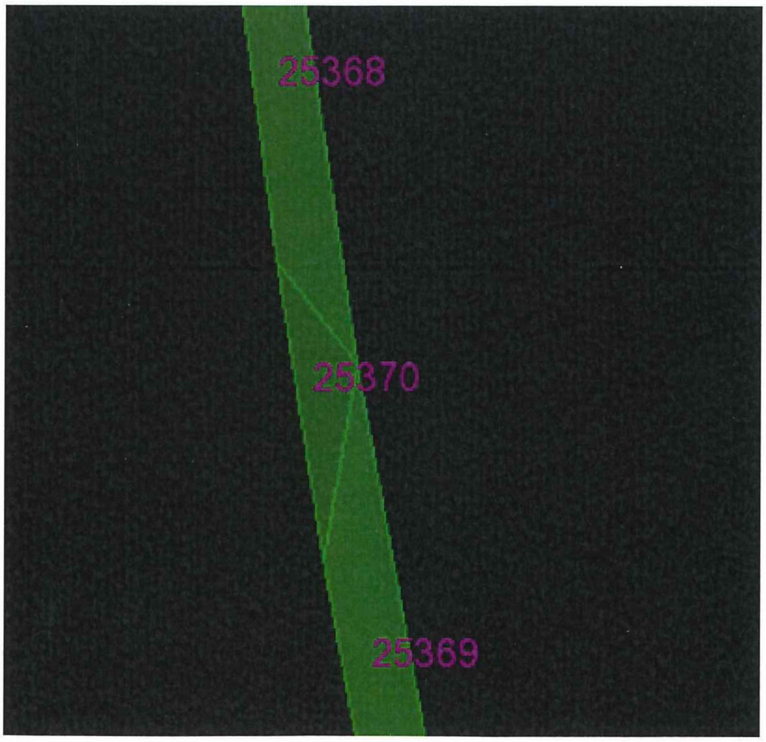


Figure 5-24 Bad element shape

The model verification in GeniE, also verifies that there are some model inaccuracies, they are however at a low level compared to what is was when the model was developed. Many of these model errors was caused by me, as I tried to model the structure as accurate as possible after the structural drawings. Inaccuracies regarding short edges is mainly caused as the GeniE software uses absolute values, so when plates were divided with a value in the global coordinate system, it could cause an element to be really small. Another consequence of dividing different plates many times, was that it could lead to sliver edges between plates. This was mainly unsolvable as it was caused by some software issues. The model verification errors that should be solved, like edges shorter than 0,01 and sliver edges, can be seen in figure 5.25 where also the position of the error is given.

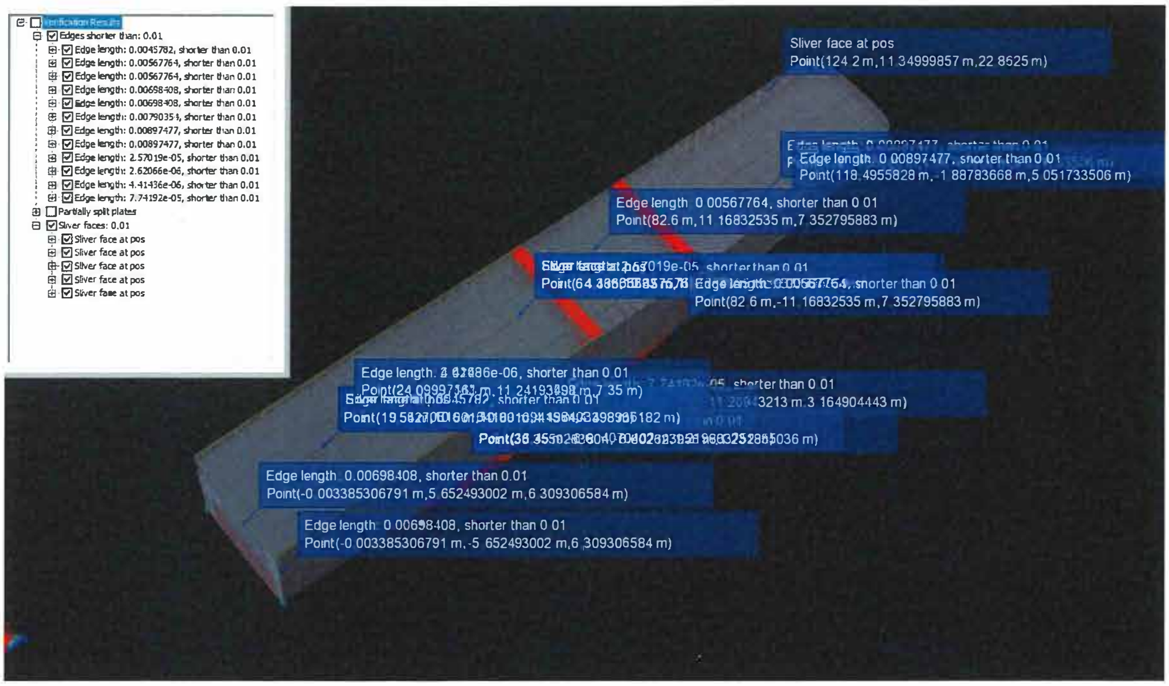


Figure 5-25 Model verification results in GeniE

The modelling of connections between transverse decks, transverse deck girders and side girders was a challenge as the “edges shorter than”-error occurred many times here. As can be seen on figure 5.26, there are many nodes which needs to be connected. On the figure, you can also see a simplification of the transverse deck girder flange, as it is not sniped, leading to higher stresses in the hull plate in the connection.

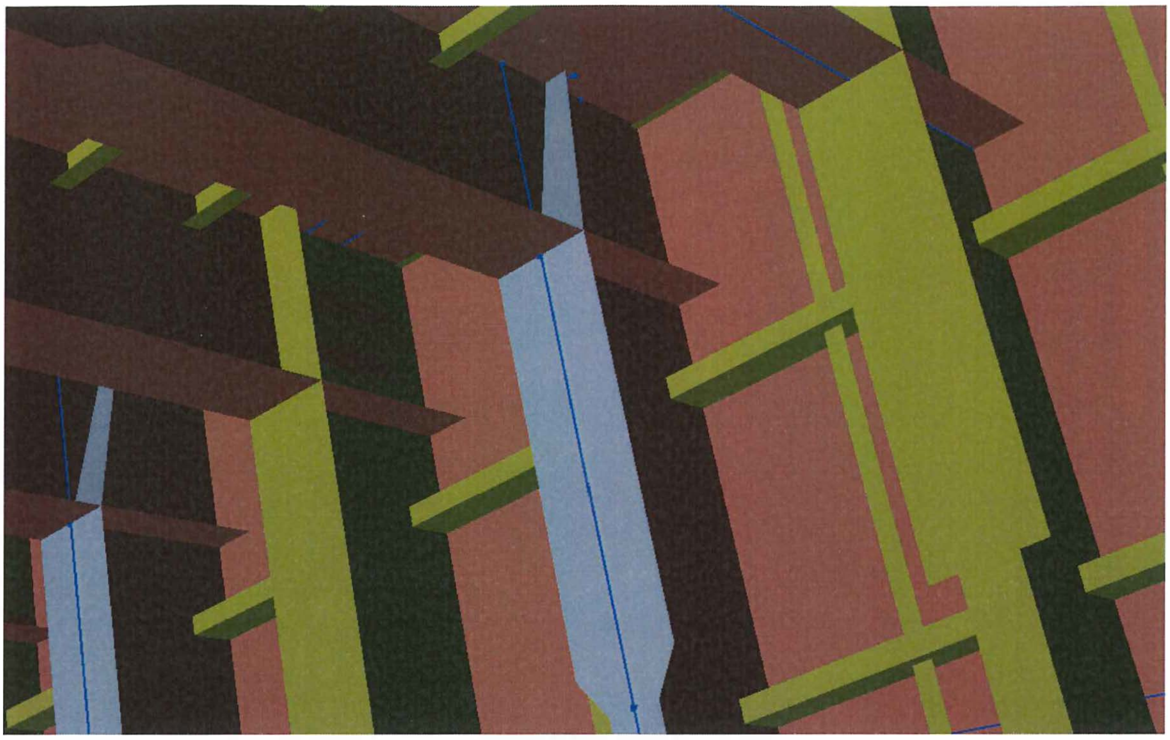


Figure 5-26 Modelling of connections

On figure 5.26 you can also see that the side girders below 2^{nd} deck are also modelled as beam elements, as the spacing is 1300 mm. This means that the connection between the transverse deck girder and the side girder will have the web thickness of each webs, although the web is reinforced in this area, so it may not lead to greatest difference other than the connection cannot be studied.

For simplification, the transverse girders above 2^{nd} deck was chosen to be modelled as beam elements, except the area with reinforced flange. As can be seen on figure 5.27, where the displacement of the evaluation area is shown, one might be a little critical to the connection between the beam and shell element. Although, the displacement is upscaled, the beam deformation at the connection point does not seem correct, the bending stress is verified. With comparison to 3D Beam, the displacement behavior is the same, except for the torsional movement which is created by the global loads.

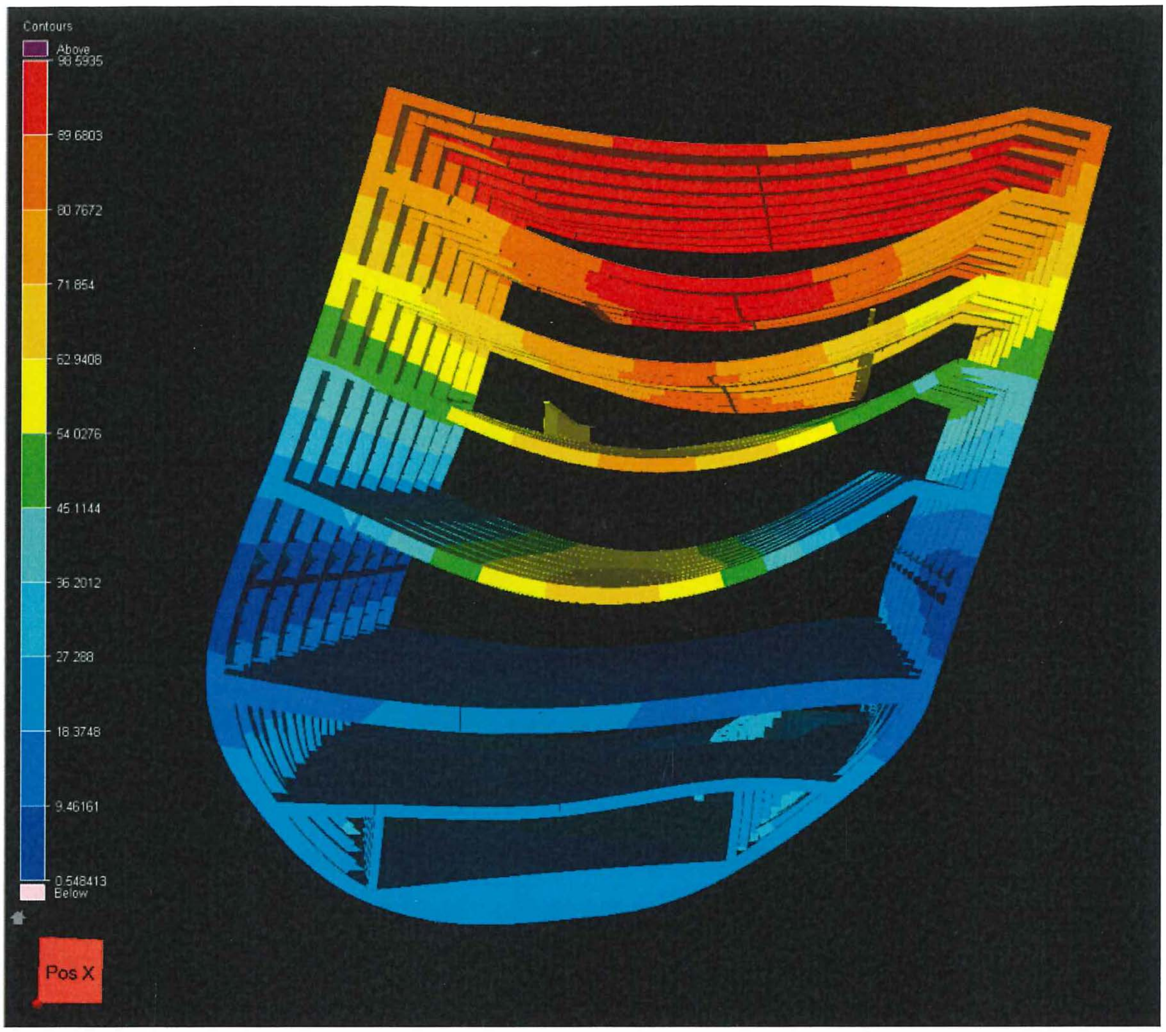


Figure 5-27 Displacement, all directions

Loads

As described the load capacities for decks intended for trucks as specified in the structural drawings was found too high, with a significant contribution to the deck loads, as well as transverse line load which together needed to be balanced with the sea pressure. After the adjustment of the deck loads, with a more normal operational deck load condition, the relationship between the structural self weight and the uniformly distributed load was more equated. The reduction also meant that the sea pressure, which balances the deck loads and the transverse loads, could be reduced with 50 %. This emphasizes how important the load specification is.

Another uncertainty for loads, was the way the load of deck 3 was applied, as this liftable deck was not modelled. The load was applied as a line load on the stringer at the position of deck 3, however, it had little effect to the decomposed stresses studied. As there were no structural drawings of this deck, the structural weight was only assumed based on the deck load for deck 4.

Sea pressure contribution

In figure 5.28, the sea pressure is the only applied load case. We can see that it creates a hogging load condition, as well as torsion to the hull. Extremely high stresses are also found in the positions of the three support points, which emphasizes that the evaluation area should not be located close to these areas, to not be affected by this. Though, I must emphasize the structure around the support points is not correct, which will lead to these high stresses, especially for the plating, a buckling problem will arise.

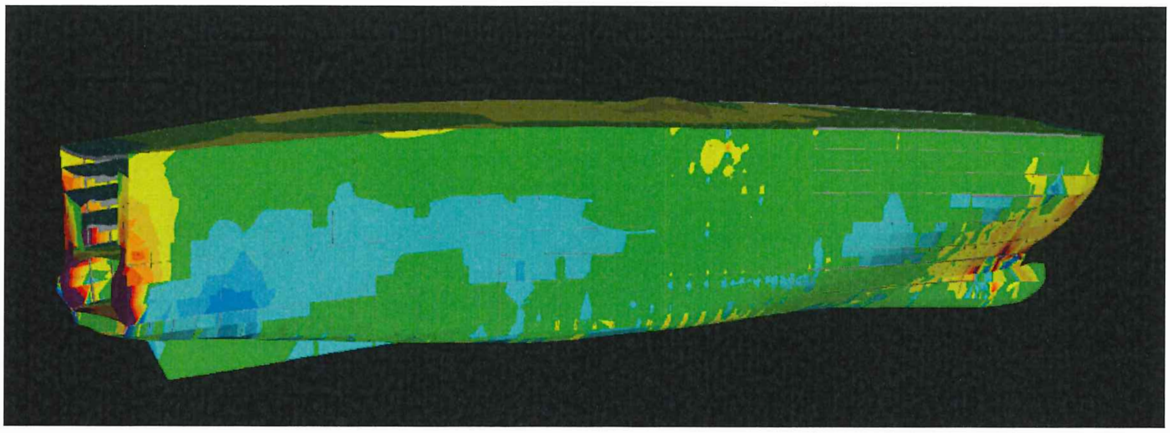


Figure 5-28 SIGMY, only sea pressure

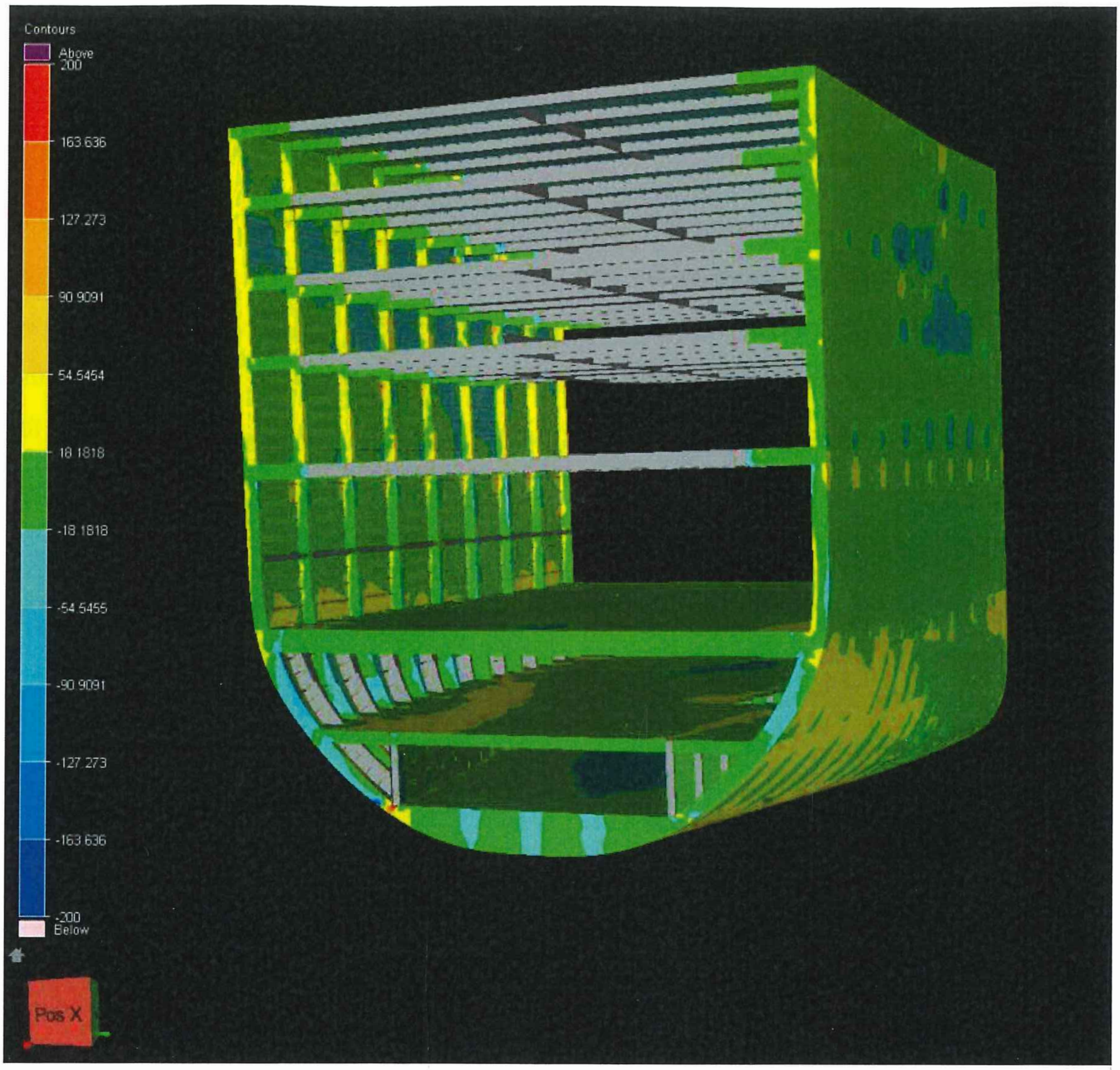


Figure 5-29 Normal membrane stress, SIGMY, without sea pressure

Figure 5.29 shows the normal membrane stress in the local y-direction, with the racking load case without sea pressure. Compared to the racking load case with applied hydrostatic sea pressure based on rule roll angle, the stresses are generally much lower. The side girders between deck 2 and 4 is not the position with highest interest anymore, as the stresses are low here. From the figure, we can see that the girders below 2nd deck on starboard is compressed, with stress up to around 100 N/mm^2. Above 4th deck, the girders on starboard experiences tension, with stress values around 50 N/mm^2. In the case of racking test, the sea pressure is therefore important as it will almost create a boundary condition which is fixed in the y-direction. Without the sea pressure, the transverse distortion, which is the reason to investigate racking strength, will not be created.

5.5 FE Model- Local Model

A FE analysis consisting of only the evaluation area is of interest to better understand the effect of global loads and the global strength contribution to the racking strength assessment. The results will only be presented very shortly as this model is not intended for use for a racking strength assessment.

5.5.1 Local Model Results

Table 5.7 Output from analysis

Total number of nodes	21602
Total number of elements	37062
Number of triangle elements	2381
Number of quad elements	21768
Number of beam elements	12913
Number of specified (fixed) degrees of freedom	6
Number of internal (free) degrees of freedom	12960
Computational time	633 seconds

From what can be seen on the figures 5.30 to 5.32, the stresses exceed all permissible stresses for a global finite element analysis. For the normal membrane stress the highest stress values are located at the port side girders between bulkhead deck and deck 4, with around 400 N/mm^2.

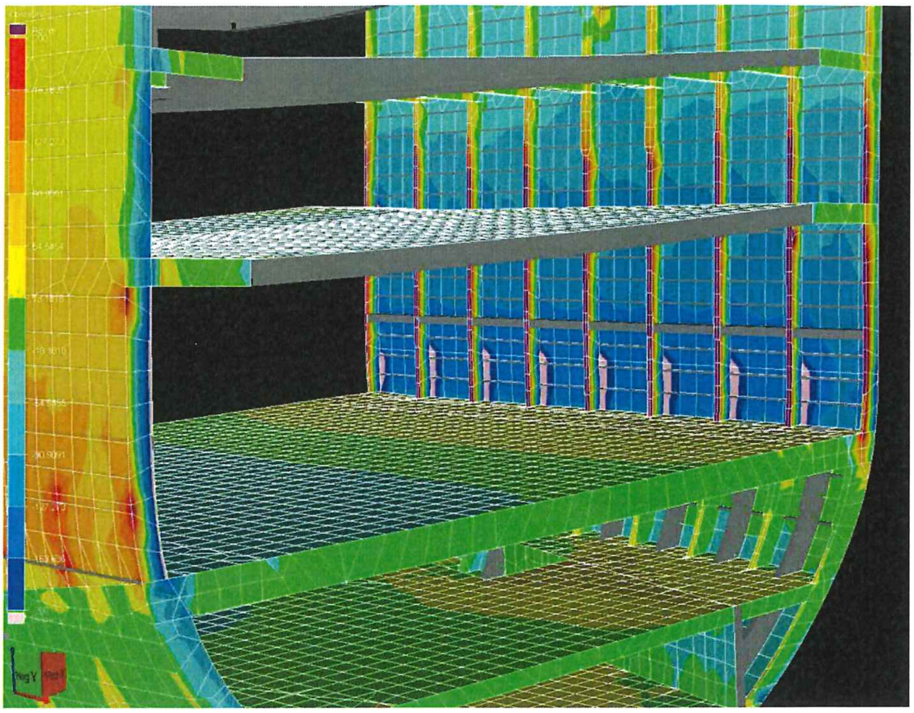


Figure 5-30 SIGMY local model

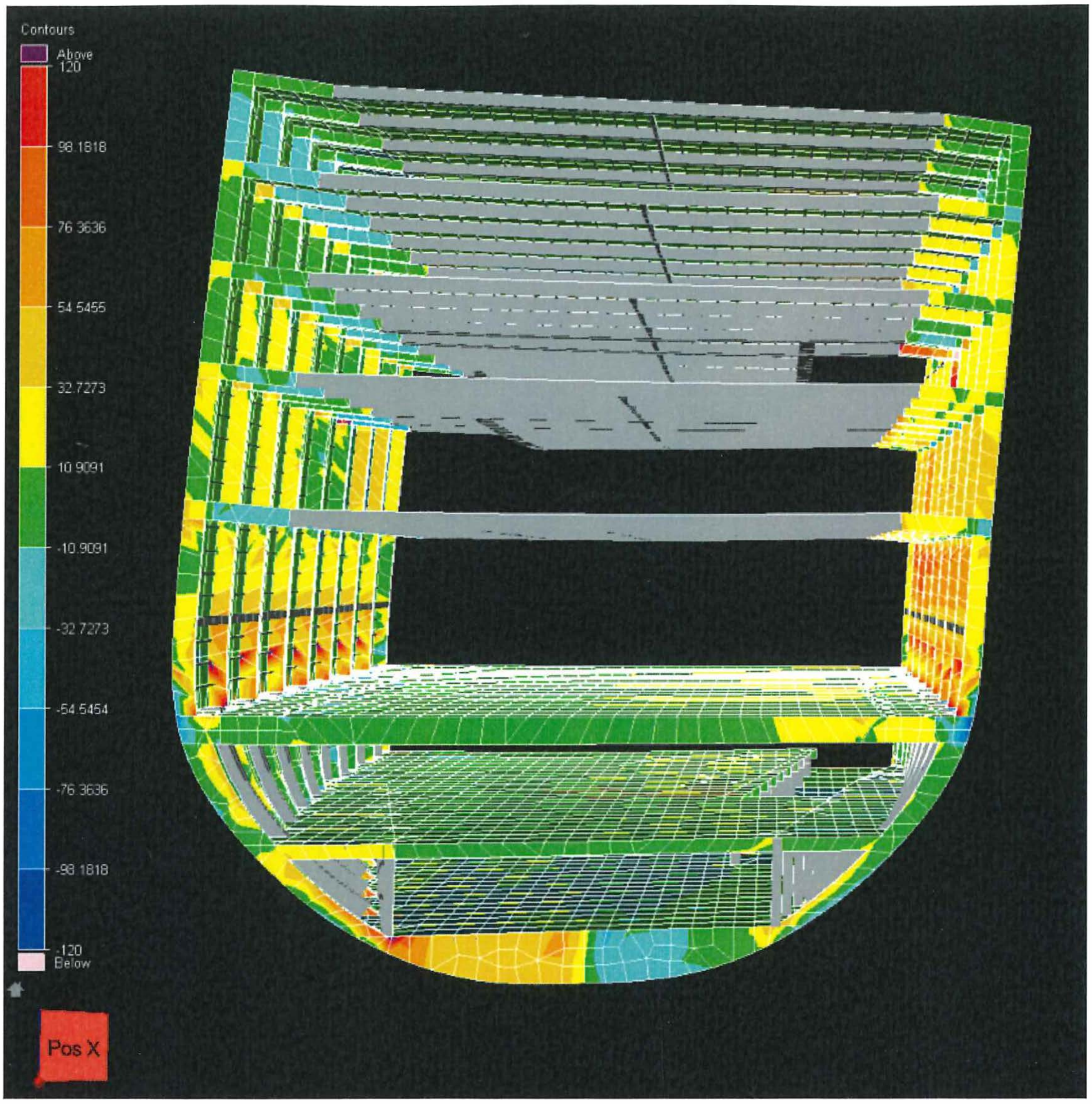


Figure 5-31 TAUMXY, local model

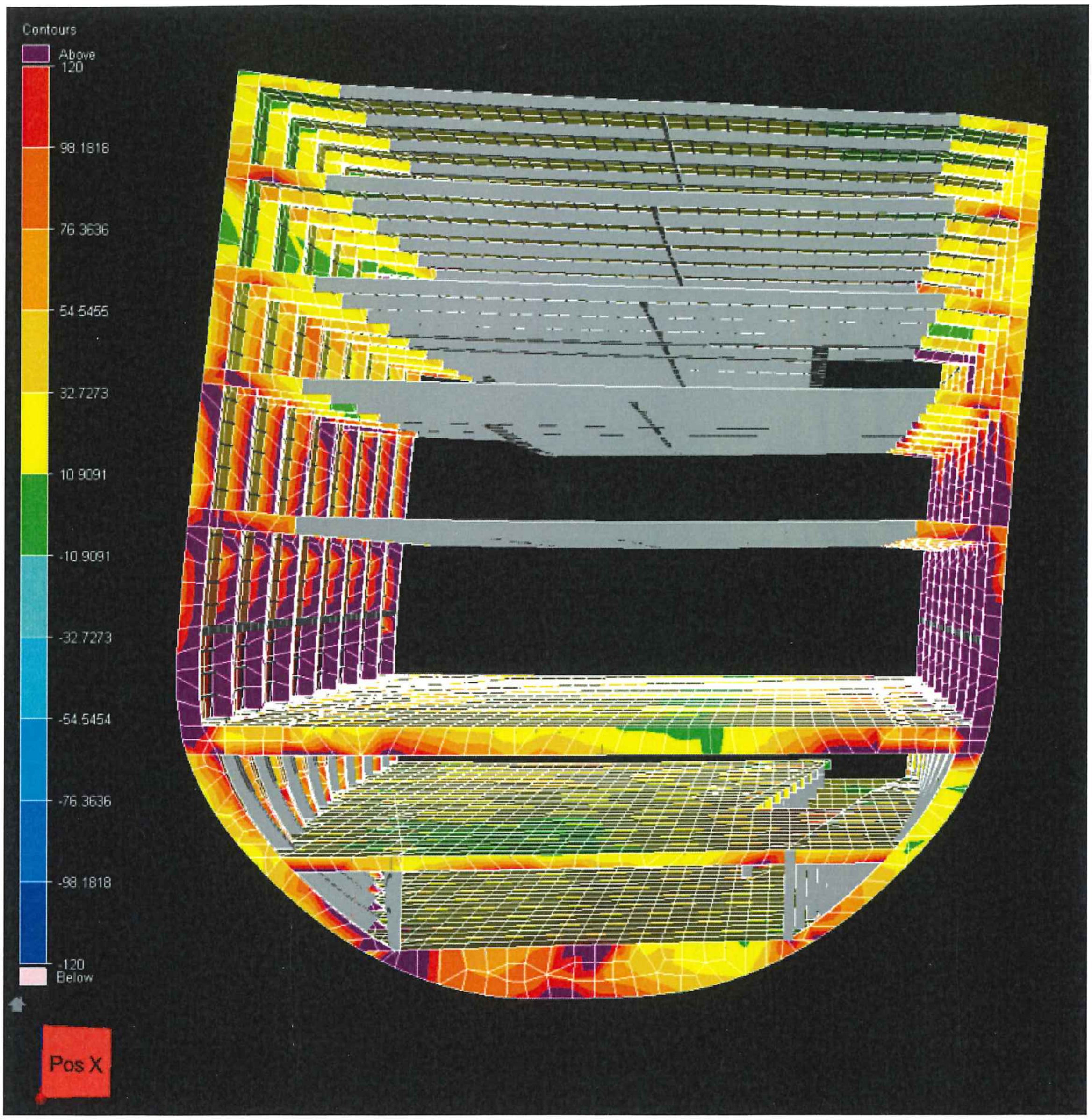


Figure 5-32 von Mises, local model

In figure 5.33 the bending stress, for a model which is fixed along the side girders at deck 2 and with a racking load case such as the one intended for beam analysis, is presented. However, there is not much deviations from the results presented in figure 5.30.

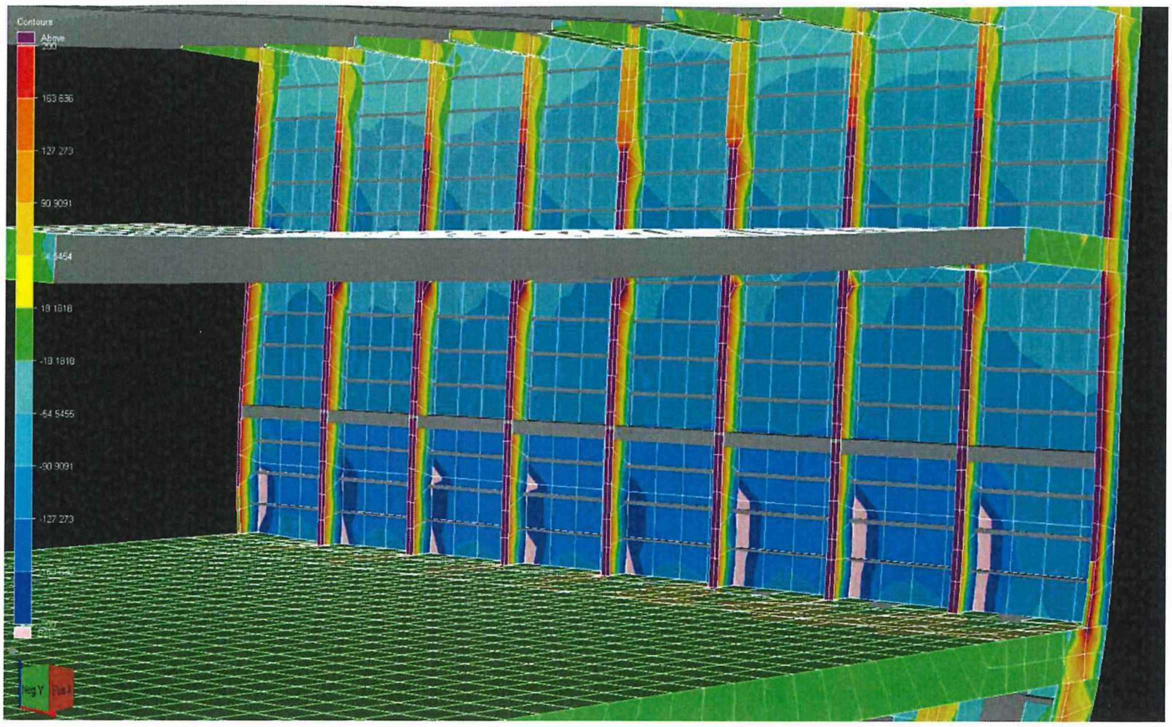


Figure 5-33 Local model, fixed at deck 2, SIGMY-stress

5.5.2 Discussion of results FE model- local model

As the evaluation area for the global analysis was modelled with structural elements, as the ship is, with only small deviations from the design. It was desirable to do a FE analysis only including the evaluation area, with the racking load case. The load case used in 3D-Beam, could also be applied, for comparison of the results, which it is done for the results presented in figure 5.33. The consequence of including only the evaluation area is that the model no longer represent the global stiffness of the ship, and the effect of the global strength can be investigated. Structural elements contributing to the racking strength, such as fixed ramps, ventilation ducks and transverse bulkheads in the fore ship is not present and cannot contribute to withstand the racking loads. Also, the sea pressure will only be applied for the evaluation area, meaning that the torsional effect of the applied sea pressure is not present. It is important to mention that the sea pressure which is not applied is not in balance with the model, and the results may not be plausible. The boundary conditions for the different calculation's method was separately applied, with two support points at the aft part of the model and one support point at the centerline at the front of the evaluation area, and support points on each side girder at 2nd deck, respectively.

The results found for this analysis is closer to the beam analysis than the global FE model. Due to time limitations, this has not been investigated further.

5.6 Discussion about Calculations Methods for Racking

Both calculations methods for a racking strength assessment shows similar behavior with regards to the transverse distortion which occurs when a ship is rolling in seas. Although this could be expected, as the application of loads are very similar. High values of bending stress are found in similar places, with the similar bending stress response.

What really differs the two methods is the computational time required for each analysis. The global FE model was found to be very demanding, as many structural members were modelled, as well as calculations for lumped stiffeners. With more elements, the possibility of errors is also larger, with respect to modelling errors and errors regarding the FE analysis solution. With more elements the calculation time for the analysis will also be longer.

One thing that is harder to take into account in the beam analysis is the effect of global loads, leading to torsion of the hull structure. The beam analysis could be modelled with more frames, but the torsional effect would not be created without a cross sections representing a hull form. If the effect of global loads was wanted to study in the beam analysis, it would demand a change of boundary conditions and application of sea pressure.

6 Conclusion

The objective of this thesis was to investigate the current practice in the industry with respects to design solutions and methods, and relevant regulations for a racking strength assessment. A ship with a common structural design for car carriers, with vertical side webs which are in line with the transverse deck girders as DNV GL CG 0137 (2016) defines it, was chosen for a racking strength assessment. The two calculations method for racking strength given by DNV GL, a simplified beam analysis and a full global FE model was analyzed.

It was found that the beam analysis gives a very conservative result, with stresses over the permissible values for bending stress. As the beam analysis is very simplified, structural members contributing to the racking strength is not contributing. The beam analysis can be considered conservative due to the calculations with effective breadths of plates, which reduces the section modulus. Another reason for the conservative results from the beam analysis may be that the method is not intended for ship sizes such as the ship studied in this case. As the stress results from the beam analysis is above the acceptance criteria, the dimensions must be bigger to cope with the large bending moment. Meaning that using the simple method for deciding the cross section, the ship's light weight will be much higher than using the advanced method.

The results for the full global model showed that the yield criteria for racking ULS was fulfilled, and the structural design could be further improved. As the global FE model is the only calculation method that have approved results, it is the method which should be applied for defining the cross section and calculate the light weight. The amount of work required to apply the global FE model is a disadvantage, but it may still be the most cost efficient solution considering steel weight savings and ship performance.

The global model is also the only model which can take the global strength and global loads into consideration. As can be seen from the displacement of the model, torsion is created by the hydrostatic pressure which is applied on the rule roll angle. The sea pressure also works to balance the global model, which is found to be important as the sea pressure will contribute to the transverse distortion of the structure. With only the transverse and deck loads applied, without the sea pressure, the structure will not have the same distortion and only create a roll movement of the ship.

The modelling of the global FE model is found to be very extensive, resulting in a large number of elements. With more elements the possibility of errors regarding the FE analysis solution is also larger.

6.1 Further work

First of all, the development of a new method for racking strength assessment in the concept design must be developed as this was not done due to the time spent on modelling and performing the global FE analysis. By evaluating the existing methods for racking calculation, this method should use a global FE model, as a beam analysis will always be too conservative. The new method should focus on low computational time for developing a global model, and a hull girder load adjustment approach should be investigated as this approach can be applied for a local model and apply moments to the ends of the model so the global moments is represented. How the global strength can be represented with this method is unknown.

The developed global model can also be used to determine the effect of the ventilation ducts, fixed ramps and transverse bulkheads in the fore ship as racking strength members. Although the ventilation ducts and transverse bulkheads in the fore ship is outside the evaluation area studied in this case, they are assumed to contribute as racking strength members.

An optimization of the current design should also be done, as the FE analysis show possibilities of reducing the web frames, especially for upper areas above deck 4. The optimization of design could later be addressed from an economical perspective, describe the cost savings of the changes or analyze the efficiency of these structural changes with regards to ship performance.

Also fatigue strength should be analyzed for the evaluation area.

7 References

Amlashi, H. K. K. (2008). Ultimate Strength and Reliability-based Design of Ship Hulls with Emphasis on Combined Global and Local Loads. PhD thesis, NTNU Norwegian University of Science and Technology Institute for Marine Technology

Amundin E. (2012) Modeling of fatigue in RORO ships

D. Doan et al. (2017), D Doan, A. Szelezinski, L. Murawski, A. Muc. Finite element method in modelling of ship structures part 1 – theoretical background. Scientific Journal of Gdynia Maritime University.

DNVGL-CG-0127 (2015) DNV GL Class Guideline 0127, Finite Element Analysis. Høvik

DNVGL-CG-0127 (2016) DNV GL Class Guideline 0127, Finite Element Analysis. Høvik

DNVGL-CG-0137 (2018) Strength analysis of hull structure in RO/RO vessels

DNVGL-RU-SHIP Pt.3 Ch.3 (2018)

DNVGL-RU-SHIP Pt.3 Ch.4 (2018) Loads

DNVGL-RU-SHIP Pt.5 Ch.3 (2018) RO/RO ships.

Eyres (2006) Ship Construction. 6th edition.

Gaspar (2013), Gaspar, Henrique Muriolo. Handling Aspects of complexity in conceptual ship design. NTNU, Trondheim.

Heder, M. and Ulfvarson A. (1991) Hull beam behavior of passenger ships

Horizonship (2018) https://horizonship.com/ Accessed: 2018-11-20.

Ilsalottodibrera(2018). Color line cruise ships http://www.ilsalottodibrera.net/color-line/. Accessed: 2018-11-20.

Kerlen (1985). Über den Einfluß der Völligkeit auf die Rumpfstahlkosten von Frachtshiffen. Hamburg : Hamburg University of Technology, 1985.

Lande (2016) Parametric Structural Analysis for a platform supply vessel at prelimary designphase- a sensitivity study via design of experiments. NTNU Ålesund.

Marine Traffic (2018) https://photos.marinetraffic.com/ais/showphoto.aspx?photoid=1260950 accessed: 2018-11-22.

Naar H. Varsta P. Kujala P. (2004) A theory of coupled beams for strength assessment for passenger ships.

Port Technology (2018). Shipping liner insight #5: Cosco. https://www. porttechnology.org/news/shipping_liner_insight_5_cosco. Accessed: 2018-11-20

Schneekluth H. and Bertram V. (1998) Ship Design for Efficiency and Economy. Second edition.

Shu (2010) Reliability Analysis of Ships. Inocean Engineering

Söder C., Rosén A., Palmquist M (2011) Motion-based monitoring of racking stresses in ro-ro ships. Sweden.

Schwebe, T. (2016) Dynamic Collapse of the Hull girder in a container ship in waves.

Varela J (2011), "Interactive Simulation of Ship Motions in Random Seas based on Real Wave Spectra". Algarve Portugal.

Wallenius Wilhelmsen Logistics (2018). http://www.2wglobal.com/ global-network/fleet/fleet-overview/. Accessed: 2018-11-20.

Wallenius Wilhelmsen Logistics (2018a). http://www.2wglobal.com/ global-network/fleet/fleet-overview/. Accessed: 2018-11-20

Y.Okumoto et al (2009), Y. Okumoto, Y. Takeda, M. Mano, T. Okado, 2009 "Design of Ship Hull Structures: A Practial Guide for Engineers"

Zanic, V. (2006). Reliability Based Optimization-Application to Racking of Multi-Deck Ships. Glasgow.

Zanic, V. (2007) Concept and preliminary structural design methods for the modern multi-deck ships.

Zanic V., Andric, J. (2010) The global structural response model for multideck ships in concept design phase.

Appendix

Profiles used in 3D Beam

Profiles

Profile	Profile Name	Type	Profile parameters	Profile properties	Profile plot
1	Default profile	Circular Tube	Outer Diameter=100 [mm], Thickness=10 [mm]	Ax = 2827 [mm2], Ay = 1425 [mm2], Az = 1425 [mm2], Wx = 115.925 [cm3], Wyt = 57.962 [cm3], Wyb = 57.962 [cm3], Wz+ = 57.962 [cm3], Wz- = 57.962 [cm3], Ix = 579.6 [cm4], Iy = 289.8 [cm4], Iz = 289.8 [cm4], Iyz = 0.0 [cm4], yNA = 0.0 [mm], zNA = 0.0 [mm], eY = 0.0 [mm], eZ = 0.0 [mm]	<#CSPic#>
2	BuiltUpTbar 795 x 250 x 10 x 32	Built up T-profile with plate	Effective plate Width=2573.5 [mm], Plate Thickness, pT=12.5 [mm], Web Height, hw=795 [mm], Web Thickness, t=10 [mm], Flange width (incl. web), bf=250 [mm], Flange thickness, tf=32 [mm], Angle Between Profile & Plate=90 [Degrees], FlipY=True	Ax = 48119 [mm2], Ay = 40901 [mm2], Az = 7578 [mm2], Wx = 330.420 [cm3], Wyt = 24346.636 [cm3], Wyb = 8061.667 [cm3], Wz+ = 13830.146 [cm3], Wz- = 13830.146 [cm3], Ix = 413.0 [cm4], Iy = 508426.6 [cm4], Iz = 1779594.0 [cm4], Iyz = 0.0 [cm4], yNA = 0.0 [mm], zNA = 0.0 [mm], eY = 0.0 [mm], eZ = 200.7 [mm]	<#CSPic#>
3	Tbar 795 x 400 x 10 x 32	Built up T-profile with plate	Effective plate Width=2573.5 [mm], Plate Thickness, pT=12.5 [mm], Web Height, hw=795 [mm], Web Thickness, t=10 [mm], Flange width (incl. web), bf=400 [mm], Flange thickness, tf=32 [mm], Angle Between Profile & Plate=90 [Degrees], FlipY=True	Ax = 52919 [mm2], Ay = 44981 [mm2], Az = 7805 [mm2], Wx = 461.479 [cm3], Wyt = 25450.398 [cm3], Wyb = 11712.490 [cm3], Wz+ = 13930.398 [cm3], Wz- = 13930.398 [cm3], Ix = 576.8 [cm4], Iy = 673372.0 [cm4], Iz = 1792494.0 [cm4], Iyz = 0.0 [cm4], yNA = 0.0 [mm], zNA = 0.0 [mm], eY = 0.0 [mm], eZ = 250.6 [mm]	<#CSPic#>
4	Tbar 800x 400 x 12 x 32	Built up T-profile with plate	Effective plate Width=797.4 [mm], Plate Thickness, pT=12.5 [mm], Web Height, hw=795 [mm], Web Thickness, t=12 [mm], Flange width (incl. web), bf=400 [mm], Flange thickness, tf=32 [mm], Angle Between Profile & Plate=90 [Degrees], FlipY=True	Ax = 32308 [mm2], Ay = 19040 [mm2], Az = 9210 [mm2], Wx = 383.101 [cm3], Wyt = 9498.485 [cm3], Wyb = 10935.086 [cm3], Wz+ = 1753.026 [cm3], Wz- = 1753.026 [cm3], Ix = 478.9 [cm4], Iy = 426729.8 [cm4], Iz = 69893.1 [cm4], Iyz = 0.0 [cm4], yNA = 0.0 [mm], zNA = 0.0 [mm], eY = 0.0 [mm], eZ = 243.4 [mm]	<#CSPic#>
5	BuiltUpTbar 800 x 300 x 10 x 30	Built up T-profile with plate	Effective plate Width=1040 [mm], Plate Thickness, pT=12.5 [mm], Web Height, hw=795 [mm], Web Thickness, t=10 [mm], Flange width (incl. web), bf=300 [mm], Flange thickness, tf=30 [mm], Angle Between Profile & Plate=90 [Degrees], FlipY=True	Ax = 29950 [mm2], Ay = 25458 [mm2], Az = 7703 [mm2], Wx = 257.587 [cm3], Wyt = 11127.073 [cm3], Wyb = 8336.260 [cm3], Wz+ = 2383.268 [cm3], Wz- = 2383.268 [cm3], Ix = 322.0 [cm4], Iy = 399135.0 [cm4], Iz = 123930.0 [cm4], Iyz = 0.0 [cm4], yNA = 0.0 [mm], zNA = 0.0 [mm], eY = 0.0 [mm], eZ = 308.0 [mm]	<#CSPic#>
6	BuiltUpTbar 800 x 200 x 10 x 30	Built up T-profile with plate	Effective plate Width=1040 [mm], Plate Thickness, pT=12.5 [mm], Web Height, hw=795 [mm], Web Thickness, t=10 [mm], Flange width (incl. web), bf=200 [mm], Flange thickness, tf=30 [mm], Angle Between Profile & Plate=90 [Degrees], FlipY=True	Ax = 26950 [mm2], Ay = 22908 [mm2], Az = 7536 [mm2], Wx = 185.605 [cm3], Wyt = 10661.711 [cm3], Wyb = 6172.398 [cm3], Wz+ = 2291.922 [cm3], Wz- = 2291.922 [cm3], Ix = 232.0 [cm4], Iy = 327397.6 [cm4], Iz = 119180.0 [cm4], Iyz = 0.0 [cm4], yNA = 0.0 [mm], zNA = 0.0 [mm], eY = 0.0 [mm], eZ = 287.1 [mm]	<#CSPic#>
7	WeldedAngle 150 x 90 x 9 x 9	L-Beam welded on plate	Effective plate Width=520 [mm], Plate Thickness=12.5 [mm], Stiffener Height, h=150 [mm], Thickness of web, t=10 [mm], Flange width (incl. web t.), w=90 [mm], Flange (average) Thickness=10 [mm], Angle between Plate and web=90 [Degrees], FlipY=True	Ax = 8800 [mm2], Ay = 4333 [mm2], Az = 1343 [mm2], Wx = 33.217 [cm3], Wyt = 584.457 [cm3], Wyb = 188.256 [cm3], Wz+ = 563.052 [cm3], Wz- = 572.148 [cm3], Ix = 41.5 [cm4], Iy = 2440.4 [cm4], Iz = 14837.9 [cm4], Iyz = -445.1 [cm4], yNA = 4.1 [mm], zNA = 4.1 [mm], eY = -4.1 [mm], eZ = 25.6 [mm]	<#CSPic#>

Profiles

Profile	Profile Name	Type	Profile parameters	Profile properties	Profile plot
8	BuiltUpTbar 550 x 200 x 8 x 22	Built up T-profile with plate	Effective plate Width=1040 [mm], Plate Thickness, pT=10 [mm], Web Height, hw=550 [mm], Web Thickness, t=8 [mm], Flange width (incl. web), bf=200 [mm], Flange thickness, tf=22 [mm], Angle Between Profile & Plate=90 [Degrees], FlipY=True	Ax = 19200 [mm2], Ay = 16320 [mm2], Az = 4239 [mm2], Wx = 102.653 [cm3], Wyt = 5752.492 [cm3], Wyb = 2986.041 [cm3], Wz+ = 1830.917 [cm3], Wz- = 1830.917 [cm3], Ix = 102.7 [cm4], Iy = 114402.7 [cm4], Iz = 95207.7 [cm4], Iyz = 0.0 [cm4], yNA = 0.0 [mm], zNA = 0.0 [mm], eY = 0.0 [mm], eZ = 185.2 [mm]	<#CSPic#>
9	WeldedAngle 150 x 90 x 9 x 9	L-Beam welded on plate	Effective plate Width=500 [mm], Plate Thickness=9 [mm], Stiffener Height, h=100 [mm], Thickness of web, t=10 [mm], Flange width (incl. web t.), w=75 [mm], Flange (average) Thickness=10 [mm], Angle between Plate and web=90 [Degrees], FlipY=True	Ax = 6150 [mm2], Ay = 3000 [mm2], Az = 902 [mm2], Wx = 17.650 [cm3], Wyt = 273.779 [cm3], Wyb = 92.899 [cm3], Wz+ = 374.470 [cm3], Wz- = 380.179 [cm3], Ix = 17.7 [cm4], Iy = 796.5 [cm4], Iz = 9480.5 [cm4], Iyz = -195.3 [cm4], yNA = 4.0 [mm], zNA = 4.0 [mm], eY = -4.0 [mm], eZ = 18.3 [mm]	<#CSPic#>
10	Side 2-4 Tbar 550 x 200 x 8 x 22	Built up T-profile with plate	Effective plate Width=1376.1 [mm], Plate Thickness, pT=10 [mm], Web Height, hw=550 [mm], Web Thickness, t=8 [mm], Flange width (incl. web), bf=200 [mm], Flange thickness, tf=22 [mm], Angle Between Profile & Plate=90 [Degrees], FlipY=True	Ax = 22561 [mm2], Ay = 19177 [mm2], Az = 4220 [mm2], Wx = 113.857 [cm3], Wyt = 7362.472 [cm3], Wyb = 3037.729 [cm3], Wz+ = 3177.436 [cm3], Wz- = 3177.436 [cm3], Ix = 113.9 [cm4], Iy = 125156.6 [cm4], Iz = 218623.5 [cm4], Iyz = 0.0 [cm4], yNA = 0.0 [mm], zNA = 0.0 [mm], eY = 0.0 [mm], eZ = 161.2 [mm]	<#CSPic#>
11	Side 4-5 Tbar 550 x 200 x 8 x 22	Built up T-profile with plate	Effective plate Width=904.7 [mm], Plate Thickness, pT=10 [mm], Web Height, hw=550 [mm], Web Thickness, t=8 [mm], Flange width (incl. web), bf=200 [mm], Flange thickness, tf=22 [mm], Angle Between Profile & Plate=90 [Degrees], FlipY=True	Ax = 17847 [mm2], Ay = 15170 [mm2], Az = 4245 [mm2], Wx = 98.143 [cm3], Wyt = 5100.387 [cm3], Wyb = 2956.634 [cm3], Wz+ = 1396.612 [cm3], Wz- = 1396.612 [cm3], Ix = 98.1 [cm4], Iy = 108930.4 [cm4], Iz = 63175.7 [cm4], Iyz = 0.0 [cm4], yNA = 0.0 [mm], zNA = 0.0 [mm], eY = 0.0 [mm], eZ = 195.4 [mm]	<#CSPic#>
12	Deck4 Tbar 510x8x250x19	Built up T-profile with plate	Effective plate Width=2573.5 [mm], Plate Thickness, pT=9 [mm], Web Height, hw=510 [mm], Web Thickness, t=8 [mm], Flange width (incl. web), bf=250 [mm], Flange thickness, tf=19 [mm], Angle Between Profile & Plate=90 [Degrees], FlipY=True	Ax = 31992 [mm2], Ay = 27193 [mm2], Az = 3900 [mm2], Wx = 134.816 [cm3], Wyt = 11042.593 [cm3], Wyb = 3015.316 [cm3], Wz+ = 9953.597 [cm3], Wz- = 9953.597 [cm3], Ix = 121.3 [cm4], Iy = 127428.2 [cm4], Iz = 1280779.1 [cm4], Iyz = 0.0 [cm4], yNA = 0.0 [mm], zNA = 0.0 [mm], eY = 0.0 [mm], eZ = 109.9 [mm]	<#CSPic#>
13	Deck5 Tbar 430x7 120x20	Built up T-profile with plate	Effective plate Width=2573.5 [mm], Plate Thickness, pT=5.5 [mm], Web Height, hw=430 [mm], Web Thickness, t=7 [mm], Flange width (incl. web), bf=120 [mm], Flange thickness, tf=20 [mm], Angle Between Profile & Plate=90 [Degrees], FlipY=True	Ax = 19564 [mm2], Ay = 16630 [mm2], Az = 2808 [mm2], Wx = 61.127 [cm3], Wyt = 5618.223 [cm3], Wyb = 1394.253 [cm3], Wz+ = 6073.241 [cm3], Wz- = 6073.241 [cm3], Ix = 42.8 [cm4], Iy = 50881.2 [cm4], Iz = 781474.3 [cm4], Iyz = 0.0 [cm4], yNA = 0.0 [mm], zNA = 0.0 [mm], eY = 0.0 [mm], eZ = 87.7 [mm]	<#CSPic#>
14	Deck4 Built Up Tbar 510x8x250x19	Built up T-profile with plate	Effective plate Width=2573.5 [mm], Plate Thickness, pT=9 [mm], Web Height, hw=510 [mm], Web Thickness, t=8 [mm], Flange width (incl. web), bf=450 [mm], Flange thickness, tf=19 [mm], Angle Between Profile & Plate=90 [Degrees], FlipY=True	Ax = 35792 [mm2], Ay = 30423 [mm2], Az = 4036 [mm2], Wx = 185.623 [cm3], Wyt = 11641.811 [cm3], Wyb = 4895.214 [cm3], Wz+ = 10046.499 [cm3], Wz- = 10046.499 [cm3], Ix = 167.1 [cm4], Iy = 185403.2 [cm4], Iz = 1292733.2 [cm4], Iyz = 0.0 [cm4], yNA = 0.0 [mm], zNA = 0.0 [mm], eY = 0.0 [mm], eZ = 148.9 [mm]	<#CSPic#>

Profiles

Profile	Profile Name	Type	Profile parameters	Profile properties	Profile plot
15	Deck5 BuiltUp Tbar 430x7 120x20	Built up T-profile with plate	Effective plate Width=2573.5 [mm], Plate Thickness, pT=5.5 [mm], Web Height, hw=430 [mm], Web Thickness, t=7 [mm], Flange width (incl. web), bf=200 [mm], Flange thickness, tf=20 [mm], Angle Between Profile & Plate=90 [Degrees], FlipY=True	Ax = 21164 [mm2], Ay = 17990 [mm2], Az = 2920 [mm2], Wx = 91.592 [cm3], Wyt = 5921.712 [cm3], Wyb = 2056.163 [cm3], Wz+ = 6081.365 [cm3], Wz- = 6081.365 [cm3], Ix = 64.1 [cm4], Iy = 69519.4 [cm4], Iz = 782519.7 [cm4], Iyz = 0.0 [cm4], yNA = 0.0 [mm], zNA = 0.0 [mm], eY = 0.0 [mm], eZ = 113.9 [mm]	<#CSPic#>
16	WeldedAngle 100x75x10x10	L-Beam welded on plate	Effective plate Width=520 [mm], Plate Thickness=9 [mm], Stiffener Height, h=100 [mm], Thickness of web, t=10 [mm], Flange width (incl. web t.), w=75 [mm], Flange (average) Thickness=10 [mm], Angle between Plate and web=90 [Degrees], FlipY=True	Ax = 6330 [mm2], Ay = 3120 [mm2], Az = 901 [mm2], Wx = 18.136 [cm3], Wyt = 284.993 [cm3], Wyb = 93.151 [cm3], Wz+ = 404.918 [cm3], Wz- = 410.754 [cm3], Ix = 18.1 [cm4], Iy = 803.2 [cm4], Iz = 10651.3 [cm4], Iyz = -196.6 [cm4], yNA = 3.9 [mm], zNA = 3.9 [mm], eY = -3.9 [mm], eZ = 17.8 [mm]	<#CSPic#>
17	WeldedAngle 65x65x6x6	L-Beam welded on plate	Effective plate Width=520 [mm], Plate Thickness=5.5 [mm], Stiffener Height, h=65 [mm], Thickness of web, t=6 [mm], Flange width (incl. web t.), w=65 [mm], Flange (average) Thickness=6 [mm], Angle between Plate and web=90 [Degrees], FlipY=True	Ax = 3604 [mm2], Ay = 1907 [mm2], Az = 357 [mm2], Wx = 6.294 [cm3], Wyt = 112.604 [cm3], Wyb = 30.106 [cm3], Wz+ = 247.296 [cm3], Wz- = 250.105 [cm3], Ix = 3.8 [cm4], Iy = 174.1 [cm4], Iz = 6488.6 [cm4], Iyz = -62.8 [cm4], yNA = 3.2 [mm], zNA = 3.2 [mm], eY = -3.2 [mm], eZ = 9.7 [mm]	<#CSPic#>
18	Center and Side Deck4 Tbar 510x7x100x19	Built up T-profile with plate	Effective plate Width=760 [mm], Plate Thickness, pT=9 [mm], Web Height, hw=510 [mm], Web Thickness, t=7 [mm], Flange width (incl. web), bf=100 [mm], Flange thickness, tf=19 [mm], Angle Between Profile & Plate=90 [Degrees], FlipY=True	Ax = 12310 [mm2], Ay = 10464 [mm2], Az = 3288 [mm2], Wx = 44.742 [cm3], Wyt = 3358.492 [cm3], Wyb = 1429.620 [cm3], Wz+ = 870.605 [cm3], Wz- = 870.605 [cm3], Ix = 40.3 [cm4], Iy = 53948.9 [cm4], Iz = 33083.0 [cm4], Iyz = 0.0 [cm4], yNA = 0.0 [mm], zNA = 0.0 [mm], eY = 0.0 [mm], eZ = 153.6 [mm]	<#CSPic#>
19	Built up Side 2-4 Tbar 550 x 200 x 8 x 22	Built up T-profile with plate	Effective plate Width=1376.1 [mm], Plate Thickness, pT=10 [mm], Web Height, hw=550 [mm], Web Thickness, t=8 [mm], Flange width (incl. web), bf=200 [mm], Flange thickness, tf=32 [mm], Angle Between Profile & Plate=90 [Degrees], FlipY=True	Ax = 24561 [mm2], Ay = 20877 [mm2], Az = 4352 [mm2], Wx = 221.437 [cm3], Wyt = 7703.144 [cm3], Wyb = 4048.579 [cm3], Wz+ = 3187.125 [cm3], Wz- = 3187.125 [cm3], Ix = 221.4 [cm4], Iy = 157105.3 [cm4], Iz = 219290.1 [cm4], Iyz = 0.0 [cm4], yNA = 0.0 [mm], zNA = 0.0 [mm], eY = 0.0 [mm], eZ = 193.4 [mm]	<#CSPic#>
20	TopOfGarage BuiltUp Tbar 430x7 120x20	Built up T-profile with plate	Effective plate Width=2573.5 [mm], Plate Thickness, pT=5.5 [mm], Web Height, hw=360 [mm], Web Thickness, t=7 [mm], Flange width (incl. web), bf=250 [mm], Flange thickness, tf=22 [mm], Angle Between Profile & Plate=90 [Degrees], FlipY=True	Ax = 22174 [mm2], Ay = 18848 [mm2], Az = 2523 [mm2], Wx = 135.715 [cm3], Wyt = 5114.458 [cm3], Wyb = 2191.155 [cm3], Wz+ = 6093.264 [cm3], Wz- = 6093.264 [cm3], Ix = 95.0 [cm4], Iy = 59441.2 [cm4], Iz = 784050.7 [cm4], Iyz = 0.0 [cm4], yNA = 0.0 [mm], zNA = 0.0 [mm], eY = 0.0 [mm], eZ = 112.1 [mm]	<#CSPic#>
21	Sides TopOfGarage BuiltUp Tbar 430x7 120x20	Built up T-profile with plate	Effective plate Width=2573.5 [mm], Plate Thickness, pT=5.5 [mm], Web Height, hw=360 [mm], Web Thickness, t=7 [mm], Flange width (incl. web), bf=400 [mm], Flange thickness, tf=22 [mm], Angle Between Profile & Plate=90 [Degrees], FlipY=True	Ax = 25474 [mm2], Ay = 21653 [mm2], Az = 2562 [mm2], Wx = 211.771 [cm3], Wyt = 5263.090 [cm3], Wyb = 3321.853 [cm3], Wz+ = 6162.188 [cm3], Wz- = 6162.188 [cm3], Ix = 148.2 [cm4], Iy = 78914.3 [cm4], Iz = 792919.5 [cm4], Iyz = 0.0 [cm4], yNA = 0.0 [mm], zNA = 0.0 [mm], eY = 0.0 [mm], eZ = 141.7 [mm]	<#CSPic#>

Profiles

Profile	Profile Name	Type	Profile parameters	Profile properties	Profile plot
22	Copy of Deck4 Built Up Tbar 510x8x250x19	Built up T-profile with plate	Effective plate Width=2573.5 [mm], Plate Thickness, pT=9 [mm], Web Height, hw=510 [mm], Web Thickness, t=22 [mm], Flange width (incl. web), bf=450 [mm], Flange thickness, tf=19 [mm], Angle Between Profile & Plate=90 [Degrees], FlipY=True	Ax = 42932 [mm2], Ay = 36492 [mm2], Az = 10619 [mm2], Wx = 153.526 [cm3], Wyt = 11739.532 [cm3], Wyb = 5740.277 [cm3], Wz+ = 10046.833 [cm3], Wz- = 10046.833 [cm3], Ix = 337.8 [cm4], Iy = 207409.8 [cm4], Iz = 1292776.3 [cm4], Iyz = 0.0 [cm4], yNA = 0.0 [mm], zNA = 0.0 [mm], eY = 0.0 [mm], eZ = 166.3 [mm]	<#CSPic#>
23	Centre girder TopOfGarage BuiltUp Tbar 430x7 120x20	Built up T-profile with plate	Effective plate Width=2600 [mm], Plate Thickness, pT=5.5 [mm], Web Height, hw=360 [mm], Web Thickness, t=7 [mm], Flange width (incl. web), bf=100 [mm], Flange thickness, tf=22 [mm], Angle Between Profile & Plate=90 [Degrees], FlipY=True	Ax = 19020 [mm2], Ay = 16167 [mm2], Az = 2376 [mm2], Wx = 59.925 [cm3], Wyt = 4734.084 [cm3], Wyb = 1047.263 [cm3], Wz+ = 6198.085 [cm3], Wz- = 6198.085 [cm3], Ix = 41.9 [cm4], Iy = 33230.3 [cm4], Iz = 805751.0 [cm4], Iyz = 0.0 [cm4], yNA = 0.0 [mm], zNA = 0.0 [mm], eY = 0.0 [mm], eZ = 67.4 [mm]	<#CSPic#>
24	Side girder 7-ToG 550 x 200 x 8 x 22	Built up T-profile with plate	Effective plate Width=588.6 [mm], Plate Thickness, pT=6 [mm], Web Height, hw=550 [mm], Web Thickness, t=8 [mm], Flange width (incl. web), bf=200 [mm], Flange thickness, tf=22 [mm], Angle Between Profile & Plate=90 [Degrees], FlipY=True	Ax = 12332 [mm2], Ay = 8831 [mm2], Az = 4171 [mm2], Wx = 90.281 [cm3], Wyt = 2431.319 [cm3], Wyb = 2686.900 [cm3], Wz+ = 396.365 [cm3], Wz- = 396.365 [cm3], Ix = 72.2 [cm4], Iy = 73773.8 [cm4], Iz = 11665.0 [cm4], Iyz = 0.0 [cm4], yNA = 0.0 [mm], zNA = 0.0 [mm], eY = 0.0 [mm], eZ = 229.5 [mm]	<#CSPic#>
25	Copy of WeldedAngle 150 x 90 x 9 x 9	L-Beam welded on plate	Effective plate Width=1 [mm], Plate Thickness=1 [mm], Stiffener Height, h=150 [mm], Thickness of web, t=10 [mm], Flange width (incl. web t.), w=90 [mm], Flange (average) Thickness=10 [mm], Angle between Plate and web=90 [Degrees], FlipY=True	Ax = 2301 [mm2], Ay = 1000 [mm2], Az = 1090 [mm2], Wx = 7.667 [cm3], Wyt = 35.658 [cm3], Wyb = 48.729 [cm3], Wz+ = 18.442 [cm3], Wz- = 27.497 [cm3], Ix = 7.7 [cm4], Iy = 538.6 [cm4], Iz = 149.6 [cm4], Iyz = -164.5 [cm4], yNA = 15.6 [mm], zNA = 15.6 [mm], eY = -15.6 [mm], eZ = -45.7 [mm]	<#CSPic#>
26	Side 5-7 Tbar 550 x 200 x 8 x 22	Built up T-profile with plate	Effective plate Width=668.5 [mm], Plate Thickness, pT=10 [mm], Web Height, hw=550 [mm], Web Thickness, t=8 [mm], Flange width (incl. web), bf=200 [mm], Flange thickness, tf=22 [mm], Angle Between Profile & Plate=90 [Degrees], FlipY=True	Ax = 15485 [mm2], Ay = 12618 [mm2], Az = 4247 [mm2], Wx = 90.270 [cm3], Wyt = 3956.428 [cm3], Wyb = 2884.200 [cm3], Wz+ = 788.770 [cm3], Wz- = 788.770 [cm3], Ix = 90.3 [cm4], Iy = 97085.8 [cm4], Iz = 26364.6 [cm4], Iyz = 0.0 [cm4], yNA = 0.0 [mm], zNA = 0.0 [mm], eY = 0.0 [mm], eZ = 208.9 [mm]	<#CSPic#>

Abbreviations

Profile: Profile identification number
Profile Name: User's profile identification
Type: Profile type
Profile parameters: Input parameters defining the profile.

Profile properties:

Cross section area: $Ax = sum(dA)$
Shear Area in Y-direction: $Ay = t \cdot Iz/Sz$

Shear Area in Z-direction: $Az = t \cdot Iy/Sy$ (Shear force / Shear Area gives largest shear-stress in Profile)

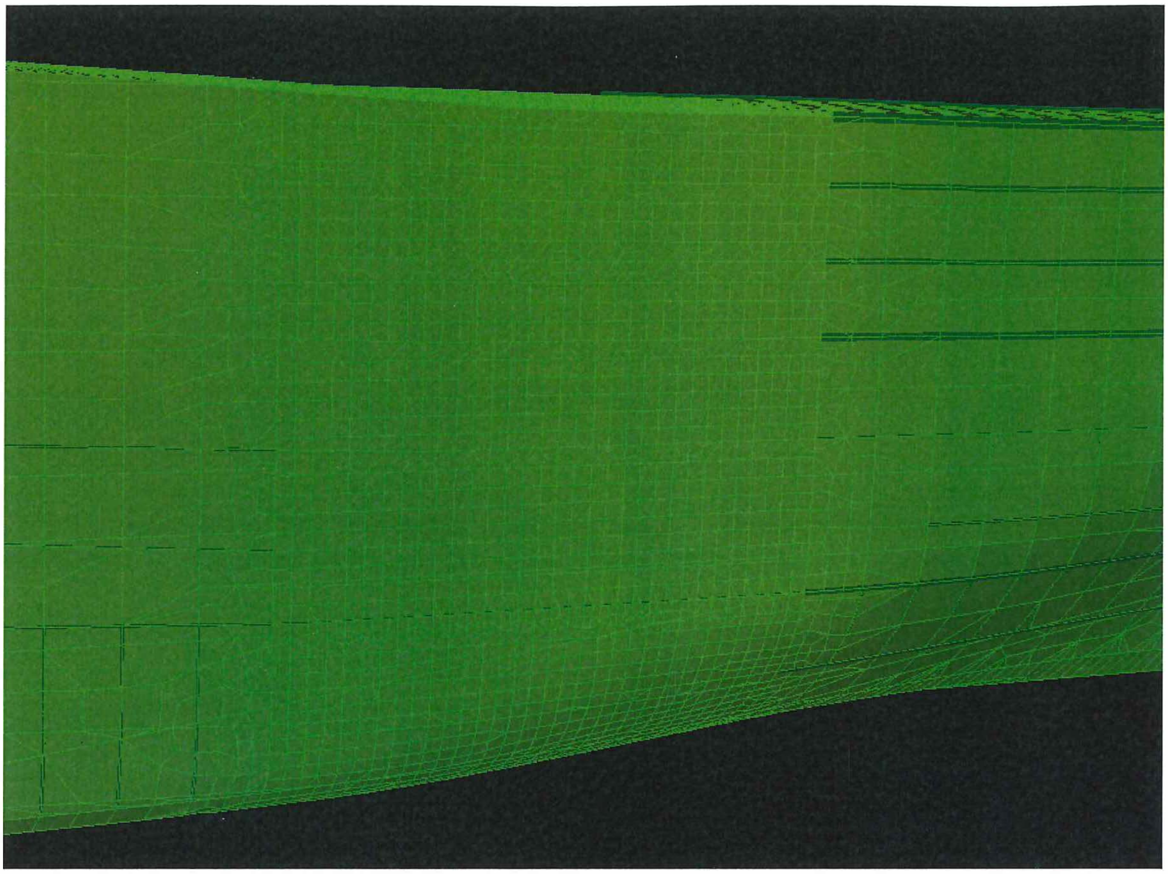
Torsional stiffness (For open profiles): $Ix = sum(ß \cdot b \cdot t^3/3)$
Moment of inertia about Y-axis: $Iy = sum(z^2 \cdot dA)$
Moment of inertia about Z-axis: $Iz = sum(y^2 \cdot dA)$
Centrifugal Moment of inertia about COG: $Iyz = sum(y \cdot z \cdot dA)$

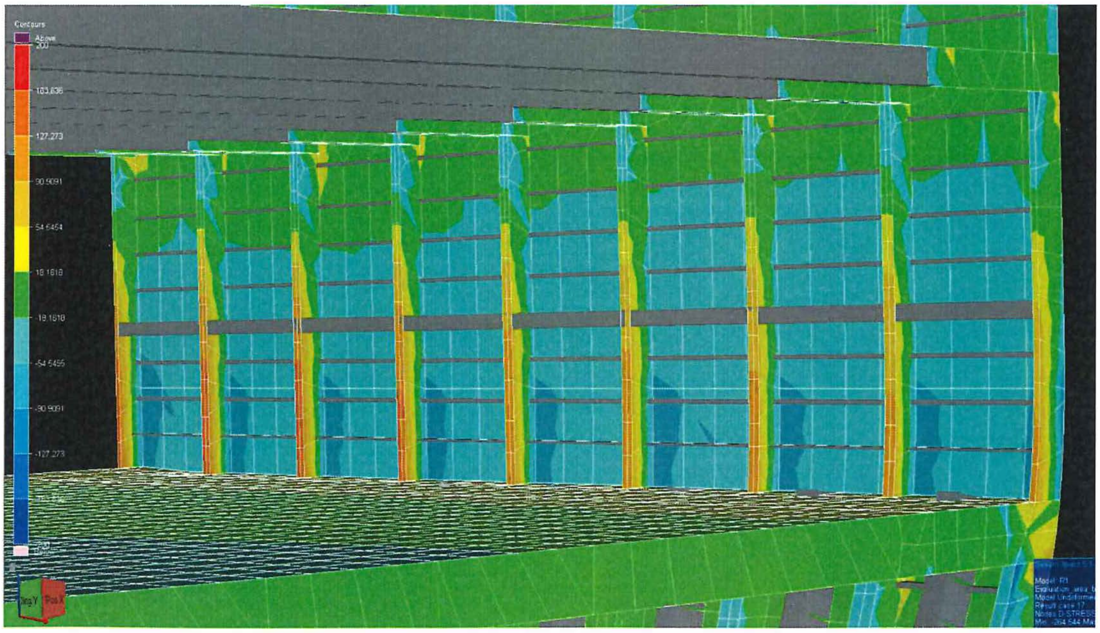
Section modulus about Y-axis: $Wy = (Iy \cdot Iz - Iyz^2)/(z \cdot Iz - y \cdot Iyz)$
Section modulus about Z-axis: $Wz = (Iy \cdot Iz - Iyz^2)/(y \cdot Iy - z \cdot Iyz)$
Moment/Section modulus gives largest bending stress
Iyz=0 for symetric profiles and then: Wy = Iy/z and Wz = Iz/y
Wyt, Wyb: at top and bottom of profile, Wz+, Wz-: on positive and negative y-side

Shear center eccentricity from COG: ey = Calculation is depending of profile type
Shear center eccentricity from COG: ez = Calculation is depending of profile type

Distance to neutral axis = location of COG. (Center Of Gravity)
About y-axis: (from center of Web or tube) $Yna = sum(z \cdot dA)/Ax$
About z-axis: (from bottom of profile) $Zna = sum(y \cdot dA)/Ax$

Global FE model





The figure shows the decomposed D-stresses for the web frames between 2nd and 4th deck. This where the highest stresses occur for the web frames.

Rulecalculator

Hull girder properties | Compartments and Loads | Description:

Pressure | Accelerations | Plate and Stiffeners | Corrugated Bulkhead | PSM - Grillage | Profiles

Calculate all | Calculate current

Input:								
X-Position, calc. point [Frame No.]	#116	#116	#116	#116	#116	#116	#116	#116
Y-Position, calc. point [mm]	0	0	0	11,35	0	0	0	0
Z-Position, calc. point [mm]	4110	7720	13685	17535	20380	23225	25730	10150
Load Scenario	-All-	-All-	-All-	-All-	-All-	-All-	-All-	-All-
Maximize	aZ	aZ	aZ	aZ	aZ	aZ	aZ	aZ
Results:								
Critical loadcase	**ExtremeSea_SD, Full load,**	**ExtremeSea_SD, Full load,**	**ExtremeSea_SD, Full load,**	**ExtremeSea_SD, Full load,**	**ExtremeSea_SD, Full load,**	**ExtremeSea_SD, Full load,**	**ExtremeSea_SD, Full load,**	**ExtremeSea_SD, Full load,**
a_x [m/s²]	-0,315	-0,385	-0,500	-0,575	-0,630	-0,685	-0,734	-0,432
a_y [m/s²]	-2,677	-2,744	-2,855	-2,926	-2,979	-3,031	-3,078	-2,789
a_z [m/s²]	4,400	4,400	4,400	4,400	4,400	4,400	4,400	4,400
Max a_{x_env} [m/s²]	1,064	1,220	1,676	2,011	2,295	2,605	2,901	1,387
Max a_{y_env} [m/s²]	5,178	5,415	5,814	6,076	6,272	6,469	6,644	5,576
Max a_{z_env} [m/s²]	5,696	5,696	5,696	5,696	5,696	5,696	5,696	5,696
Max $a_{z\_env\_pitch}$ [m/s²]	5,765	5,765	5,765	5,765	5,765	5,765	5,765	5,765
Max $a_{z\_env\_roll}$ [m/s²]	5,119	5,119	5,119	5,119	5,119	5,119	5,119	5,119
Intermediate results:								
Applied load comb. factors for the EDW giving max acceleration.	CXS=0 CXP=-0,2 CXG=0,2 CYS=-0,9 CYR=0,3 CYG=-0, CZH=1 CZR=0,3 CZP=-0,2	CXS=0 CXP=-0,2 CXG=0,2 CYS=-0,9 CYR=0,3 CYG=-0, CZH=1 CZR=0,3 CZP=-0,2	CXS=0 CXP=-0,2 CXG=0,2 CYS=-0,9 CYR=0,3 CYG=-0, CZH=1 CZR=0,3 CZP=-0,2	CXS=0 CXP=-0,2 CXG=0,2 CYS=-0,9 CYR=0,3 CYG=-0, CZH=1 CZR=0,3 CZP=-0,2	CXS=0 CXP=-0,2 CXG=0,2 CYS=-0,9 CYR=0,3 CYG=-0, CZH=1 CZR=0,3 CZP=-0,2	CXS=0 CXP=-0,2 CXG=0,2 CYS=-0,9 CYR=0,3 CYG=-0, CZH=1 CZR=0,3 CZP=-0,2	CXS=0 CXP=-0,2 CXG=0,2 CYS=-0,9 CYR=0,3 CYG=-0, CZH=1 CZR=0,3 CZP=-0,2	CXS=0 CXP=-0,2 CXG=0,2 CYS=-0,9 CYR=0,3 CYG=-0, CZH=1 CZR=0,3 CZP=-0,2
Roll period, Tθ [s]	16,2	16,2	16,2	16,2	16,2	16,2	16,2	16,2
Roll angle, θ [deg]	29,4	29,4	29,4	29,4	29,4	29,4	29,4	29,4
Pitch period, Tφ [s]	10,0	10,0	10,0	10,0	10,0	10,0	10,0	10,0
Pitch angle, φ [deg]	15,9	15,9	15,9	15,9	15,9	15,9	15,9	15,9
a surge [m/s²]	1,812	1,812	1,812	1,812	1,812	1,812	1,812	1,812
a sway [m/s²]	2,802	2,802	2,802	2,802	2,802	2,802	2,802	2,802
a heave [m/s²]	5,119	5,119	5,119	5,119	5,119	5,119	5,119	5,119
a roll [rad/s²]	0,077	0,077	0,077	0,077	0,077	0,077	0,077	0,077
a pitch [rad/s²]	0,121	0,121	0,121	0,121	0,121	0,121	0,121	0,121
Acceleration parameter, a0	0,562	0,562	0,562	0,562	0,562	0,562	0,562	0,562
Heading corr. factor, fβ	0,800	0,800	0,800	0,800	0,800	0,800	0,800	0,800
Draught ratio, fT	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000
Applied GM [m]	1,589	1,589	1,589	1,589	1,589	1,589	1,589	1,589
Applied kr [m]	8,853	8,853	8,853	8,853	8,853	8,853	8,853	8,853
Ship rotation centre, R [m]	10,108	10,108	10,108	10,108	10,108	10,108	10,108	10,108
Rule length, L [m]	131,300	131,300	131,300	131,300	131,300	131,300	131,300	131,300
Moulded breadth, B [m]	22,700	22,700	22,700	22,700	22,700	22,700	22,700	22,700
Block coefficient, CB [-]	0,602	0,602	0,602	0,602	0,602	0,602	0,602	0,602

Lumped stiffener calculation

Position/Area	Type	Area	No of Lumped Stiff	Additional area	Type of stiff in pos	Area of stiffener in pos	New area	New profile
	Top of Garage							
Center	L65x65x6	0,000744	5	0,00372	T360x7_F100x22	0,004566	0,008286	Sct1
Side	L65x65x6	0,000744	5	0,00372	L65x65x6	0,000744	0,004464	Sct2
	Deck 7							
Centerline	L65x65x6	0,000744	5	0,00372	T430x7_F100x20	0,00487	0,00859	Sct3
#80-#112 center	L65x65x6	0,000744	5	0,00372	T430x7_F150x20	0,00587	0,00959	Lumped_Deck7_#80-112
Side	L65x65x6	0,000744	5	0,00372	L65x65x6	0,000744	0,004464	Sct2
	Deck 5 & 6							
Center	L65x65x6	0,000744	5	0,00372	T430x7_F150x20	0,00587	0,00959	Sct4
Center outside	L65x65x6	0,000744	5	0,00372	T430x7_F100x20	0,00487	0,00859	Sct3
Side	L65x65x6	0,000744	5	0,00372	L65x65x6	0,000744	0,004464	Sct2
Opening	L65x65x6	0,000744	4,5	0,003348	L65x65x6	0,000744	0,004092	Sct5

Position/Area	Type	Area	No of Lumped Stiff	Additional area	Type of stiff in pos	Area of stiffener in pos	New area	New profile
	Deck 4							
Center	L100x75x10	0,00165	5	0,00825	T510x7_F100x19	0,005337	0,013587	Sct7
Center Opening	L100x75x10	0,00165	5,5	0,009075	T510x7_F100x19	0,005337	0,014412	Sct9
Side	L100x75x10	0,00165	5	0,00825	L100x75x10	0,00165	0,0099	Sct8
Side #169-#172	L100x75x10	0,00165	5	0,00825	T510x7_F250x19	0,008187	0,016437	Sct10
	Deck 3							
#162-#172	L150x90x9	0,002079	7	0,014553	L150x90x9	0,002079	0,016632	Lumped_Deck3_162
#172-#184	L65x65x6	0,000744	2	0,001488	L65x65x6	0,000744	0,002232	Lumped_Deck3_172

	Deck 2							
Aft, center	L150x90x10	0,0023	5	0,0115	T525x12F450x12	0,01725	0,02875	
Aft, side	L150x90x10	0,0023	5	0,0115	T525x9F270x25	0,01125	0,02275	Deck 2 Aft Side
ev.center	L150x90x10	0,0023	5	0,0115	T795x10F300x32	0,01723	0,02873	Deck2 FrontCenter
ev.side	L150x90x10	0,0023	5	0,0115	T800x10F200x32	0,01408	0,02558	Deck2 Large800
Side-Side	L150x90x10	0,0023	5	0,0115	L150x90x10	0,0023	0,0138	Deck2 OnlyL-beams

Position/Area	Type	Area	No of Lumped Stiff	Additional area	Type of stiff in pos	Area of stiffener in pos	New area	New profile
	Deck 1							
#68-82	T_W400x7_F180x22	0,006606	1	0,006606	T_W400x7_F180x22	0,006606	0,013212	Lumped_Deck1_Ramp
#84-100	T_W400x7_F150x25		2		T_W400x7_F150x25	0,006375		
Center	L65x65x6	0,000744	5	0,00372	T_W400x7_F150x25	0,006375	0,010095	Lumped_Deck1_Center
Side	L65x65x6	0,000744	5	0,00372	L65x65x6	0,000744	0,004464	Sct3
Side, Bulkhead	L65x65x6	0,000744	3,5	0,002604	L65x65x6	0,000744	0,003348	Lumped_Deck1_Sidebulk
Side, Bulkh ramp	L65x65x6	0,000744	2,5	0,00186	NA	0	0,00186	Lumped_Deck1_bRAMP
Aft inside Bulkhead area	L100x75x9	0,001494	3	0,004482	L100x75x9	0,001494	0,005976	Lumped_Deck1_AftIn
Aft sloped ramp	L65x65x6	0,000744	5	0,00372	NA	0	0,00372	Lumped_D1to2_ramp
Platform deck								
Pl.D. SB side	L125x75x12	0,002256	3	0,006768	L125x75x12	0,002256	0,009024	Lumped_PlD_SB_Side
Pl.D. SB	L125x75x10	0,0019	3	0,0057	L125x75x10	0,0019	0,0076	Lumped_PlD_SB
Pl.D. PS	L100x75x10	0,00165	3	0,00495	L100x75x10	0,00165	0,0066	Lumped_PlD_PS

Side											
Aft			Top of Garage	7 Deck	6 Deck	5 Deck	4 Deck	3 Deck	2 Deck	1 Deck	0 Deck
L65x65x6	0,000744		0,00372	0,002232	0,002232	0,002976	0,00516	0,01915	0,006414	0,004764	
L100x75x10	0,00165										
L125x75x10	0,0019						0,014735	0,009575	0,015989		
L200x85x9x14	0,002864										
L550x250x25	0,01255										

Aft Ice and girder				Area of girder in position	New area	New profile
L125x75x10	0,0019		6 small	0,015616	0,042632	Lumped_Girder_ice
T_800x12_F200x32	0,015616		1 large			

Front	Type	Area	No of Lumped Stiff	Additional area	Rest from lumped stiffener deck	New area	New profile
Position/Area							
5th to #184	Same as aft area						
5th from #172	L75x75x9	0,001269	6,5	0,0082485		0,00825	Lumped_5th_f172
Deck 4 from #160	L100x75x9	0,001494	5	0,00747			
	L75x75x9	0,001269	5	0,006345		0,01382	Lumped_4th_f160
Deck 3 from #140	L100x75x9	0,001494	5	0,00747			
	HP230x11	0,00323011	1	0,00323011		0,01070	Lumped_3rd_f140
Deck2	L500x100x12	0,0082	1	0,0082			
	L600x100x12	0,0094	1,5	0,0141		0,0223	Lumped_2nd_F
Deck 1	L600x100x12	0,0094	1,5	0,0141			
	HP230x11	0,00323011	1	0,00323011		0,01733	Lumped_1st_F

Tanktop	L600x100x12	0,0094	1	0,0094		0,0094	Lumped_TT_F

Transverse Bulkheads								
Position/Area	Type	Area	No of Lumped Stiff	Additional area	Type of stiff in pos	Area of stiffener in pos	New area	New profile name
Frame 28	L100x75x7	0,001176	3	0,003528	L100x75x7	0,001176	0,004704	Lumped_Frame 28
Frame 28 Side	L100x75x7	0,001176	7	0,008232	L100x75x7	0,001176	0,009408	Lumped_Frame 28_Side
Frame 36	L100x75x7	0,001176	1	0,001176	L100x75x7	0,001176	0,002352	Lumped_Frame 36
Frame 36 PSide	L100x75x10	0,00165	3	0,00495	L100x75x10	0,00165	0,0066	Lumped_Frame 36 Side
Frame 36 SB Side	L100x75x7	0,001176	6	0,007056	L100x75x7	0,001176	0,008232	Lumped_Frame 36SBSide
Frame 40 2nd 3rd Deck	HP180x9,5	0,00214702	3	0,00644106	HP180x9,5	0,00214702	0,00858808	Lumped_Fr40_2nd3rd
Frame 40	L150x150x10	0,0029	3	0,0087	L150x150x10	0,0029	0,0116	Lumped_Frame 40
Frame40 5th 6th	L65x65x6	0,000744	1	0,000744	L65x65x6	0,000744	0,001488	Lumped_Fr40_5th6th

Frame 68	L150x150x12	0,003456	5	0,01728	L150x150x12	0,003456	0,020736	Lumped_Frame 68
Frame 68 SB	L150x150x12	0,003456	3,5	0,012096	L150x150x12	0,003456	0,015552	Lumped_Frame 68SB
Frame 68 PS ramp	L150x150x12	0,003456	1,5	0,005184	L150x150x12	0,003456	0,00864	Lumped_Fr68_ramp
Frame 68 PS below ramp	L150x150x12	0,003456	3	0,010368	L150x150x12	0,003456	0,013824	Lumped_Fr68_bel_ramp

Front area								
Frame 160, D2-3	L125x75x10	0,0019	8	0,0152			0,0152	Lumped_Fr160_2to3
Frame 160, D1-2	L250x90x9x15	0,003465	3	0,010395				
	L100x75x7	0,001176	3	0,003528			0,013923	Lumped_Fr160_1to2
Frame 160, TT-1st	L150x150x10	0,0029	4	0,0116			0,0116	Lumped_Fr160_TTto1
Frame 172, D3-4	L200x90x9x14	0,002934	9	0,026406			0,026406	Lumped_Fr172_3to4

Frame 172, D2-3	L125x75x10	0,0019	3	0,0057			0,0057	Lumped_Fr172_2to3
Frame 172, D1-2	L250x90x11x16	0,004014	1	0,004014				
	L150x150x10	0,0029	2	0,0058				
	L100x75x10	0,00165	2	0,0033			0,013114	Lumped_Fr172_1to2
Frame 172, TT-1st	L100x75x7	0,001176	4	0,004704			0,004704	Lumped_Fr172_TTto1

Frame 192								
Frame 192, 6&up	L65x65x6	0,000744	5	0,00372	L65x65x6	0,000744	0,004464	Sct2
Frame 192, upper side	L65x65x6	0,000744	2	0,001488	L65x65x6	0,000744	0,002232	

Longitudinal bulkheads									
Position/Area	Type	Area	No of Lumped Stiff	Additional area	Type of stiff in pos	Area of stiffener in pos	New area	New profile	
PS Bulk Ramp Platform to 2nd	L100x75x10	0,00165	1	0,00165	T_W350x9_F250x25	0,009175	0,02165	Lumped_PS_Platform_2nd	For s=2.6 Times2

Reduced plate thickness due to openings

	Position				
Frame	28				
	L	5950 mm			
	H	3920 mm		A1	23324000
	t_0	7 mm		A2	1480000
	l	800 mm			
	h	1850 mm		p	6,3453953
	$t_{red}(y)$	3,70		tred	6,36
	tred(x)	6,06			
	t_{red}	min			

Balancing of sea pressure

SUM OF LOAD AND MOMENTs FOR SUPERELEMENT TYPE 1 ON LEVEL 1				
Loadcase nr	Loadcase name	X-load	Y-load	Z-load
1	Sea Pressure roll	12314	-34791000	115610000
2	Deckload Tanktop	-1,9099E-11	-1,1018E-11	-71531000
3	Deckload Deck 7	-5,0439E-13	3,4825E-13	-3400300
4	Deckload Deck 6	6,8029E-13	2,5024E-13	-3306400
5	Deckload Deck 5	5,6488E-13	-9,2558E-14	-3375400
6	Deckload Deck 4	-2,2737E-13	3,6332E-13	-8509500
7	Deckload Deck 2	1,6175E-12	-3,6169E-12	-7944700
8	Deckload Deck 1	-7,9452E-13	-2,5435E-12	-3656700
9	Top of Garage UDL+SW	9,1138E-13	1509400	-6,6233E-14
10	Deck 7 UDL+SW	1,871E-13	3896900	-1,7988E-13
11	Deck 6 UDL+SW	2,0617E-12	3987500	-2,6708E-13
12	Deck 5 UDL+SW	-3,3555E-12	3946700	3,9781E-13
13	Deck 4 UDL+SW	6,2006E-12	7896700	-1,0959E-10
14	Deck 3 UDL+SW	-2,3136E-11	3995900	-2,3556E-10
15	Deck 2 UDL+SW	-4,2232E-11	9548700	-1,146E-10
16	Load of deck 3	-1,696E-11	-1,5098E-10	-13893000
SUM		12314	-9200	-7000
	Sea Pressure	12314	-34791000	115610000
	Loads	-9,4085E-11	34781800	-115617000
	Difference	12314	-9200	-7000
	Fraction %	100	0,03	-0,01

Scientific Article

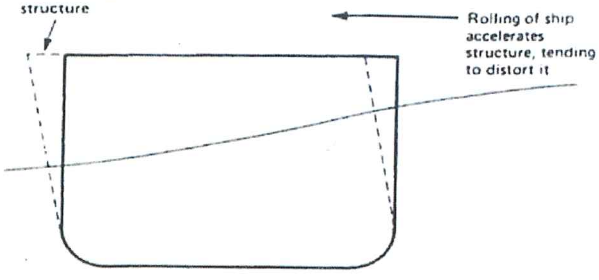
Development of Racking calculations in Concept Design Phase for a ROPAX Vessel

Ship design is a complex and iterative process to design the best possible vessel for a customer. The concept design phase is particularly important as the main dimensions of the ship is decided. The main dimensions decide many of the ship's characteristics, e.g. stability, hold capacity, power requirements and economic efficiency.

Schneekluth and Bertram (1998) says that a ship should not be larger than necessary, as the characteristics desired by the shipping company can usually be achieved with various combinations of dimensions. Further they say that an iterative procedure is needed when determining the main dimensions and ratios. The following sequence is appropriate for cargo ships:

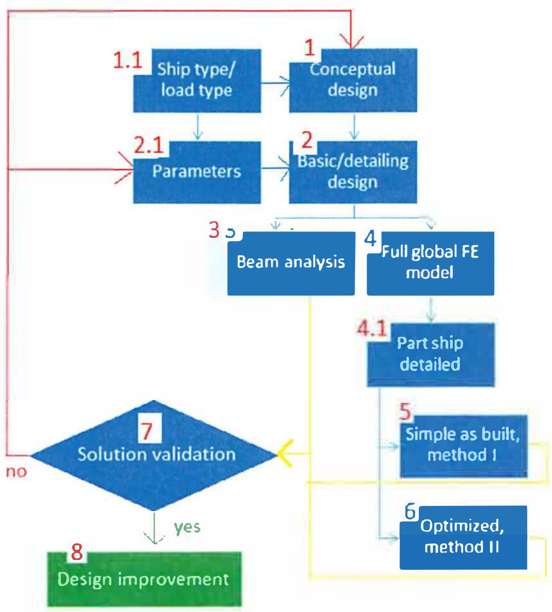
1. Estimate the weight of the loaded ship. The first approximation to the weight for cargo ships uses a typical deadweight/displacement ratio for the ship type and size.
2. Choose the length between perpendiculars using the Schneekluth's formula
3. Establish the block coefficient
4. Determine the width, draught, and depth collectively.

Car carriers often consists of multiple decks with little or no transverse bulkheads. Where the transverse bulkheads are widely spaced, or not present at all, deep web frames and beams is introduced to carry the deck load without pillar support. The transverse bulkheads primarily resist the transverse deformation which is caused when a ship is rolling, this is referred to as racking. Racking is considered as one of the main strength problems for Car Carriers as these ships have little or no transversal bulkheads, and it is therefore important to include racking calculations in the early design phase.



When the ship is rolling, the accelerations on the ship's structure and deck load will create a force tending to distort the structure transversally and may cause deformation at the corners. The deck will move laterally relative to the bottom structure, while the outer shell on one side will move vertically relative to the other side, as seen in figure 1.3. The connections between transverse structural members to the bulkhead deck, or the uppermost deck level should therefore be given special attention in a racking strength assessment.

Methodology



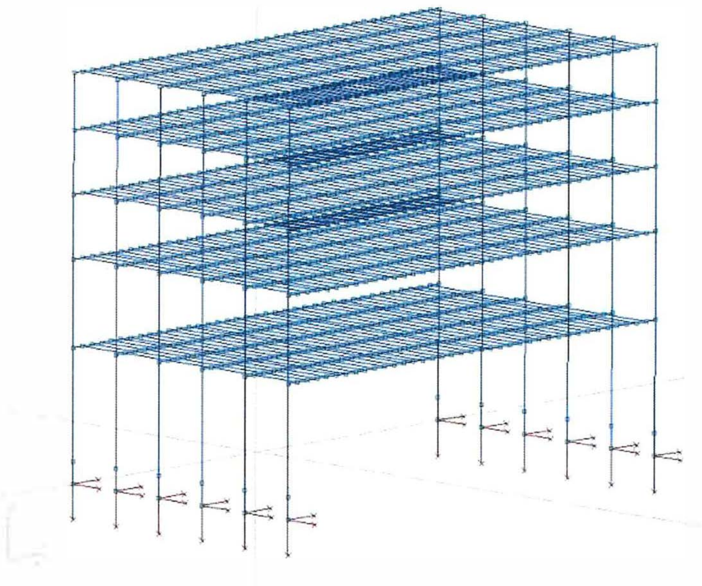
For this case two calculations method for racking strength is given by DNV GL, and can be summarized as in table 1.

Simplified method (Category I)	**Advanced method (Category II)**
Simplified racking assessment using beam or FE model	Global FE model representing the global stiffness
PSM shall be modelled with beam elements	Evaluation area: plates and finer mesh (Sub-modelling technique)
Fixed in all freedoms of translation at bulkhead deck	BC: 3 points: two at each side at the transom and one point in the centerline at the bulbous bow
Dynamic loads: transverse and vertical	Static deck loads and selfweight for critical loading condition, with sea pressure

The loading condition, which in combination with relevant dynamic load cases results in the maximum racking moment about the bulkhead deck, shall be chosen for the ULS transverse strength analysis. The racking moment is calculated according to 3.2.2. For the simplified racking analysis, using beam elements, the dynamic loads which is applied, shall be taken as

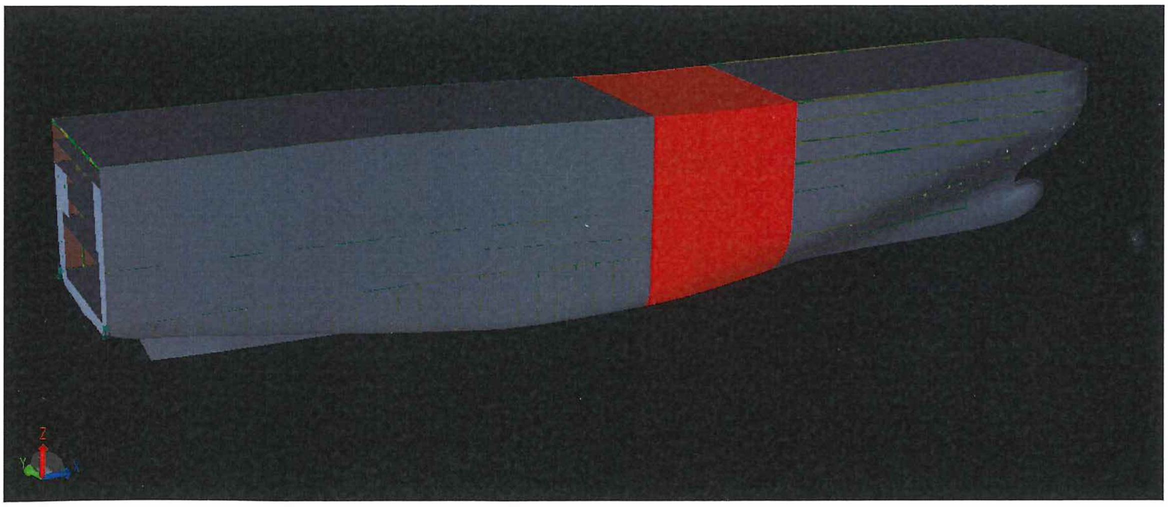
$$Transverse = (UDL + selfweight) \times a_{y-env}$$

$$Vertical = (UDL + selfweight) \times g$$

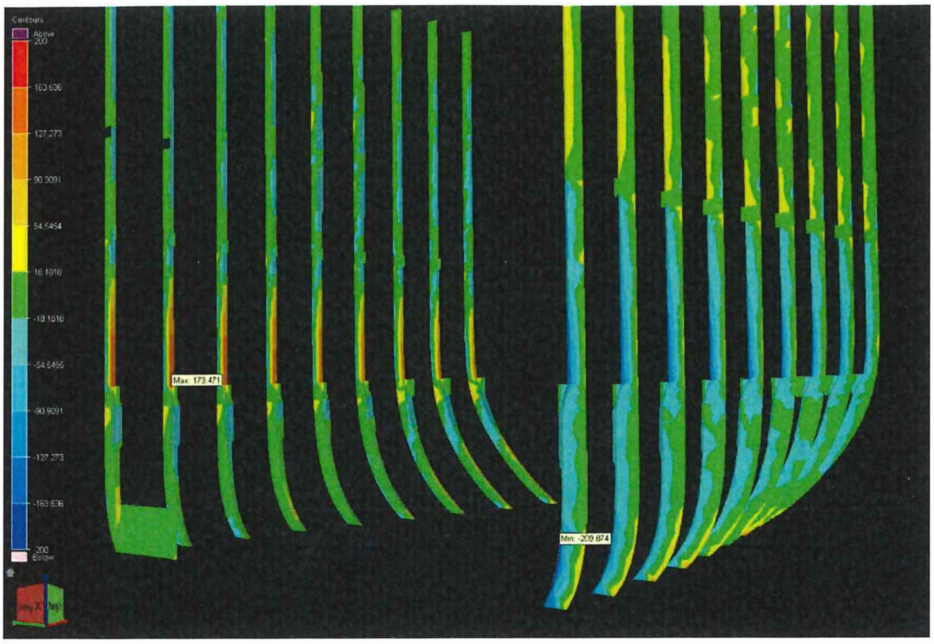


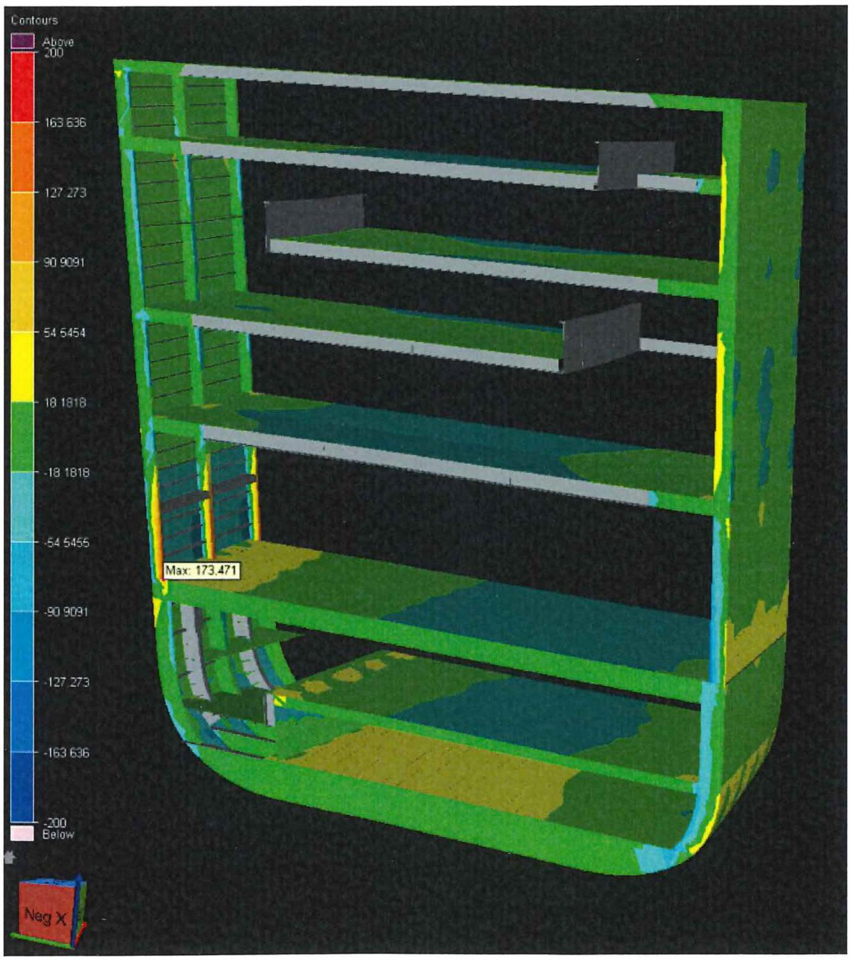
with the highest bending stress of 269 N/mm^2. This gives the usage factor of 1,35 for this beam, in total there are now 48 beams with usage factor above 1.

The figure below shows the global FE model.



Results for normal membrane stresses are showed in the figure below.





Position	Highest normal membrane stress [N/mm^2]	Permissible stresses [N/mm^2]
Port, above 2nd deck	147	200
Starboard, above 2nd deck	114	200

It was found that the beam analysis gives a very conservative result, with stresses over the permissible values for bending stress. As the beam analysis is very simplified, structural members contributing to the racking strength is not contributing. The beam analysis can be considered conservative due to the calculations with effective breadths of plates, which reduces the section modulus. Another reason for the conservative results from the beam analysis may be that the method is not intended for ship sizes such as the ship studied in this case. As the stress results from the beam analysis is above the acceptance criteria, the dimensions must be bigger to cope with the large bending moment. Meaning that using the simple method for deciding the cross section, the ship's light weight will be much higher than using the advanced method.

The results for the full global model showed that the yield criteria for racking ULS was fulfilled, and the structural design could be further improved. As the global FE model is the only calculation method that have approved results, it is the method which should be applied for defining the cross section and calculate the light weight. The amount of work required to apply the global FE model is a disadvantage, but it may still be the most cost efficient solution considering steel weight savings and ship performance.

The global model is also the only model which can take the global strength and global loads into consideration. As can be seen from the displacement of the model, torsion is created by the hydrostatic pressure which is applied on the rule roll angle. The sea pressure also works to balance the global model, which is found to be important as the sea pressure will contribute to the transverse distortion of the structure. With only the transverse and deck loads applied, without the sea pressure, the structure will not have the same distortion and only create a roll movement of the ship.