Analysis of Classification Societies' Rules for Yacht Superstructure Scantlings – Application to a Light Alloy Superstructure

Michael Kramer

Master Thesis

presented in partial fulfilment
of the requirements for the double degree:
"Advanced Master in Naval Architecture" conferred by University of Liege
"Master of Sciences in Applied Mechanics, specialization in Hydrodynamics, Energetics and Propulsion" conferred by Ecole Centrale de Nantes

developed at University of Genoa
in the framework of the

"EMSHIP"
Erasmus Mundus Master Course
in "Integrated Advanced Ship Design"

Ref. 159652-1-2009-1-BE-ERA MUNDUS-EMMC

Supervisor: Prof. Dario Boote, University of Genoa

Reviewer Prof. André Hage, University of Liège

Genoa, February 2014

CONTENTS

DECLARATION OF AUTHORSHIP

I declare that this thesis and the work presented in it are my own and has been generated by me as the result of my own original research.

Where I have consulted the published work of others, this is always clearly attributed.

Where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own work.

I have acknowledged all main sources of help.

Where the thesis is based on work done by myself jointly with others, I have made clear exactly what was done by others and what I have contributed myself.

This thesis contains no material that has been submitted previously, in whole or in part, for the award of any other academic degree or diploma.

I cede copyright of the thesis in favour of the University of Genoa.

Date: Signature

ABSTRACT

The objective of this master thesis is to analyse the main Classification Societies Rules about superyacht superstructures and compare their scantling rules. Then a finite element analysis of the superstructure of a yacht is carried out in order to compare the results with those obtained by the Rules.

In a time where safety and efficiency is ever so important this could be the starting point of a procedure to optimize the overall performance of the yacht by better understanding the loads and stresses in the superstructure and then trying to optimise them.

For the comparison of the different scantling rules for displacement aluminium yachts, the main focus will be on the scantling of plates and structures of the superstructure. For reference a 45m Benetti semi-custom yacht was chosen, where a parametric analysis will not be considered (i.e. dependence of the rules according to the main dimensions of a boat).

The idea of the FEM analysis is to better understand how the superstructure performs with different load conditions. Therefore this analysis will provide a more detailed understanding of possible critical areas. Modelling will be done with MSC Patran and MSC Nastran will be used as the solver.

The thesis was done in collaboration with the Azimut-Benetti shipyard, a world leader in the production of superyachts, which gave the permission to use one of their steel/aluminium yachts for this thesis; to undertake a large amount of the work at their R&D office; to provide support from the designer and structural engineers from the host institution; to insert part of their technical documentation.

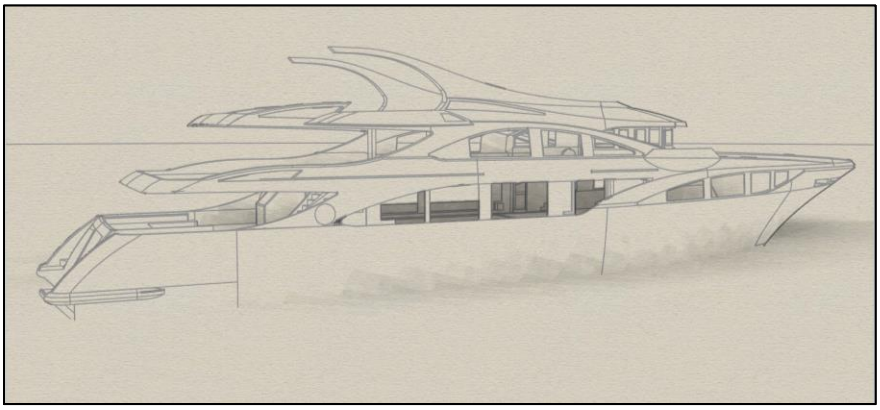


Figure 1 – Benetti semi-custom (courtesy of Azimut-Benetti spa)

1. INTRODUCTION

The reason it was decided to focus on superstructure scantling rules is because, nowadays this area is becoming an ever more complex area from a structural point of view. Compared to a hull, where the loads are higher and the structure is mostly regular, the structure of the superstructure decks are highly irregular. This is due to the fact that these upper deck areas require large open spaces, big windows, while still withstanding concentrated static loads such as whirlpools and luxurious furnishing. Another problem is the use of aluminium alloys in the superstructures, which resistance to compressive loads is reduced due to its low elastic modulus.

This thesis is divided into three main areas. First an overview of the main Classification Societies will be given, with some detail about rules for motor yachts. Then the scantling of semi-custom yacht will be analysed and compared to the scantling requirements given by the Rules. The final part consists of a direct calculation analysis where different load cases will be tested. The findings of this analysis will then be evaluated and a comparison with the Rule findings will be carried out.

When analysing the rules, the focus was upon yachts with an overall length greater than 24m built in aluminium. Three main Classification Societies will be analysed in depth:

- Registro Italiano Navale (RINA)
- Lloyd's Register (LR)
- American Bureau of Shipping (ABS)

The case study of the thesis will be of a 45 m Benetti semi-custom motor yacht, with a steel hull and aluminium superstructure. General information is presented in the following table.

Table 1 - General Characteristics

Length Overall	45.14m
Breadth Overall	9.1m
Waterline Length	37.21
Depth	4.45m
Draught	2.40m
Design Speed	14.50 kn
Displacement	445t

2. RULES AND REGULATIONS

2.1. Overview

The Regulation environment is a very complicated one. There are many national and international rules and regulations that motor yachts have to comply to. Firstly the type of service distinction for a yacht must be known as it is of great importance. These are:

- Private yachts: designed and managed for the personal use of the owner and cannot be engaged in any kind of trade

- Commercial yachts: designed and managed in order to allow charter activity (trade). Although, sometimes they might also be registered and managed as private yachts.

In addition to the Classification Societies, the International Maritime Organisation (IMO), and National Regulations, large motor yachts must meet the following International Conventions:

- Safety of Life at Sea (SOLAS)
- International Load Line Convention (ILLC)
- MARPOL, devoted to the control of the marine pollution
- International Regulations for Preventing Collisions at Sea (COLREG)
- Standards of Training, Certification and Watchkeeping (STCW)

The choice and application of the rules is in based upon the characteristics of the yacht such as dimensions, type of service and number of passengers.

Figure 2 presents an overview of the rules for private and charter yachts.

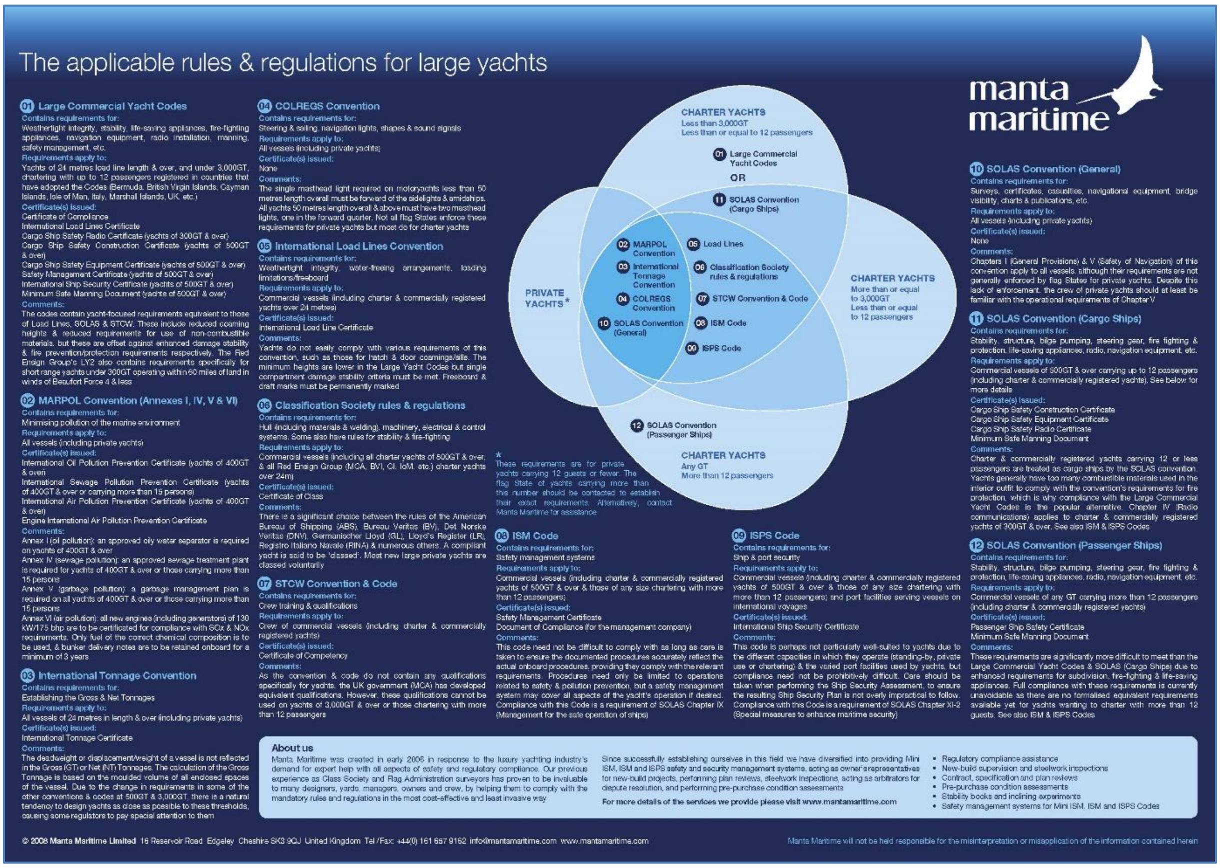


Figure 2 - The applicable rules & regulations for large yachts (Manta Marine)

The rules for private yachts are far less as they are only required to comply with MARPOL Rules, the International Tonnage Convention and COLREG. They do not need to comply with ILLC and SOLAS requirements.

Charter yachts are considered as ships and therefore must comply with the International Conventions. These Conventions were written mainly for cargo and passenger ships and merely adapted for luxury yachts. Therefore, in 1997, the UK Maritime and Coastguard Agency (MCA) issued a new code specifically for large yachts, known as the MCA Large Yacht Code (LY1). There have since been two updates of that code, the latest one, LY3, in 2012. To date, the LY3 code is the most frequently used code by the industry.

MCA-LY3 recognises most Classification Societies that have rules stating the construction and strength requirements for large motor yachts. Furthermore, these Classification Societies are authorised to carry out plan approval, surveys and issue certificates of compliance with certain parts of the MCA Large Commercial Yacht Code.

The structural design and scantlings of any kind of yacht are regulated by the Classification Societies' Rules. There are very limited structural aspects contained in MCA-LY3. Therefore, a slightly more detailed overview of the structural procedures contained in some of the most important Classification Societies will be given. Since for the comparison only three different Classification Societies were used, namely RINA, LR and ABS, a brief outline of the various design loads with also be given.

2.2. RINA (2013)

The RINA *Rules for the Classification of Pleasure Yachts* is intended for yachts engaged in private use with a length above 16m and is divided into five parts:

- Part A: Classification and Surveys
- Part B: Hull and Stability
- Part C: Machinery, Electrical Installation, Fire Protection
- Part D: Materials and Welding
- Part E: Additional Class Notations

Part B – Hull and Stability is the most relevant for the structural design of a yacht as it contains design loads and scantling criteria for yachts made of steel, aluminium, FRP and wood. Within this part there are six chapters where Chapter 1 deals with the general requirements, definitions, equipment and most importantly loads which are in turn subdivided into overall global loads and local loads (static and dynamic). Chapters 2 and 3 regard steel and aluminium structures and are valid for lengths up to 90m and 120m respectively. Mechanical characteristics and welding procedures are also presented in these chapters. Plating and internal scantlings are provided for bottom, sides, decks, bulkheads and superstructures. The minimum section modulus for reinforcements is calculated by formulas depending on parameters such as design pressure, stiffener span and spacing and material coefficients. Similar as above, the minimum plating thickness is obtained by formulas as a function of design pressure, stiffener spacing and material coefficients. Apart from the vertical acceleration, RINA also provides a formula for the transverse acceleration which can be used in direct calculations to analyse the racking effect (this effect will be discussed later on in the thesis).

2.3. LR (2013)

The rules for motor yachts are contained in the *Rules and Regulations for the Classification of Special Service Craft*. The rules are applicable to high speed craft, light displacement craft, and multi-hull craft built in steel, aluminium alloy, or composite materials with an overall length between 24 and 150m. The Rules are composed of eight volumes, which are divided into 17 parts. The parts most relevant to the structural scantling are considered in Parts 5 to 8. Design load criteria are assessed in Part 5, which are divided in global and local loads. Parts 6, 7 and 8 contain scantling procedures for steel, aluminium and FRP vessel respectively. The minimum plating thickness and stiffener modulus are governed by the same equations as a function of design pressure, minimum yield strength of the material, stiffener spacing and span, and panel aspect ratio. A table with the minimum thickness requirements for different hull locations and vessel typologies is provided as a function of the material coefficient and the yacht length. The final chapters of all three Parts 6, 7, and 8 are dedicated to hull girder strength for mono and multi-hull and failure mode control. This last section provides criteria to evaluate deflection, stresses, buckling and vibrations.

2.4. ABS (2000)

The 2000 edition of the *Guide for Building and Classing Motor Pleasure Yachts* from the American Bureau of Shipping Rules are applicable to motor pleasure crafts between 24m and 61m in overall length that are not required to be assigned a load line. The rules comprise of a total of 24 sections, where ten of them (Sections 3 to 12) deal with structural scantlings. Sections 3 and 4 consist of general definitions, such as standard bracket proportions and effective width of a plate and the mechanical properties of the main building materials such as steel, aluminium alloys, FRP and wood. Section 5 talks about fabrication and quality control. The regulations for structural arrangements, details and fastenings for the materials considered by the Rules are described in Sections 6 and 7. Design loads are dealt with in Section 8. Section 9, High Speed Craft, and Section 10, Displacement Craft, both deal with the hull scantling. The minimum thickness of shells and minimum section modulus of reinforcement's modulus must be calculated by formulas as a function of stiffener span and spacing, design pressure and allowable material stress. Finally Sections 11 and 12 consider the longitudinal strength as well as keel, stems, stern frames and shaft struts structures.

2.5. DNV (2012)

DNV considers yachts as a special service vessel and these rules apply to yachts greater than 24m in length and not intended for operation on a commercial basis.

High Speed, Light Craft and Naval Surface Craft Rules are the ones offered by Det Norske Veritas Regulations for motor yachts. The document consists of a total of 8 Parts. Parts 0 and 1 contain general regulations, Part 2 metallic materials, welding and composites, Part 3 structure and equipment requirements, Part 4 machinery and systems/equipment and operation, Part 5 special service and type, Part 6 special equipment and systems, and finally Part 7 HSLC (High Speed Light Craft) in operation.

Structural scantlings are listed in Parts 2 and 3 where mainly the hull structural design of steel and aluminium built yachts are dealt with. Part 2 is specifically dedicated to material and welding characteristics. The section about the hull structure scantlings starts with the verification of a minimum hull section modulus. The minimum thickness of platings are given by rather simple formulas containing design pressures and stiffener spacing. DNV considers reinforcement scantlings separately for secondary stiffeners and primary web frames and girders, however, in both cases the formulas for minimum section modulus are provided as a function of stiffener span and spacing, design pressure, and allowable material stress. Design loads, which can be found in Chapter 1 of Part 3, are subdivided into local and global loads. The chapter starts off with a detailed description of bottom, side, deck, bulkhead and superstructure layouts, then continues with common design rules for the most important details.

2.6. GL (2003)

Special Craft are the rules offered by Germanischer Lloyd and apply to large, seagoing motor and sailing yachts with a length L ≥ 24m intended for private, recreational use. They can be found in Part 3 of *Rules for Classification and Construction – Ship Technology*. GL states that these Rules for Special Craft were developed assuming that, contrary to merchant ships, the following aspects will apply:

- Less severe operating conditions than for ships in regular trade
- Limited yearly sea hours in relation to harbour hours
- Special care by the owner and usually good maintenance

Section 1 of the Rules is about general requirements. All the information about hull structures can be found in Section 2. Within this section there are two categories of yachts that are considered. These are motor and sailing yachts with a length between 24 and 48m and yachts larger than 48m in length. Part A of Section 2 states the general definitions for the principle dimensions and structural details. Part B considers materials, corrosion protection and joining technology, however all the materials used must be in accordance with the *GL Rules II – Materials and Welding Part 1-3*. Design principles are found in Part C of Section 2, where a list of general criteria for hull structural elements made from metallic materials as well as indications concerning structural details are provided. Parts D, E, and F consider motor and sailing yachts between 24m and 48m in length built in steel and aluminium, composite materials and wood respectively. Generally the layout of the various parts is the same. Design loads for all three types of materials are defined as a function of a vessels speed. Minimum plating thickness of hull, decks, superstructures, bulkheads and tanks is calculated by a formula containing design pressure, allowable stress of the material, dimension parameters and a correction factor for curved panels. Also, for steel and aluminium, an additional corrosion allowance is considered. The formula for the minimum section modulus contains the usual parameters such as stiffener spacing and span, design pressure and allowable stress. Pillar scantling and buckling verification is considered separately in a dedicated chapter. Lastly, Part G deals with steel and aluminium motor and sailing yachts with lengths greater than 48m in length.

3. SUPERSTRUCTURE RULES

As mentioned in the beginning the superstructure of yacht is a very complicated subject. There is a trend where owners and their designers want big open spaces, large windows, Jacuzzis on upper decks, increased headroom, luxurious furnishing, etc. This however has huge implications on the structural design of the superstructure as it has to withstand a great amount of load with a limited amount of space for the supporting structures. Various studies and improvements have been suggested by the different Classification Societies, however each one has its own theory behind it. In the following sections, the main ideas and procedures will be discussed and compared for three Classification Societies, RINA, LR and ABS. Each section will be broken down in the same way, first assessing the plate thickness and then the section moduli of the reinforced stiffening members.

The structure is composed of two types of aluminium alloy, 5083 H321 for the plates and 6082 T6 for all stiffening members

Table 2 - Material Characteristics

Alloy	Minimum guaranteed yield stress for welded construction [N/mm^2]	Minimum guaranteed shear stress [N/mm^2]
5083 (plates)	125	72
6082 (sections)	250	144

The Rules state that a value of 250 N/mm^2 may be used in non-heat affected zones and where there are no welds.

3.1. RINA

The superstructure rules issued by RINA for each type of material, steel, aluminium and FRP are well summarised and can all be found in Section 11 of the corresponding material chapter. Paragraph 1.1.1 of the RINA Rules for the Classification of Pleasure Yachts defines the superstructure as follows:

"First tier superstructures or deckhouses are intended as those situated on the uppermost exposed continuous deck of the yacht, second tier superstructures or deckhouses are those above, and so on."

3.1.1. Plating thickness

The thickness of the boundary bulkhead plating and superstructure deck plating are obtained by the same formula. The minimum calculated thickness must not be less than.

$$t = 3.9 \times s \times \sqrt{K \times h}\ [mm] \tag{1}$$

Where s, K and h are defined as:

- s: stiffener spacing in mm
- K: material factor equal to $K = \frac{110}{(\eta \times R_{p0.2})}$, where η is the joint coefficient for the welded assembly and $R_{p0.2}$ is the minimum guaranteed yield stress in N/mm^2
- h: conventional scantling height in mm, to be taken from the table below

Table 3 - Scantling height h

Type of Bulkhead	Scantling height h [m]
1st tier front	1.5
2nd tier front	1.0
Other bulkheads wherever situated	1.0

However the minimum thicknesses obtained previously must not be less than the values below.

Table 4 - Minimum Plate Thicknesses

Member	Minimum thickness [mm]
Superstructure bulkhead	$t = 1.75 \times L^{1/3} \times K^{0.5}$
Deck plating	$t = 1.50 \times L^{1/3} \times K^{0.5}$

3.1.2. Stiffening section modulus

The superstructure reinforced beams (beams, stringers and pillars) must be dimensioned as stated in Section 9 of the corresponding material chapter (in our case Ch. 3 Sec. 9 Decks). The section modulus must not be less than the value Z, in cm^3, calculated with the following formula:

$$Z = 9 \times b \times S^2 \times K \times h\ [cm^3] \tag{2}$$

Where b and S are defined as:

- b: average width of the strip of deck resting on the beam, in m
- S: conventional span of the reinforced beam, equal to the distance between two supporting members, in m

3.2. LR

Lloyds Register defines a superstructure as follows:

> *"A decked structure on the freeboard deck, extending from side to side of the craft, or with the side plating being less than four per cent of the breadth, B, inboard of the shell plating."*

The standard height of the superstructure for yacht of 75m or less in overall length is to be taken as 1.8m.

3.2.1. Plating thickness

The requirements for the thickness of plating, t_p, is to be in accordance with the following formula:

$$t_p = 22.4 s \gamma \beta \sqrt{\frac{p}{f_\sigma \sigma_a}} \times 10^{-3} \; [mm] \quad (3)$$

Where:

- s: stiffener spacing, in mm
- γ: convex curvature correction factor
- β: panel aspect ratio correction factor
- p: design pressure, in kN/mm^2
- f_σ: limiting bending stress coefficient for the plating element under construction
- σ_a: guaranteed minimum 0.2 per cent proof stress of the alloy in welded condition, in N/mm^2 = 125 N/mm^2

However the minimum thicknesses obtained previously must not be less than the values below.

Table 5 - Minimum Plate Thicknesses

Member	Minimum thickness [mm]
Strength/Main deck plating	$t_{min} = \omega\sqrt{k_m}(0.5\sqrt{L_R} + 1.4) \geq 3.5\omega$
Inside deckhouse	$t_{min} = \omega\sqrt{k_m}(0.3\sqrt{L_R} + 1.3) \geq 3.0\omega$
Superstructure and side plating	$t_{min} = \omega\sqrt{k_m}(0.4\sqrt{L_R} + 1.1) \geq 3.0\omega$

Where:

- ω: service type correction factor → for yachts ω = 1.0
- k_m: 385/(σ_A + σ_U)
- σ_A: specified minimum yield stress (= 125 N/mm^2)
- σ_U: specified minimum ultimate tensile strength of the alloy (= 260 N/mm^2)
- L_R: Rule length, is the distance in metres, on the summer load waterline from the forward side of the stern to the after side of the rudder post or to the centre of the rudder stock if there is no rudder post. L_R is not to be less than 96 per cent, and need to be greater than 97 per cent, of the extreme length on the summer load waterline. In craft without rudders, the Rule length, L_R, is to be taken as 97 per cent of the extreme length on the summer load waterline.

3.2.2. Stiffening section modulus

The Rule requirements for section modulus, inertia and web area for lower deck/inside deckhouse stiffening are to be determined from the general equations using the design pressure head from Pt. 5, Ch. 4, Sec. 3.1 and the coefficients Φ_Z, Φ_I, Φ_A.

Section modulus Z:

$$Z = \Phi_Z \frac{psl_e^2}{f_\sigma \sigma_a} \; [cm^3] \tag{4}$$

Where:

- Φ_Z: section modulus coefficient dependent on the loading model assumption
- f_σ: limiting bending stress coefficient for stiffening member
- p: design pressure in kN/m^2,
- s: stiffener spacing, in mm
- l_e: effective span length, in metres,
- σ_a: guaranteed minimum 0.2 per cent proof stress of the alloy, in the welded condition, in N/mm^2; here equal to 125 N/mm^2

3.2.3. Loads

Differently to RINA rules, to calculate the section modulus and plate thickness with LR one must first calculate two pressures, the pressure on the weather deck P_{wh} and the pressures for the plating of deckhouses, bulwarks and first tier and above superstructures P_{dhp}.

The pressure acting on the weather decks, is to be taken as

$$P_{wh} = f_L(6 + 0.01L_{WL})(1 + 0.05\Gamma) + E \; [kN/m^2] \tag{5}$$

Where f_L, E, D, T, Γ are defined as:

- f_L: location factor for weather decks

= 1.0 from aft end to $0.88L_R$

= 1.25 from $0.88L_R$ to $0.925L_R$

= 1.50 from $0.925L_R$ to forward end

= 1.0 for interior decks

$$E = \frac{0.7 + 0.08L_{WL}}{D - T} \quad [kN/m^2] \tag{6}$$

For exposed decks but not to be taken greater than 3 kN/m^2

- E = 0.0 for sheltered decks
- D: depth in metres at the middle of the Rule length, from top of keel to top of the deck beam at side on the uppermost continuous deck
- T: Draught, in metres, is the summer draught measured from top of keel
- Γ : Taylor Quotient

$$\Gamma = \frac{V}{\sqrt{L_{WL}}} \tag{7}$$

Where

- V: allowable speed = design speed
- L_{WL}: Waterline length

The design pressure, P_{dhp}, for the plating of deckhouses, bulwarks and first tier and above superstructures is given by:

$$P_{dhp} = C_1 \times P_d \; [kN/m^2] \tag{8}$$

C_1 = 1.25 for deckhouse and superstructure fronts on upper deck within the forward third of L_R

= 1.15 for deckhouse and superstructure fronts on the upper deck outside the forward third of L_R and exposed machinery casings on the upper deck

= 1.0 for deckhouse and superstructure fronts above the lowest tier

= 0.8 for superstructure sides

= 0.5 elsewhere

$P_d = P_{wh}$

3.3. ABS

The definition of a superstructure according to ABS is

> *"An enclosed structure on the main weather deck having side plating as an extension of the shell plating, or fitted inboard of the hull side not more than 4% of the breadth B."*

3.3.1. Plating thickness

Rule 9A.1.2 from ABS Guide for Building and Classing Motor Pleasure Yachts states that the thickness of the shell, deck or bulkhead plating is not to be less than:

$$t = s\sqrt{\frac{pk}{1000\sigma_a}}\ [mm] \qquad (9)$$

Where:

- s: spacing, in mm, of the shell, deck, superstructure, deckhouse or bulkhead longitudinals or stiffeners.
- p: design pressure, in kN/m^2
- k: plate panel aspect ratio factor, → k=0.5
- σ_a: design stress, in N/mm^2

The thickness of all plating is to be not less than the value obtained from the table below:

Table 6 - Minimum Plate Thicknesses

Member	Minimum thickness [mm]
All plating	$t_{al} = 0.012s$ mm

s = stiffener spacing, in mm

As can be noted, when using ABS rules to calculate the thickness of a plate, it is first necessary to obtain a design pressure. This is done by using the formulas found in table 8.

3.3.2. Stiffening section modulus

As with LR Rules, also ABS requires to use a previously defined design pressure in order to obtain the minimum section modulus SM.

$$SM = \frac{83.3 \times psl^2}{\sigma_a}\ [cm^3] \qquad (10)$$

Where:

- p: design pressure, in kN/m^2
- s: spacing, in m, of the longitudinal, stiffener, transverse web or girder, etc.
- l: length, in m, of the longitudinal, stiffener, transverse web or girder, between supports
- σ_a: design stress, in N/mm^2

Table 7 - Design stress σ_a

Members	Design Stress σ_a
Shell	0.70 σ_γ
Stiffener	0.70 σ_γ

σ_γ: yield stress of unwelded aluminium = 250 N/mm^2

3.3.3. Loads

The values of the design pressures depend on the area of interest. The obtained values can then be used to calculate the plate thicknesses and section moduli of the various stiffening members.

Table 8 - Deck Design Pressures

Location	Design Pressure P_d [kN/m^2]
Exposed Main Weather Deck and Superstructure deck for 0.25L from forward	0.2L+4.5
Exposed Superstructure deck elsewhere and internal decks	0.10L+4.5

3.4. Summary

Although the formulas may seem different all three Classification Societies use similar approaches. The only major difference is the fact that RINA does not require you to calculate a design pressure beforehand in order to determine the scantling of the superstructure.

4. CASE STUDY – 45 m MOTOR YACHT – RULES

The essence of this chapter will be to use the above listed formulas of each Classification Society in order to determine the minimum requirements which will then be compared with traditional beam theory scantling calculation process. But first here is a reminder of the semi-custom yacht that will be assessed.

4.1. General Characteristics

Table 9 - General Parameters

Length Overall	**45.14m**
Breadth Overall	9.10m
Waterline Length	37.21m
Depth	4.45m
Draught	2.40m
Design Speed	14.50 kn
Displacement	445t

The construction materials of the yacht are steel for the hull and aluminium alloys for the superstructure which in turn is connected to the main deck with bimetallic joints.

The main aspects of the layout of the yacht are six en-suite guest cabins, three twin crew cabins, captain's cabin, two saloons, two external dining and seating areas as well as a whirlpool on the sundeck.

4.2. Superstructure Scantling

The structural layout that is to be assessed is presented in the following images. It was decided to compare all six transverse supporting beams. Figure 4 shows where those beams are located.

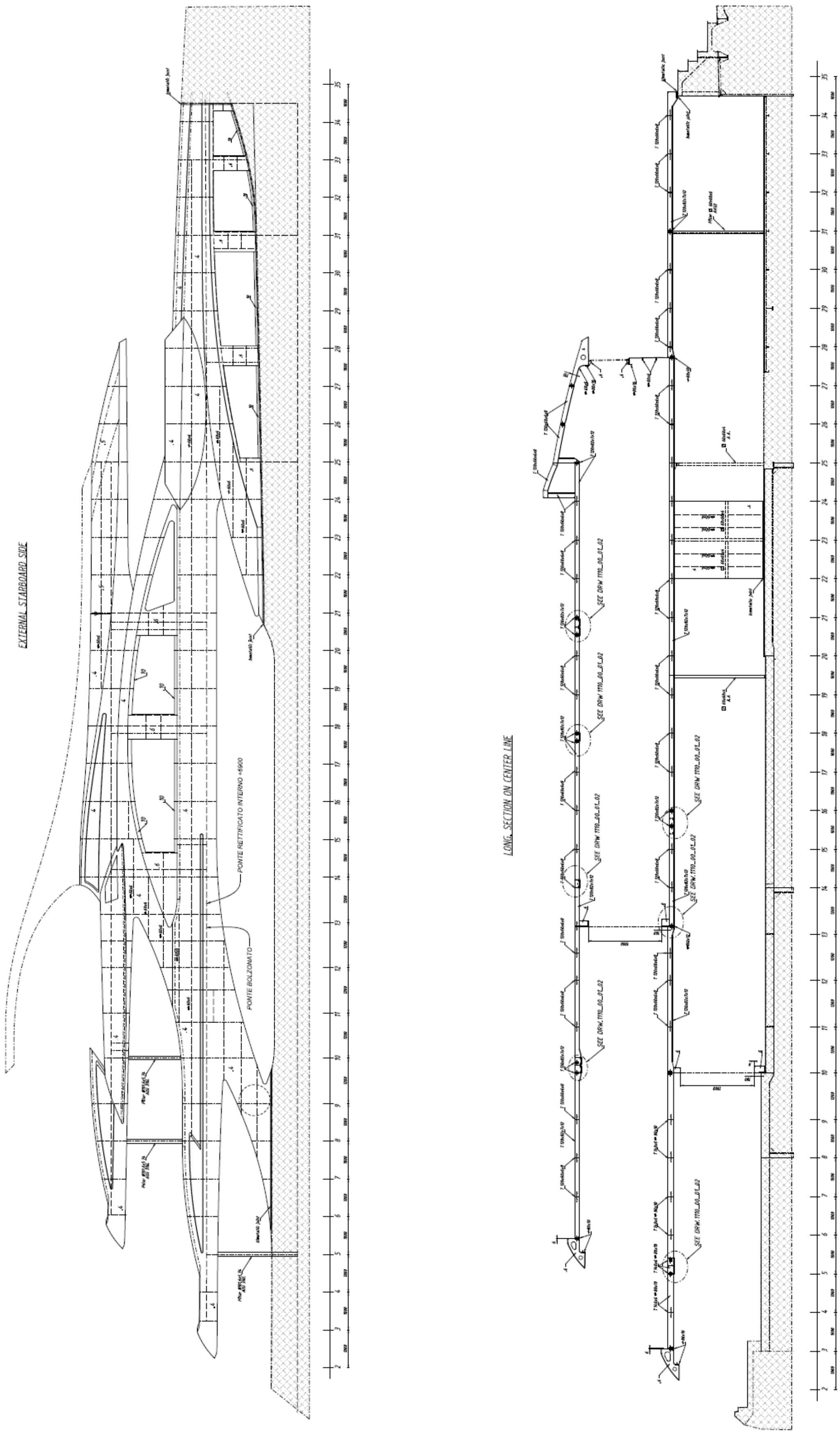


Figure 3 - Superstructure Scantling - Longitudinal Sections (courtesy of Azimut-Benetti spa)

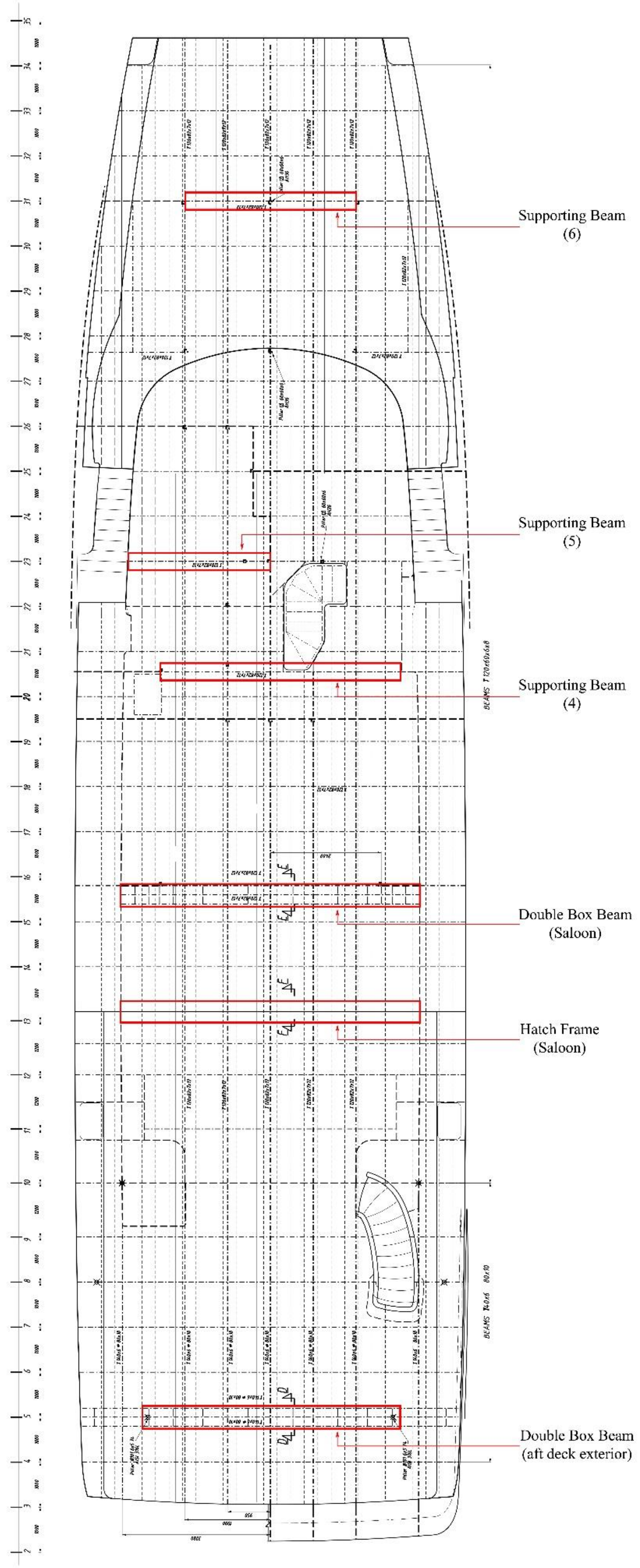


Figure 4 - Superstructure Scantling - Plan view (courtesy of Azimut-Benetti spa)

4.3. Scantling Calculation

In the following sections only the obtained values will be presented. All computation values can be found in the appendix.

4.3.1. Plate thickness

Table 10 - Minimum plate thickness

Component	RINA	LR	ABS	*Yacht*
		Dedicated formula		*4 mm*
Superstructure deck plating	1.10 mm	1.85-2.44 mm	1.80-2.21 mm	
		Minimum allowed		
Superstructure deck plating	4.70 mm	4.45 mm	3.6 mm	

What must be noted is that when determining the thickness of the plates with RINA, LR and ABS, the values that were obtained with the dedicated formulas were always below the minimum required equations.

Interestingly both RINA and LR values are higher than the actual thickness of the plates of the semi-custom yacht. There are two possible explanations to this. Firstly, it was not able to find the exact material characteristics of the actual material that was used for the deck plate, which was a *Hydro Aluminium HMA0286* alloy. Secondly, regarding RINA, there is a type error in their Rules. In Section 11 of Part B Chapter 3, when it is advised that the minimum thickness must not be less than the values given in Section 1, they mistakenly refer you to Chapter 2 instead of Chapter 3. Chapter 2 is intended for steel structures, while Chapter 3 is for aluminium structures. Not surprisingly, when calculating the minimum allowed thickness with the formula the Rules refer you to, the resulting thickness is equal to 3.60mm, which is below the actual deck plate thickness currently on the yacht.

4.3.1. *Calculation of the effective breadth b_e*

To determine the geometric characteristics of the section of the stiffened panel it is necessary to know the effective breadth, b_e of the strip of the plate that collaborates with the beam. Therefore a simplification is done where a strip of plate with the breadth b_e is considered in a way where the stress can be assumed constant along that breadth. In other words, the resulting product of the effective breadth and the maximum stress σ_{max} must be equal to the total stress acting on the length B of that plate according to the following relation:

$$\int_{-B/2}^{B/2} \sigma dz = \lambda \sigma_{max} \tag{11}$$

The effective breadth depends from the following factors:

- Span of the reinforcement L
- Stiffener spacing B
- Type of load (concentrated or distributed)
- Boundary condition (simply supported or clamped)

To determine this in an analytical way is a very complex process. Therefore simplified equations have been proposed by Schade for simply supported and clamped conditions.

$$\frac{b_e}{B} = \frac{1.1}{1 + \frac{2}{(L/B)^2}} \tag{12}$$

and

$$\frac{b_e}{B} = \frac{1.1}{1 + \frac{2}{(0.6L/B)^2}} \tag{13}$$

To calculate the effective breadth of the plates the clamped condition was chosen as the scantling analysis was to be done on supporting transverse beams.

4.3.2. Manual calculation of Inertia and Section Modulus

In order to compare the section moduli values obtained with the Rules it was necessary to perform a manual calculation of the six beams so that it would be possible to evaluate the results. Below is an example of how the procedure was done.

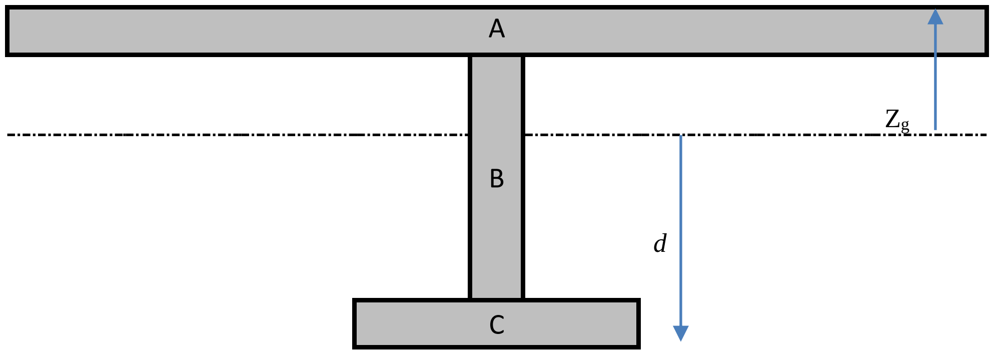


Figure 5 - Example of a stiffened plate

It is always necessary to calculate two section moduli which are at both areas furthest away from the neutral axis. Therefore to obtain them it is necessary to calculate both the distance of the plate and flange from the neutral axis. To calculate the section moduli, the following formula applies:

$$Z = \frac{I}{d}\ [cm^3] \tag{14}$$

Where *I* is the total moment of inertia and *d* is the distance from the neutral axis to the flange.

Therefore the moment of inertia I_o of each rectangle must first be obtained:

$$I_o = \frac{a_i b_i^3}{12}\ [mm^4] \tag{15}$$

Where a_i is the breadth and b_i is the height of the rectangle.

The area of a rectangle is:

$$A_i = a_i \times b_i\ [mm^2] \tag{16}$$

Once the area of the rectangle is known, it is then possible to calculate the static moment of that element by multiplying the area with the height of the element's neutral horizontal axis d_i.

$$S_i = A_i \times d_i \ [mm^3] \tag{17}$$

Now the neutral axis of the entire section Z_g can be found by dividing the total static moment, S, by the total area, A.

$$Z_g = \frac{S}{A} \ [mm] \tag{18}$$

In order to calculate the second moment of area J_i the distance d_i' from the neutral axis has to be found for each component. The second moment of area is necessary to calculate the final total inertia I of the entire stiffened plate.

$$d_i' = Z_g - d_i \ [mm] \tag{19}$$

$$J_i = A_i \times d'^2_i \ [mm^4] \tag{20}$$

The final moment of inertia I is simply a sum of all moments of inertia of the components, I_t, and all the second moments of area, J_t.

$$I = I_t + J_t \ [mm^4] \tag{21}$$

Now the distance d from the neutral axis can be found by subtracting the total height h of the stiffened plate with the neutral axis Z_g.

$$d = h - Z_g \ [mm] \tag{22}$$

Finally the section moduli can be obtained.

4.3.3. Double Box Beam Aft Exterior Deck

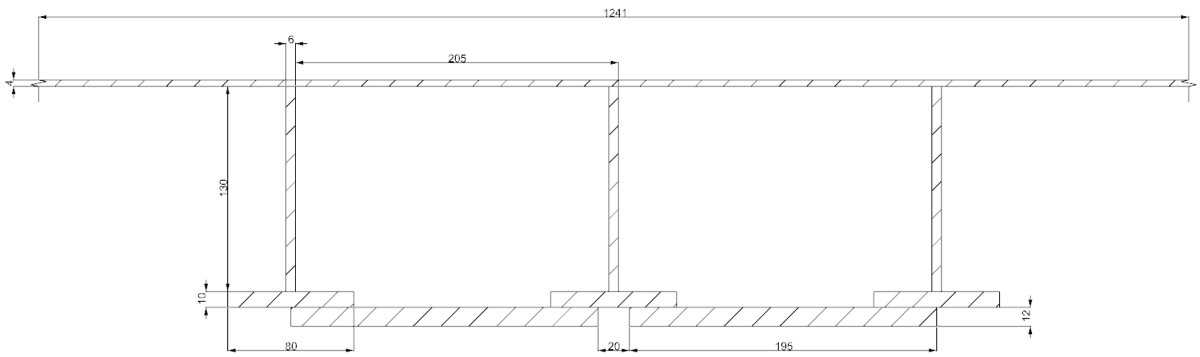


Table 11 - Section modulus of double box beam aft exterior deck

Minimum required			*Actual minimum SM*
RINA	**LR**	**ABS**	
833 cm^3	1069 cm^3	1002 cm^3	*774 cm^3*

4.3.4. Hatch Frame

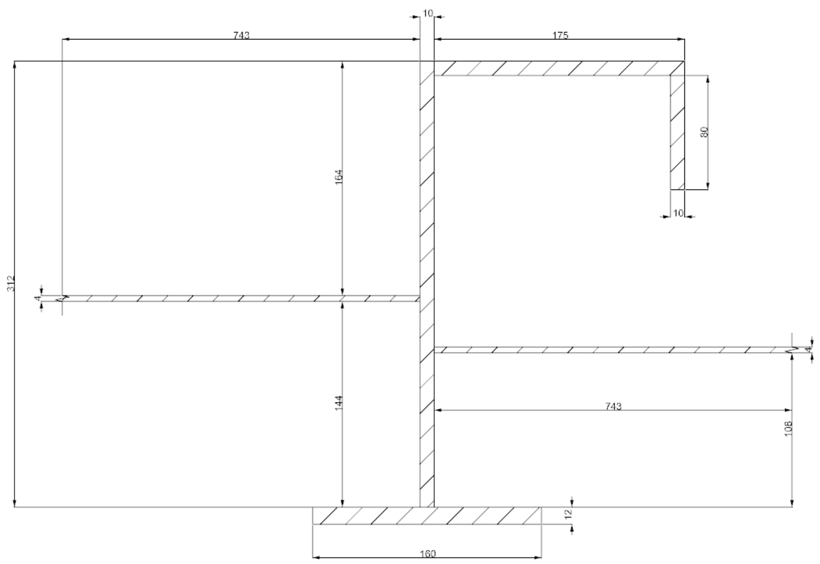


Table 12 - Section modulus of hatch frame

Minimum required			*Actual minimum SM*
RINA	**LR**	**ABS**	
988 cm^3	1013 cm^3	1189 cm^3	*755 cm^3*

4.3.5. *Double Box Beam Saloon*

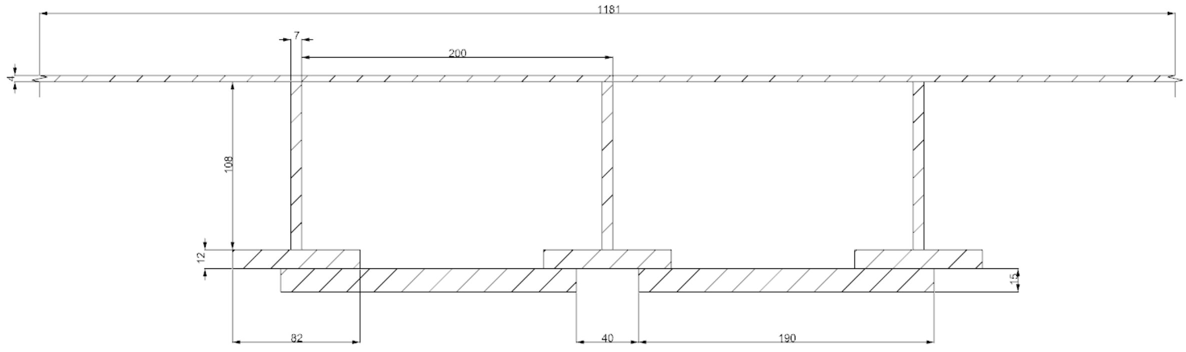


Table 13 - Section modulus of double box beam saloon

Minimum required			*Actual minimum SM*
RINA	**LR**	**ABS**	
671 cm^3	688 cm^3	807 cm^3	*651 cm^3*

4.3.6. *Beam 4*

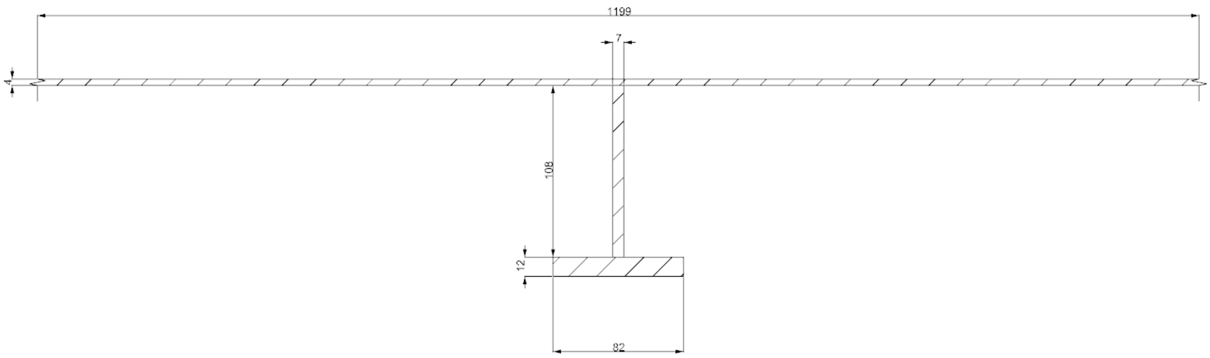


Table 14 - Section modulus of beam 4

Minimum required			*Actual minimum SM*
RINA	**LR**	**ABS**	
350 cm^3	359 cm^3	422 cm^3	*129 cm^3*

4.3.7. Beam 5

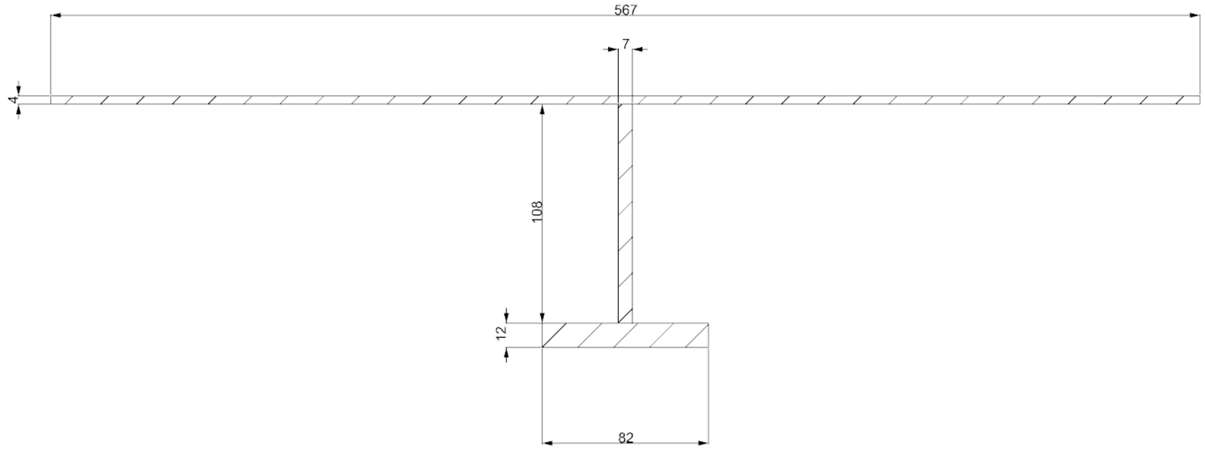


Table 15 - Section modulus of beam 5

Minimum required			*Actual minimum SM*
RINA	**LR**	**ABS**	
186 cm^3	191 cm^3	224 cm^3	*124 cm^3*

4.3.8. Beam 6

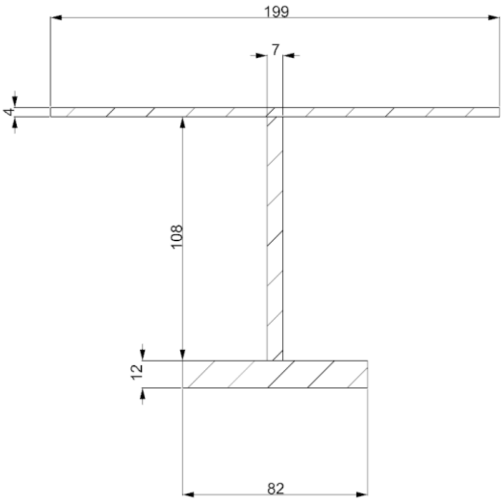


Table 16 - Section modulus of beam 6

Minimum required			*Actual minimum SM*
RINA	**LR**	**ABS**	
87 cm^3	135 cm^3	158 cm^3	*105 cm^3*

4.4. Summary

Table 17 - Minimum stiffening section modules in cm^3 with $\sigma_a = 125$ N/mm^2

Component	Minimum required			*Actual minimum SM*
	RINA	LR	ABS	
Double Box Beam aft	833	1069	1002	*774*
Hatch frame saloon	988	1013	1189	*755*
Double Box Beam saloon	671	688	807	*651*
Beam 4	350	359	422	*129*
Beam 5	186	191	224	*124*
Beam 6	87	135	158	*105*

Since all stiffening members apart from one failed to comply with any of the Rules a second comparison was down using a higher σ_a of 250 N/mm^2 because the stiffening members are made from a different aluminium alloy. The reason for this was to investigate to what extent this new value would have on the minimum section modulus. As can be seen from the table below, the effect is substantial.

Table 18 - Minimum stiffening section modules in cm^3 with $\sigma_a = 250$ N/mm^2

Component	Minimum required			*Actual minimum SM*
	RINA	LR	ABS	
Double Box Beam aft	416	534	501	*774*
Hatch frame saloon	494	507	595	*755*
Double Box Beam Saloon	355	344	404	*651*
Beam 4	175	180	211	*129*
Beam 5	93	96	112	*124*
Beam 6	44	67	79	*105*

Now all components apart from Beam 4 meet the required minimum section modulus.

5. CASE STUDY – 45 m MOTOR YACHT – FEM

5.1. Introduction to Finite Element Method

The finite element method has been developed to solve problems numerically by computing algebraic equations with the help of solvers. This is done by discretising a continuous system. Structures are divided into a certain amount of elements (usually it is advised to have 2-3 elements across the shortest side of an *element* to obtain a more accurate result) which are connected to each other by so called *nodes*. This procedure is called *meshing*. Within the nodes three principles of the structural analysis must be verified:

- Equilibrium of the applied external forces and calculated internal stresses
- Congruency between shifts and deformations
- Link between stresses and deformation due to the behaviour of the material

If these principles were only to be applied onto the nodes, the model would deform much more than in reality, due to the fact that gaps or penetrations could occur along the borders of the single elements. Thus *shape functions* are defined that allow each single element to deform with a precise configuration. These functions vary according to the structural entity that is used to discretise the model, which depend on the nodes of each element, the degrees of freedom of each node and can be defined by the user.

The main steps for a finite element method analysis are the following:

- Modelling and discretisation of the structure (*meshing*)
- Defining the properties of the various elements
- Stiffness matrix assembly
- Boundary conditions and load application
- Solving of linear algebraic equations
- Stress and deformation calculation of the various elements depending on the link relation of the material

It must be noted how only steps three and five from the above list do not require any input from the user. This shows how the correctness of the results are heavily based on the experience and technical knowledge of the structural engineer.

The type and extent of the analysis mainly depends on what kind of structural response is to be evaluated. These are:

- Stresses and deformation for specified load conditions
- Failure behaviour and magnitude of the ultimate load
- Eigenvalues to determine the critical structural responses

The loads usually comprise of external forces and pressures, dead weight forces and accelerated masses. The structural response depends on the loading magnitude in a linear and nonlinear manner. Given the fact that for this analysis only specified loads were considered a linear analysis was sufficient.

The structural conditions on which the stresses and deformations of ship structures depend on are the following:

- Global deformations and stresses of the hull girder and primary structural components
- Local deformations and stresses of the primary and secondary structural components
- Locally increased stresses at structural details

For the analysis of this model, only local deformations and stresses of the primary and secondary reinforcements were of interest.

The solver that was used for the FEM of this thesis is *MSC Nastran*, which is one of the oldest and most globally diffused solvers due to its versatility and stability even with a large number of nodes. As a pre (modelling and meshing) and post processor (result analysis) *MSC Patran* was used.

5.2. Procedure

5.2.1. Defeaturing

Due to the complexity of the structure, simplifying the model is necessary. Instead of modelling the entire geometry in Patran, it was advised to begin by defeaturing an already existing 3D model of the superstructure in Rhino in order to facilitate the meshing procedure. To obtain a regular mesh it is critical to have simple geometry, with no fillets or small highly curved surfaces, and surface edges that align with one another.

Needless to say this process was a very laborious one. The original model was created with *solids*, meaning that the first step to be done was to recreate all the elements with just one surface. At this point it was vital to understand which face of the solid should be used, interior, exterior or middle face. Regardless on which the choice fell upon it still required to make sure that all elements were connected to each other, i.e. no gaps or misalignments.

The next step was to simplify the individual elements as much as possible, thus removing all trimmed surfaces and converting them to rectangles and parallelograms, remove fillets, and small cut outs. (To simplify the meshing of components, the curves of larger cut outs were imported into Patran and then used as stencils to remove any elements and nodes within that area).

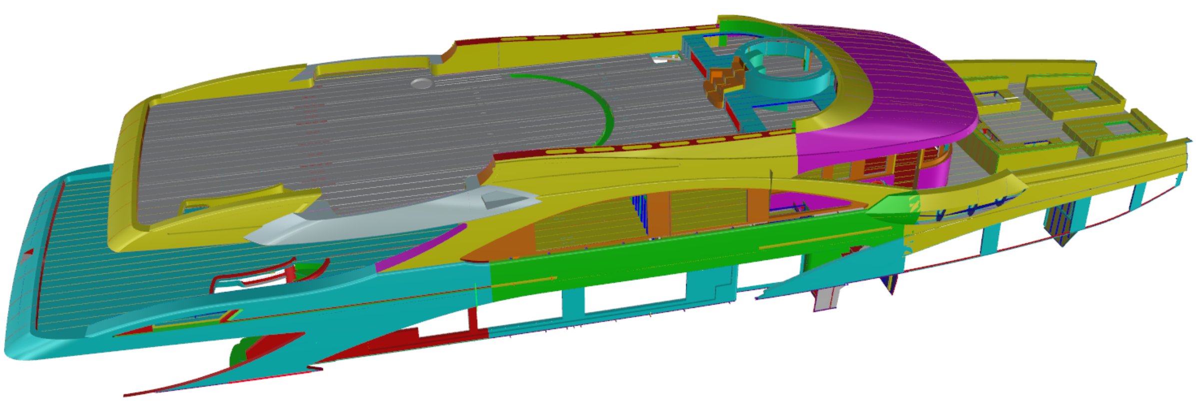


Figure 6 - Original 3D model

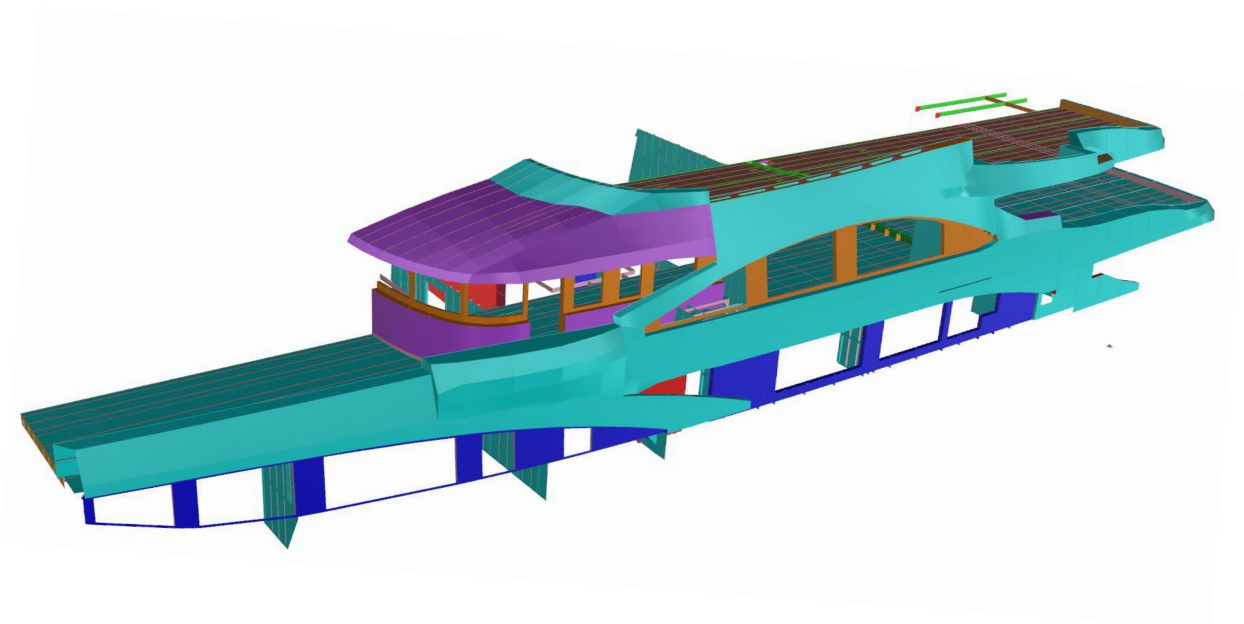


Figure 7 - Defeatured model of the 1st and 2nd tier superstructure

Another simplification was to use the symmetry of the model, meaning that for all components, apart from the aft trunks and interior bulkheads and their reinforcements, only one half of the superstructure needed to be defeatured and subsequently imported into Patran.

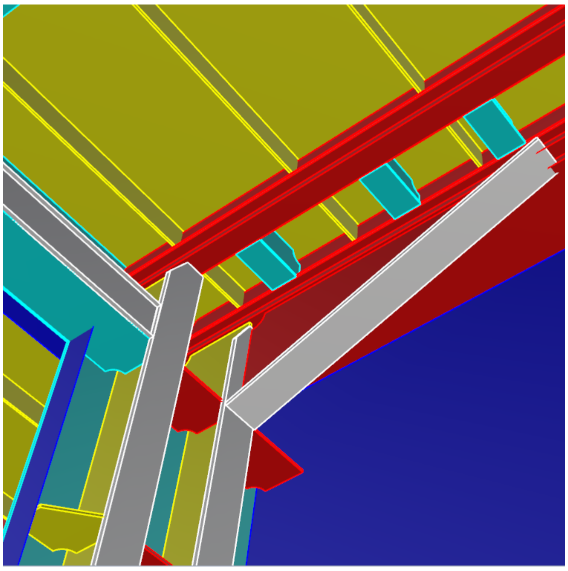


Figure 8 - Detail showing thickness of the elements

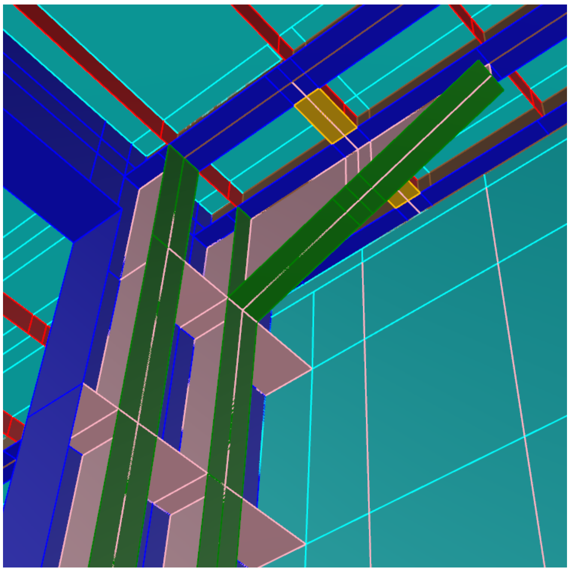


Figure 9 - Detail showing defeatured elements

At this stage it is important to keep in mind that due to this simplification procedure the local stresses are falsified (e.g. sharp edges and corners have much higher tensions).

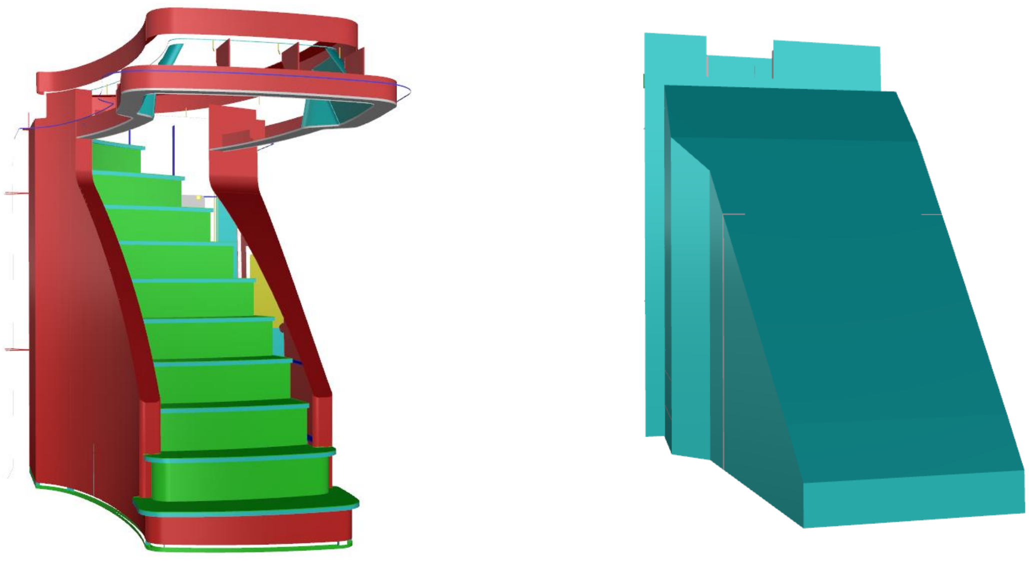


Figure 10 – Original and Simplified aft stairs

Since we were not interested in local stresss and the stairs were not considered a supporting structural component it was possible to strongly simplify them. The importance of this area is to know if it is strong enough globally.

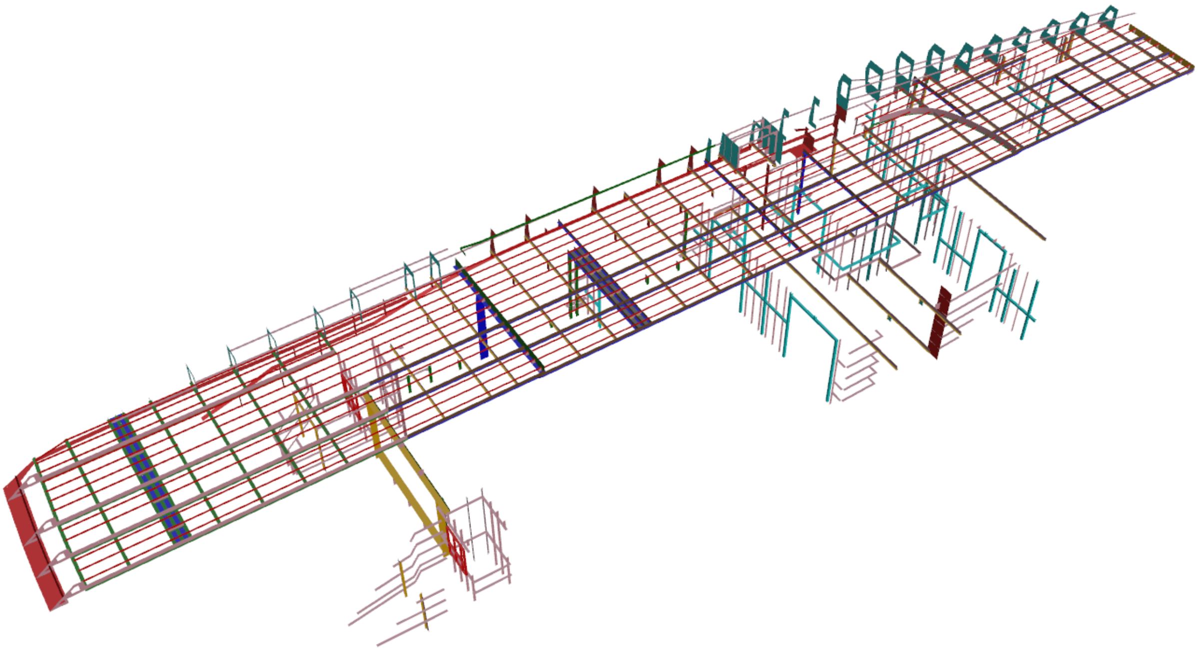


Figure 11 - 1st tier Superstructure

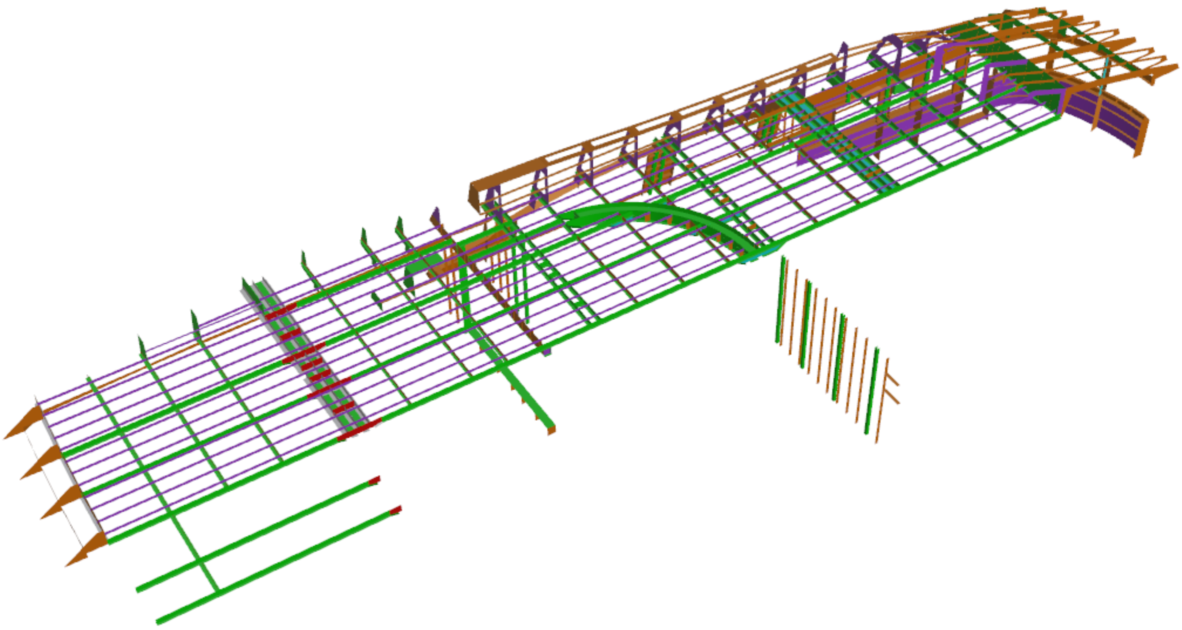


Figure 12 - 2nd tier Superstructure

During the process, apart from simplifying all the surfaces, new elements had to be modelled as they were missing in the original. An example was the whole aft exterior deck beam and girder structure, where the details were taken from the provided structural drawings.

During this process it was discussed if it was necessary to incorporate the large windows situated on the two decks. It was decided to leave them out since, from a global point of view, the glass should not be considered as contributing to the structural strength, (i.e. the structure itself must be able to withstand the load without the glass). However if local stresses and tensions are required then it is necessary to model the glass panels.

5.2.2. Meshing

The meshing fineness was chosen considering the characteristics of the elements in such a way that the stiffness conditions of the structure and the types of stresses that were to be analysed were modelled with sufficient accuracy. The mesh fineness has a great influence on the calculation of locally increased stresses and also of the ultimate load. Thus, if the mesh of a structure is coarse the local stress peaks are considerably underestimated resulting in an overestimated ultimate load.

In this case it was decided to try and have a minimum of 2-3 elements (on the shortest edge) per item, meaning that the smallest areas (e.g. junction of two beams) would have an element size of around 30mm x 30mm. This size gradually increases according to the members and reaches a maximum size of around 100mm x 100mm on the plating of the sides, bulwarks and decks.

Table 19 - Element size

Member	Element size in mm
Beam junction	30 x 30
Stiffeners	30 x 100
Plates	100 x 100

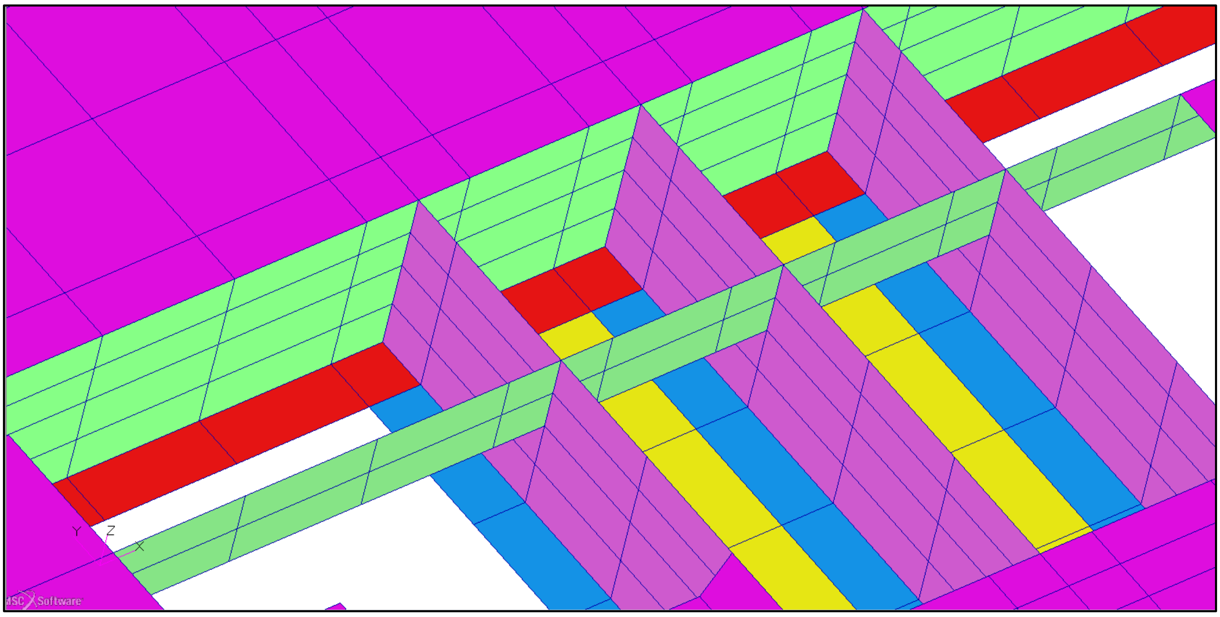


Figure 13 - Example of varying mesh size from beam junction to deck plates

When meshing, particular attention had to be kept on the various characteristics of the *quad* and *tria* elements such as the aspect ratio, warp and skew angle, and taper.

Table 20 - Patran default tria and quad parameters

Element		Value
Tria	Aspect ratio	Maximum 5
	Skew angle	Minimum 10°
Quad	Aspect ratio	Maximum 5
	Warp	Maximum 3°
	Skew angle	Maximum 30°
	Taper ratio	Minimum 0.5

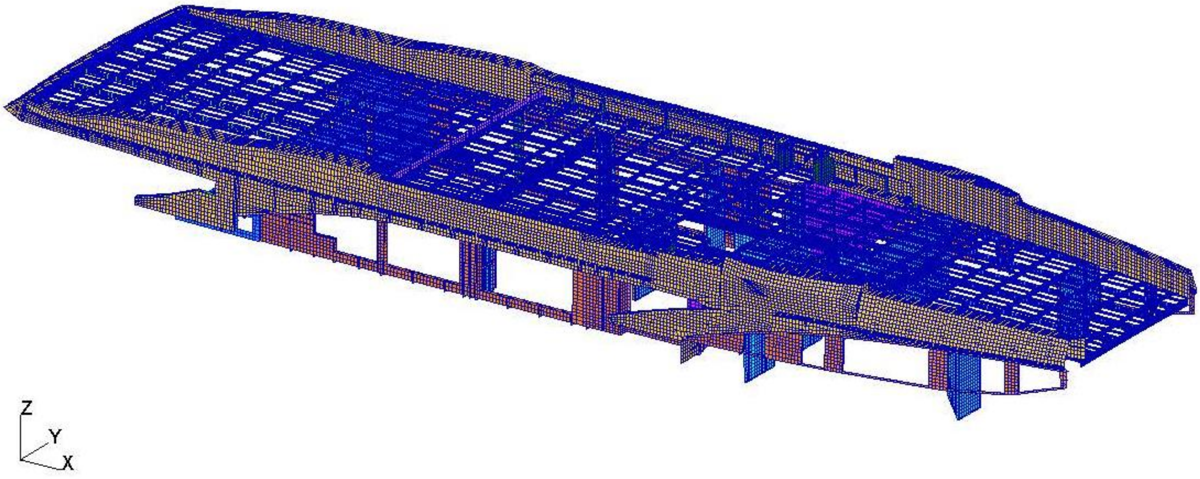


Figure 14 - Complete meshed model

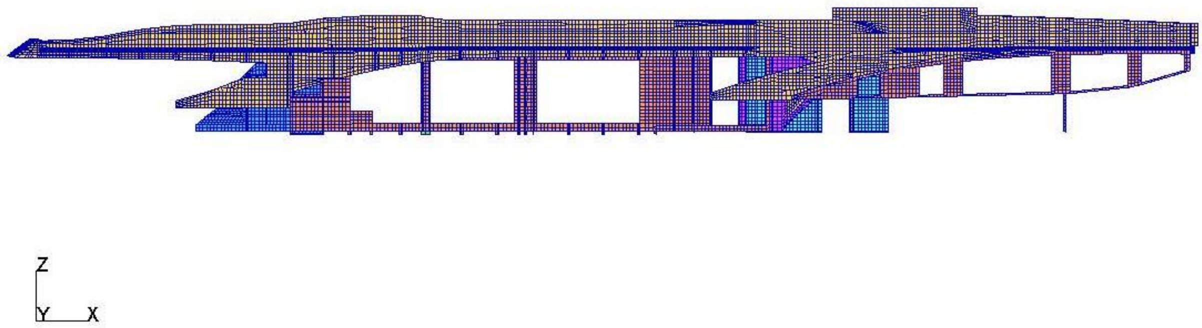


Figure 15 - Complete meshed model

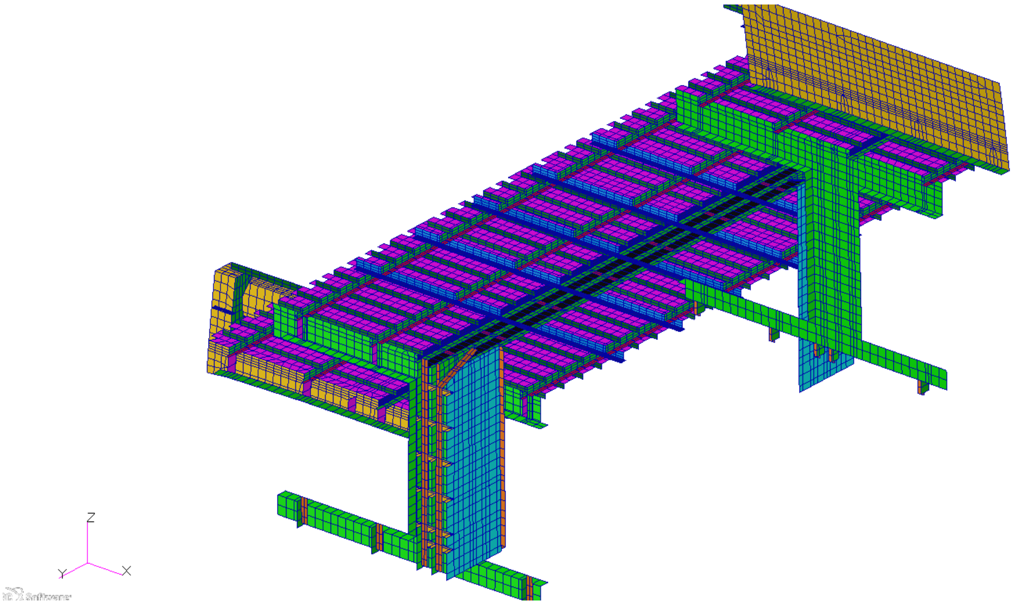


Figure 16 - Interior saloon mesh detail

The final meshed model had a total of 142'277 elements and 135'882 nodes

5.2.3. Properties

Once the model was meshed it was time to assign the material properties to the elements. Two isotropic materials were present in the superstructure: steel pillars and aluminium stiffening components and plates.

Table 21 - Material Properties

Material	Elastic Modulus E	Poisson Ratio ν	Density ρ
	N/mm²		*t/mm³*
Aluminium	70'000	0.33	2.66×10^{-9}
Steel	200'000	0.33	8×10^{-9}

For each element a shell had to be created defining the thickness of that member and plate offset, the value of which depends on the face (interior, middle or exterior) of the element and orientation of the normals.

Table 22 - Shell properties

Set Name	Thickness in mm	Plate Offset
alu_int_4mm	4	-2
alu_int_5mm	5	-2.5
alu_int_6mm	6	-3
alu_int_8mm	8	-4
alu_int_10mm	10	-5
alu_int_12mm	12	-6
alu_int_15mm	15	-7.5
alu_mid_4mm	4	0
alu_mid_5mm	5	0
alu_mid_6mm	6	0
alu_mid_7mm	7	0
alu_mid_10mm	10	0
alu_ext_4mm	4	2

5.3. Load Cases

Once the FEM model was ready, the time came to define the various pressures, forces and boundary conditions acting on the structure. All nodes on structures welded to the main deck and hull (such as side plates, pillars, bulkheads, trunks as well as certain webs and flanges) where considered clamped.

Various load cases were defined in order to evaluate the behaviour of the whole superstructure in different conditions. The first load case regarded an equally distributed deck pressure.

The following load cases were set:

- **Load case 1 – RINA Deck Pressure**

The load on the deck is assumed uniformly distributed with a mass density of 0.7 t/m^3 and a consequent load per square metre of deck, in kN/m^2, equal to 6.9h_d.

From RINA Rules for Pleasure Yachts Part B Chapter 1 Section 5.5.1 h_d is equal to 0.9 as the deck that is being analysed is located above the design deck.

➔ 0.9 x 6.9 kN/m^2= 6.21 kN/m^2

- **Load case 2 – RINA Side Pressure**

The side pressure was defined as 9.8 kN/m^2

- **Load case 3a**

The next three cases consist of local (real) loads placed in defined areas on the deck and distributed pressure due to the aluminium weight of the superstructure and outfitting.

The various loads and pressures were defined as follows.

- Distributed load of outfitting of the deck
  - ➔ 350 kg/m^2
- Total aluminium weight of the upper deck

For this type of weight an inertial static force was considered, defined through the materials density.

➔ Inertial Force = *m* x *g* (*m:* mass; *g:*gravity acceleration) (23)

- Total weight of the sun deck

Since the sun deck was not in the model, it was decided to take the total weight of that structure and convert it into a force acting on the border where the sun deck is welded onto the upper deck. The total weight of the sun deck is equal to 20.2 tonnes. Therefore,

- 20.2 tonnes x 9.81 m/s^2 x 1000 = 198000 N
- Number of nodes to divide force by is equal to 713
  - ➔ Force per node: 277 N

- Load of 20 people

The areas were chosen in a way that they would not influence each other – in this case the extreme stern and saloon zones were considered

- 20 people x 100 kg x 9.81 m/s^2 = 24525 N
- Concentrated area of the 20 people = 6 m^2
  - ➔ Resulting pressure = 0.004 MPa

- **Load case 3b**

The load conditions are the same as in case 3a, the only difference is the application zone of the 20 people. In this case the dining zone and extreme bow area were considered.

    - 20 people x 100 kg x 9.81 m/s^2 = 24525 N
    - Concentrated area of the 20 people = 6 m^2
        - ➔ Resulting pressure = 0.004 MPa

- **Load case 4**

This is the first dynamic condition case, obtained by considering load case 3a with the application of the vertical acceleration calculated with the formula given by the RINA Rules.

The only load that changed is the load of people, which in this case is six instead of 20.

  - Load of six people:
    - 6 people x 100 kg x 9.81m/s^2 = 5886 N
    - Concentrated area of the 6 people = 1.5 m^2
        - ➔ Resulting pressure = 0.003924 MPa

Since load case 4 was a dynamic condition the various loads as well as the force of the sun deck had to be modified with the vertical acceleration a_{CG} (expressed in g).

$$a_{CG} = S \times \frac{V}{\sqrt{L}} \qquad (24)$$

Where S is given by:

$$S = 0.65 C_F \qquad (25)$$

And C_F is given by:

$$C_F = 0.2 + \left[\frac{0.6}{V/\sqrt{L}}\right] \geq 0.32 \qquad (26)$$

➔ a_{CG} = 0.7 g

- **Load case 5 – Racking**

Racking is a phenomenon that occurs due to a transverse acceleration acting onto a structure. When a yacht rolls the accelerations on its structure cause a distortion in the transverse direction. Decks tend to move laterally while the side shells distort vertically. Apart from inducing elevated stresses on the joints, it also has a significant effect on partition bulkheads which may cause that local structure to collapse.

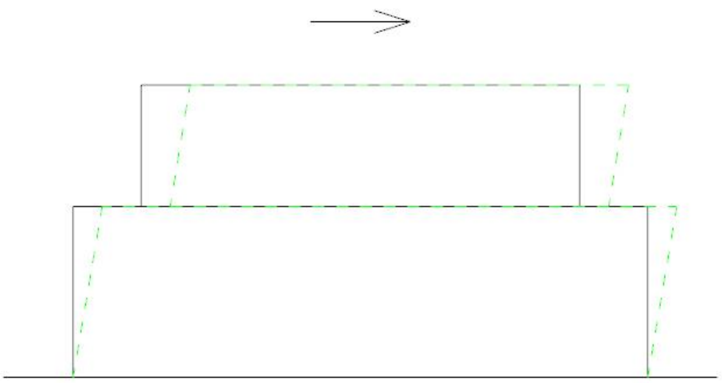


Figure 17 - Racking effect

However the Classification Societies do not set any racking limits that must be met, but rather suggest to use a transverse acceleration, a_t (expressed in g), to be used in direct calculations for yachts with many tiers of superstructure for which significant racking effects are anticipated which is defined either by model tests and full scale-models or calculated. For this Benetti semi-custom yacht, the value of a_t was obtained by the following formula:

$$a_t = 2.5 \times \frac{H_{sl}}{L} \times \left[1 + 5 \times \left(1 + \frac{V/\sqrt{L}}{6}\right)^2 \times \frac{r}{L}\right] \qquad (27)$$

Where H_{sl} and r are defined as:

- H_{sl}: permissible significant wave height, in m, at speed V
- r: distance at the calculation point from 0.5D

➔ a_t for main deck = 2.72g

➔ a_t for upper deck = 3.21g

The following forces were considered (which are the same loads as defined before, expressed in a nodal transverse force).

1) Transverse force of 20 people:
   - 20 people x 100 kg = 2000 kg
     - ➔ Mass per node = 2 kg
     - ➔ Transversal force per node = *m* x a_t = 53.4 N
2) Transverse force of the outfitting:
   - 350 kg/m^2 x 259.3 m^2 = 90755 N
     - ➔ Mass per node = 2.7 kg
     - ➔ Transversal force per node = *m* x a_t = 72.1 N
3) Transverse force of the aluminium weight upper deck (inertial load):
   - Defined as an inertial load
4) Transverse force of the total weight of the Sun Deck:
   - Weight = 20200 kg
   - Number of nodes to divide force by is equal to 713
     - ➔ Mass per node: 28.33 N
     - ➔ Transversal force per node: *m* x a_t = 892.1 kg

Table 23 - Load Case Overview

	Static analysis				Dynamic Analysis	
					vertical acceleration	*transverse acceleration*
	Load Case 1	**Load Case 2**	**Load Case 3a**	**Load Case 3b**	**Load Case 4**	**Load Case 5**
Static weight			x	x	x	x
RINA Pressure Deck	x					
RINA Pressure Side		x				
Distributed Outfitting			x	x	x	x
Sun deck			x	x	x	x
20 people stern zone			x			x
20 people saloon			x			x
20 people dining area aft exterior				x		
20 people seating area bow				x		
6 people stern zone					x	
6 people saloon					x	

5.4. Results

5.4.1. Deformation

5.4.1.1. Load Case 1 – RINA Deck Pressure

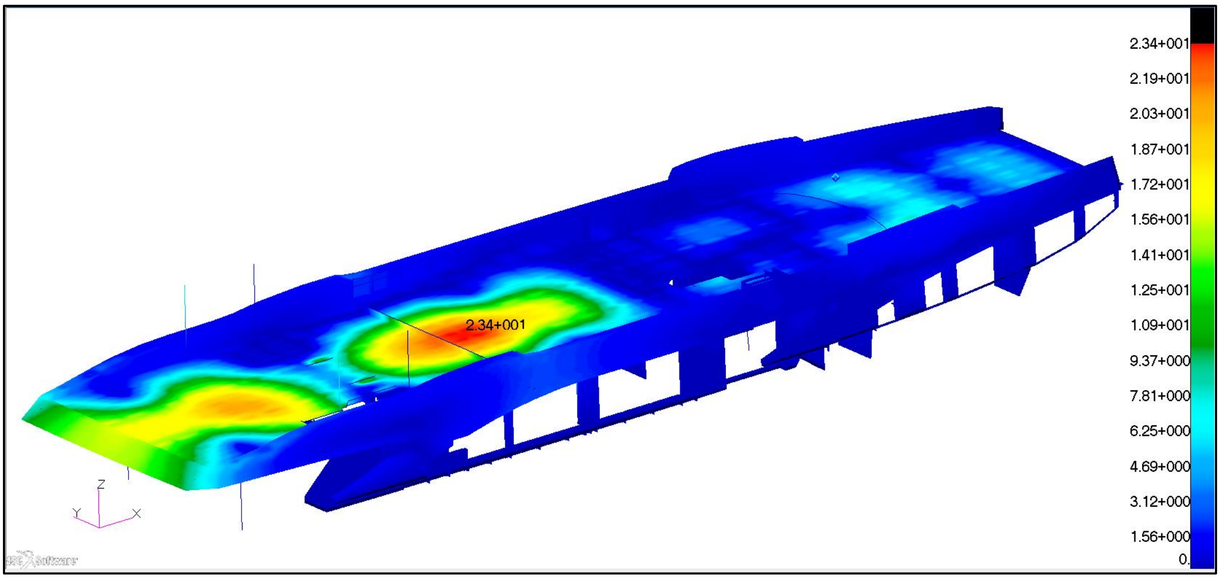


Figure 18 – Global view of the deformation

The deformation of the deck, loaded with the previously defined RINA deck pressure, has a maximum value of 23.4mm located in the interior saloon just after the aft hatch. It is noticeable that the aft hatch, where the saloon door is located, also has a rather elevated deformation. However, the maximum value of deformation is lower than the limit, defined as 1 per cent of the short edge of the global panel (in this case the width of the saloon).

5.4.1.2. Load Case 2 – RINA Side Pressure

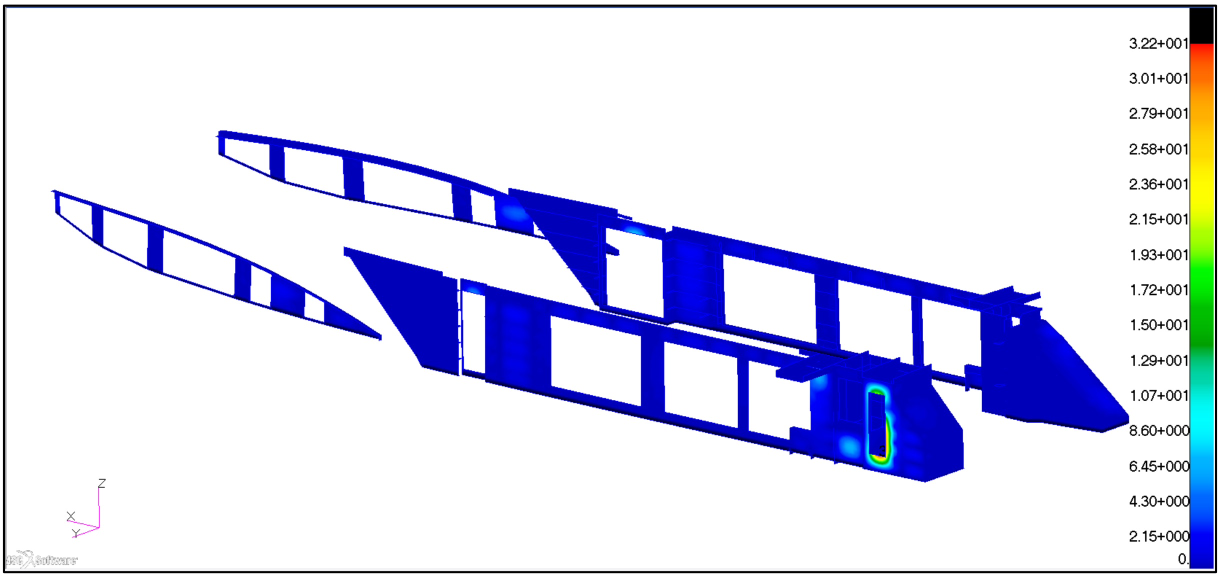


Figure 19 – Global view of the deformation

The deformation due to a side pressure resulted very low. This is most definitely due to the fact that the glass of the windows was not modelled. Since the ratio of glass/side shell is more or less one half, half of the pressure on these side structures is missing. Not considering more than one half of the total pressure could lead to higher values of deformation and stress. Thus, it is safe to say that these results are insignificant. However, there is one area around the door opening of the trunk that deforms greatly. This is due the fact that the side plate is not sufficiently stiffened in that section. It must be investigated if the actual structure was built in this way or if the stiffeners were forgotten to be added in the structural drawings.

5.4.1.3. Load Case 3a – Static

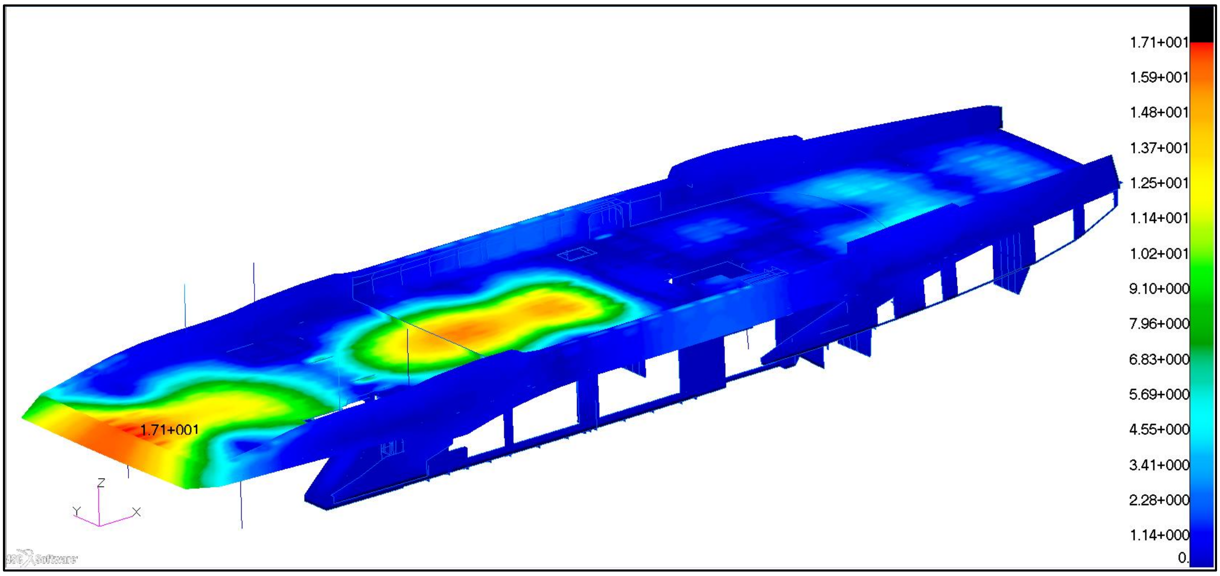


Figure 20 - Global view of the deformation

The concentrated loads were placed on the exterior deck and inside the upper deck in the saloon, each covering an area of 6m^2. Interestingly the global deformation looks similar to Load Case 1, however the maximum deformation occurs on the aft part of the exterior deck.

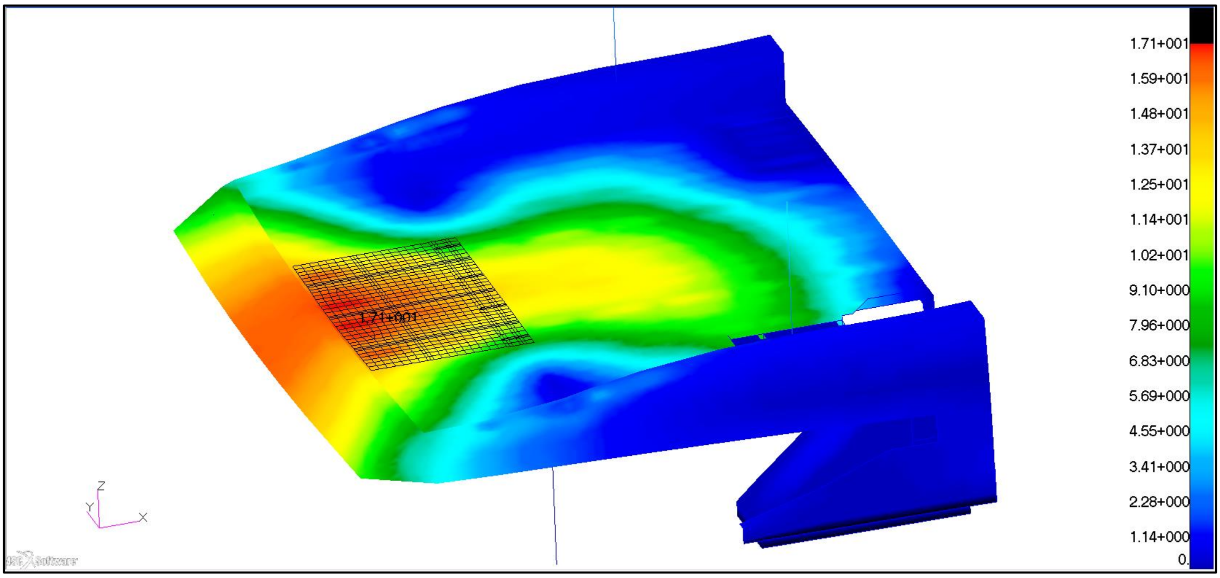


Figure 21 - Detail of local deformation exterior deck aft – 20 People

Locally the structure deforms by a maximum of 17.1 mm.

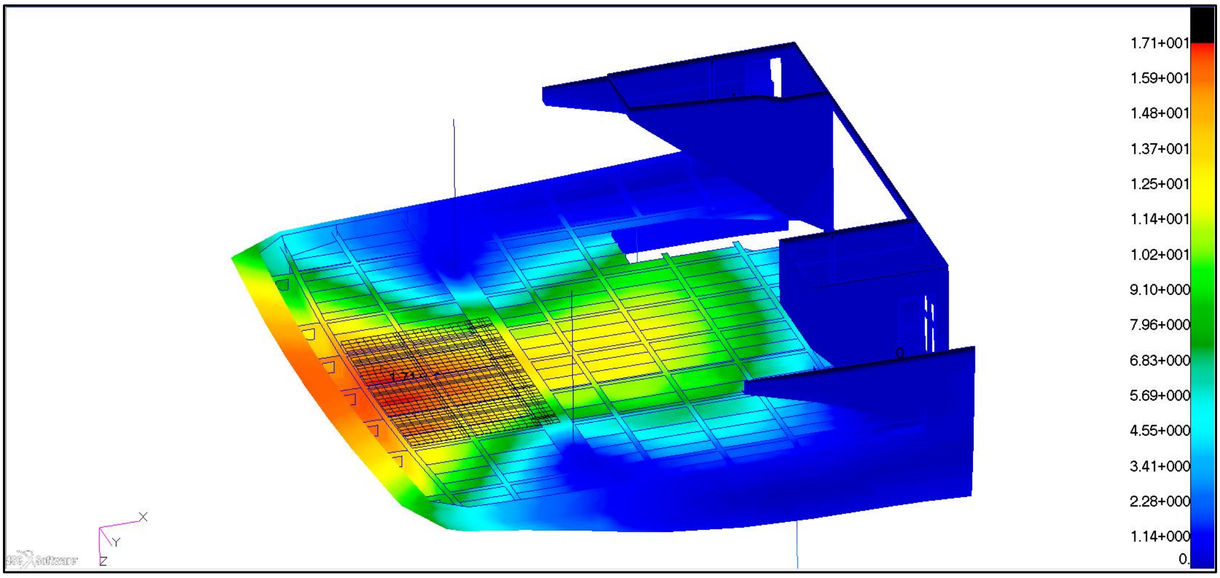


Figure 22 - Inverted structural view of local deformation exterior deck aft – 20 people

As can be seen in this view, the load was placed on the plates between the transverse supported beam and the aft structure. It is clearly visible that the maximum deformations occurs where the load was placed.

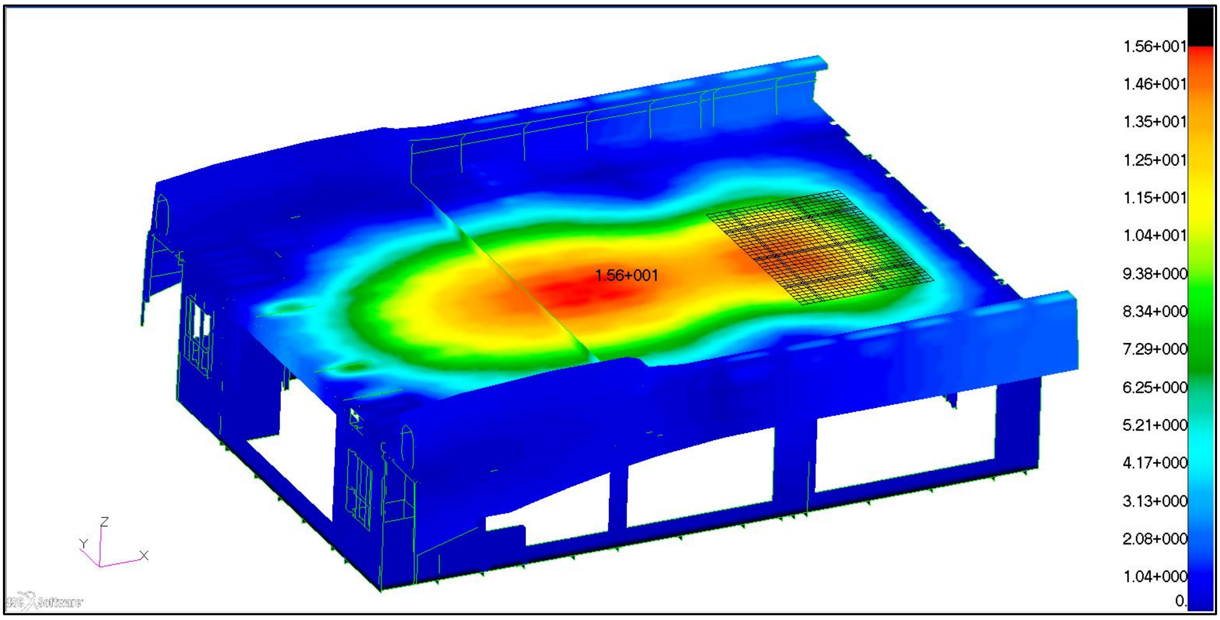


Figure 23 - Detail of local deformation of the interior saloon – 20 people

In the saloon area however, the plates that deform the most are only subject to the outfitting load located aft of where the 20 people were placed. The reason being, that the width of the plate area where the people are located is smaller and better supported than where the maximum deformation of 15.6mm occurs, as can be seen below.

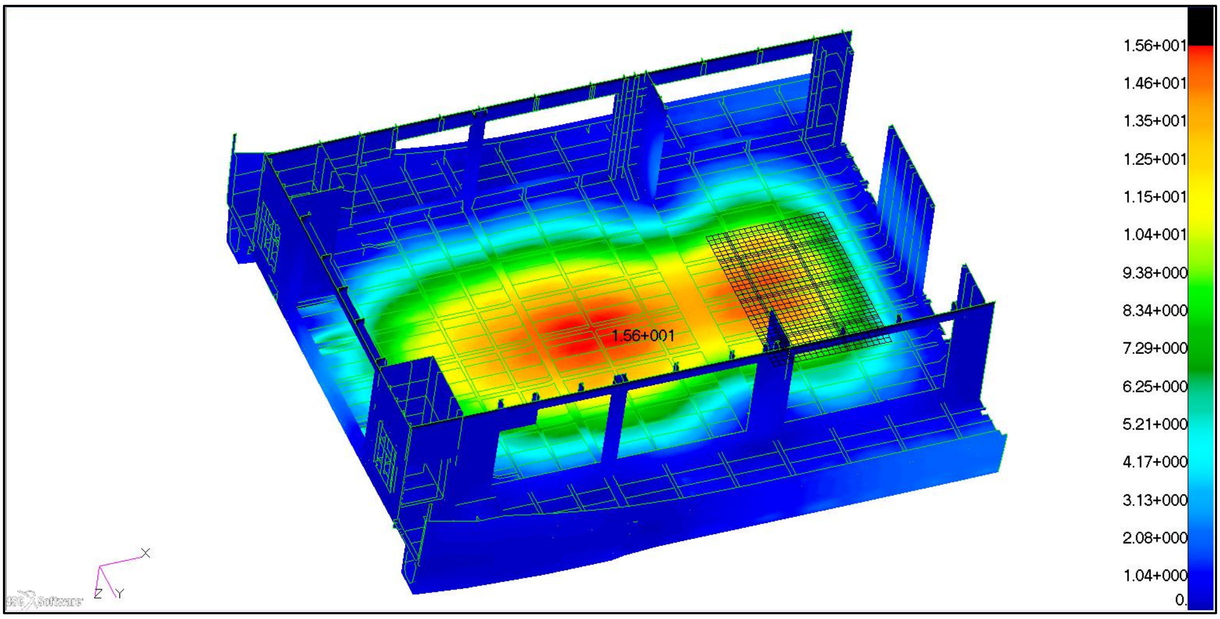


Figure 24 - Inverted structural view of local deformation interior saloon – 20 people

5.4.1.4. *Load Case 3b – Static*

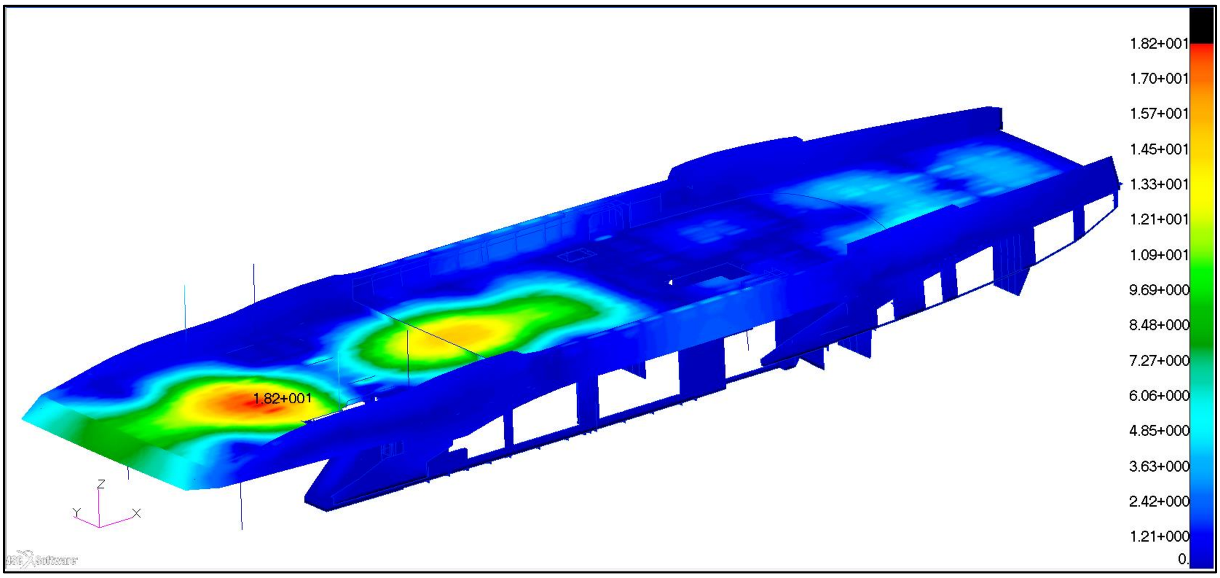


Figure 25 - Global view of the deformation

The concentrated loads were placed in the aft dining area of the exterior deck and in the bow seating area, each covering an area of 6m^2. Here the maximum deformation occurs in the dining area.

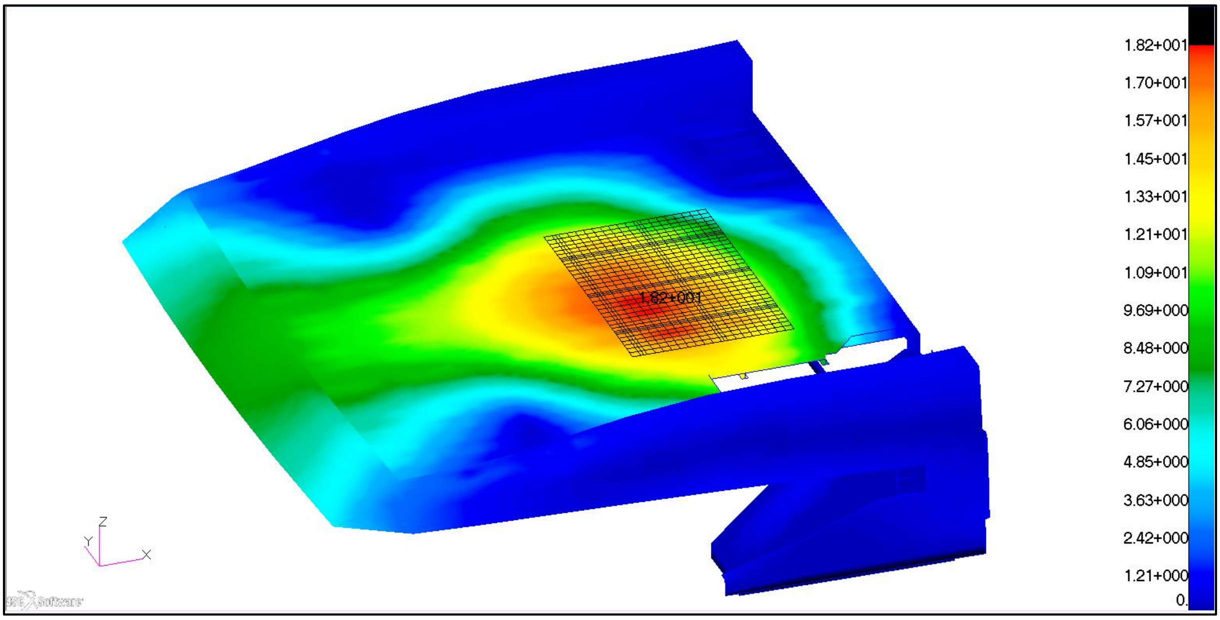


Figure 26 - Detail of local deformation of the aft dining area – 20 people

In this area the structure deforms to a maximum of 18.2 mm. The length of the plate between the two transverse supporting members (aft bulkhead and aft pillars) is 5m.

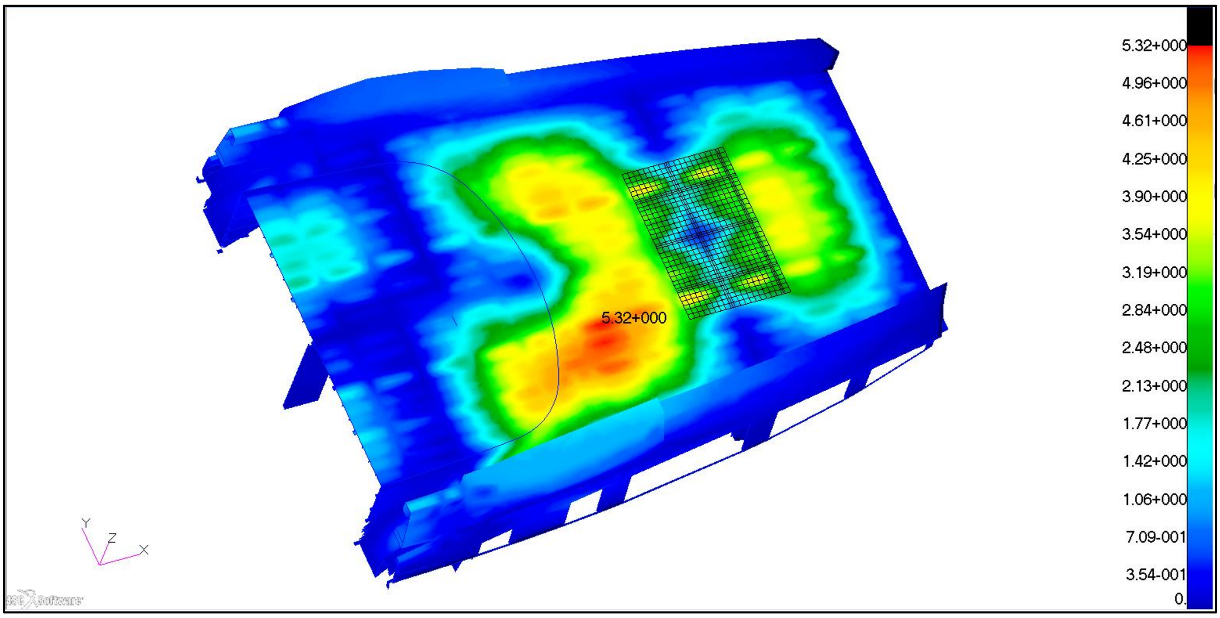


Figure 27 - Detail of local deformation of the bow seating area – 20 people

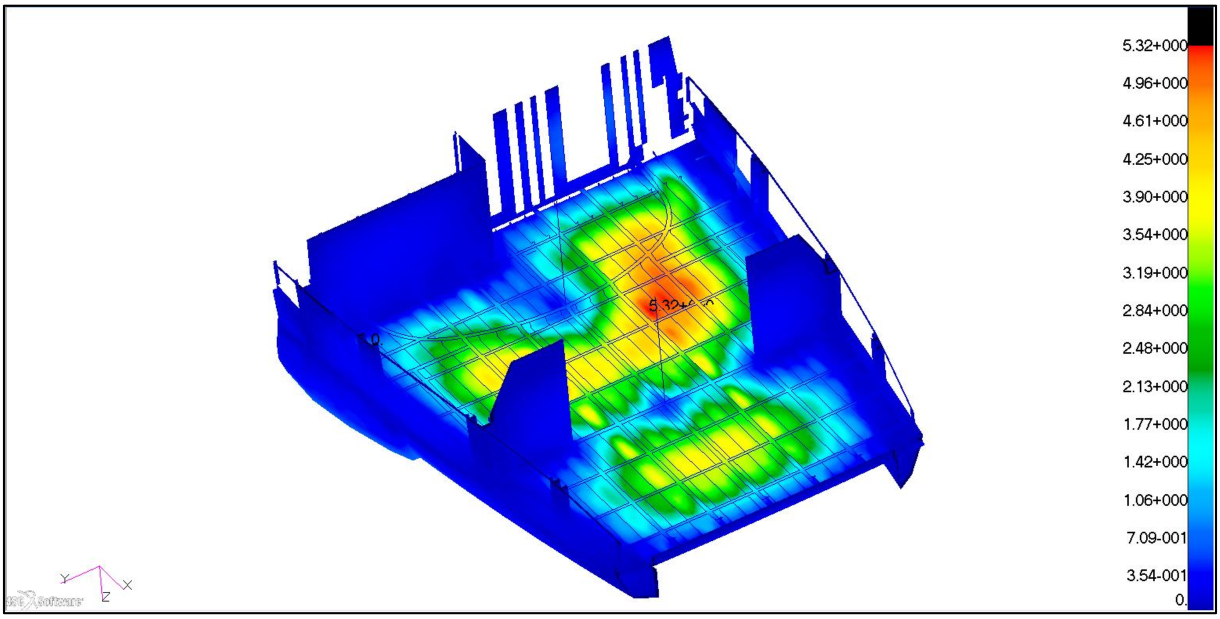


Figure 28 - Inverted structural view of local deformation of the bow seating area – 20 people

In the bow seating area the deformation is minimal with a maximum value of 5.32mm.

5.4.1.5. Load Case 4 - Dynamic

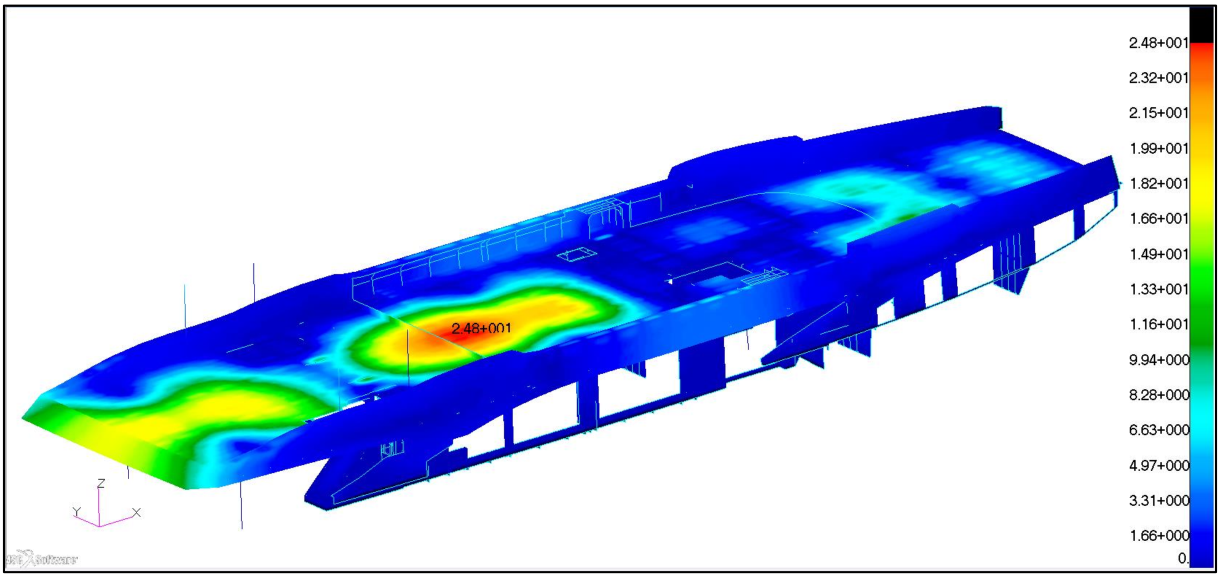


Figure 29 - Global view of the deformation

This dynamic condition consisted of accelerated local loads placed in the saloon and at the aft area of the exterior deck as well as accelerated overall structural and outfitting pressures. Once again the plates with the highest deformation are the ones just after the saloon door, in the same area as in Load Case 1.

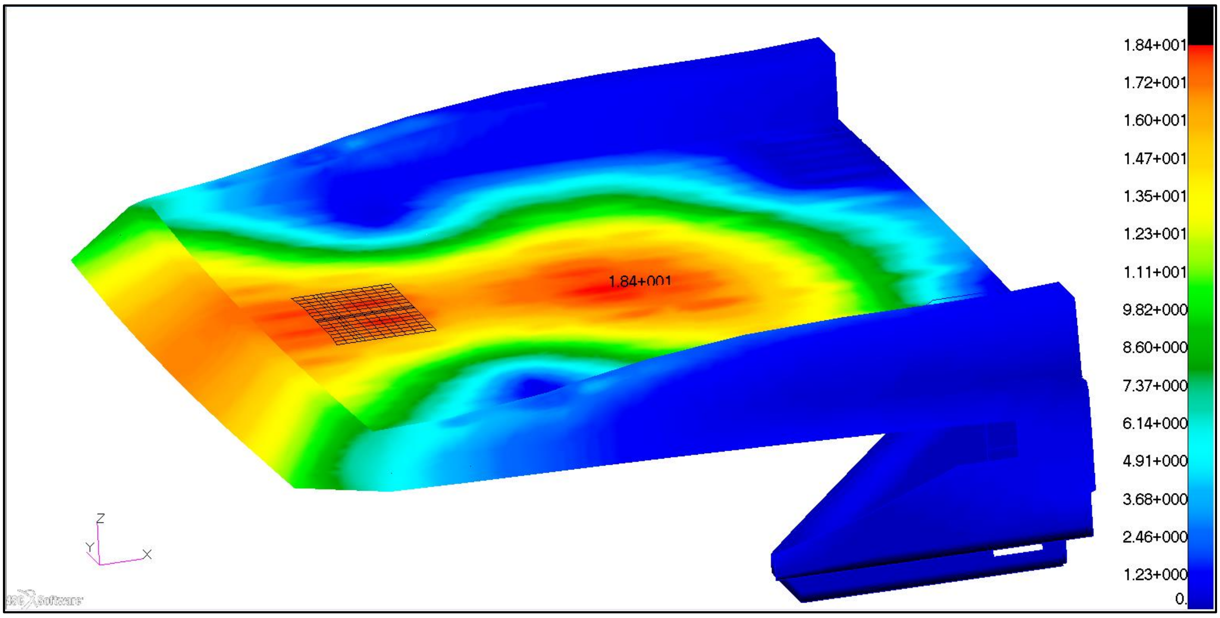


Figure 30 - Detail of local deformation exterior deck aft – 6 people

Focusing on the aft exterior deck, one can see that the accelerated pressure of the 6 people does deform the plate by 18.3mm, although the maximum deformation is found further forward of the specified area.

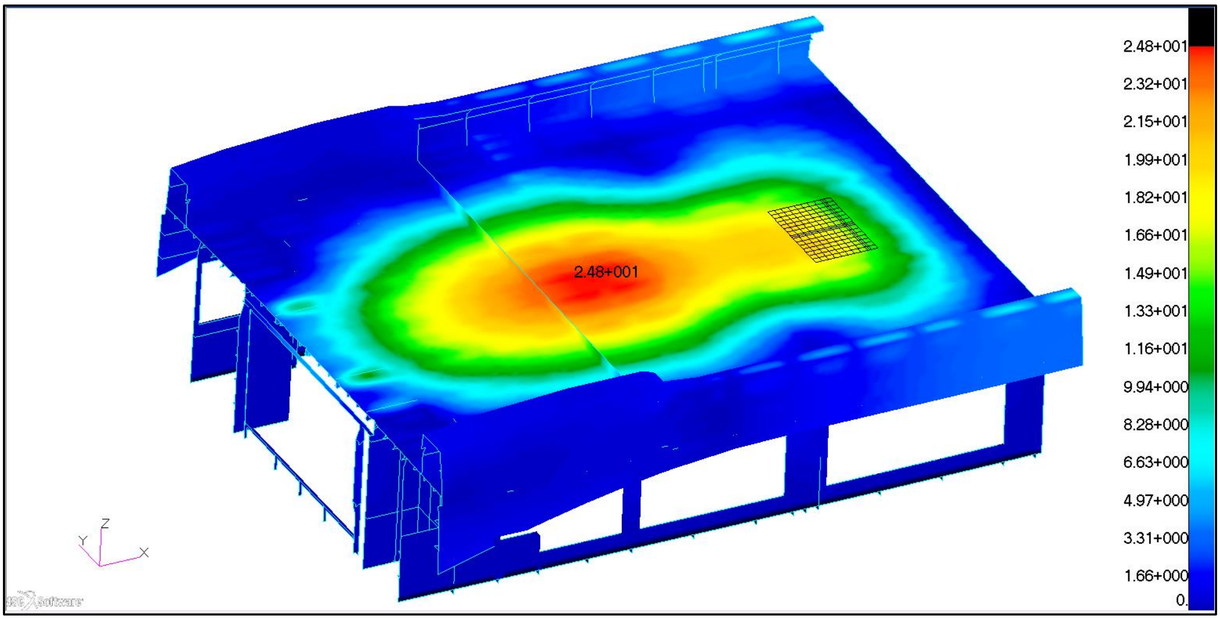


Figure 31 - Detail of local deformation interior saloon – 6 people

The area with the highest deformed plates is in the interior saloon between the aft hatch frame and the supported triple T-beam and not where the accelerated load is located.

5.4.1.6. *Load Case 5 - Racking*

In this special case the deformation occurs along the y-axis, contrary to the previous ones where it occurred in the vertical direction. Apart from the structural and outfitting loads, two local loads where also placed in the saloon and at the aft most part of the deck.

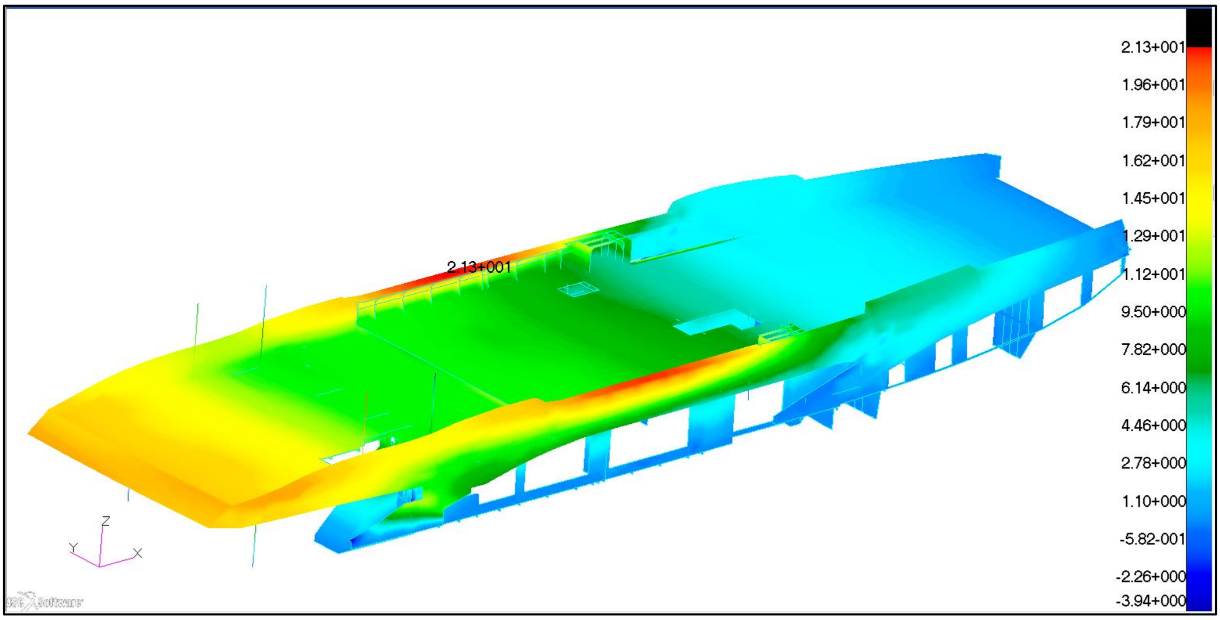


Figure 32 - Global view of racking deformation

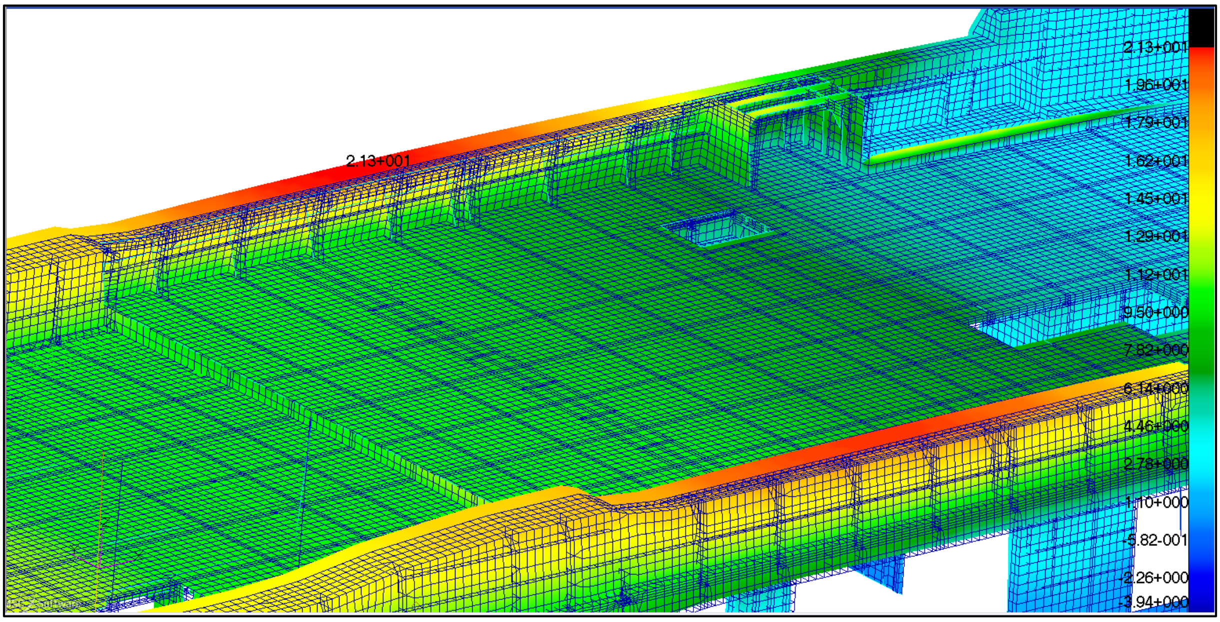


Figure 33 - Detail of bulwark deformation (not true scale)

The deformation in the transverse direction is evidenced in the image above where the meshed area is the undeformed structure, while the fringe coloured area is the deformed structure due to the racking effect. The bulwark has a relatively large local deformation of about 14mm over a shell height of 750mm. Although this may not seem critical at this stage, it must be noted that when adding the actual 2nd tier it is expected that this deformation will worsen as there will be the added effect of the bending moment of that entire sun deck structure acting on the bulwark.

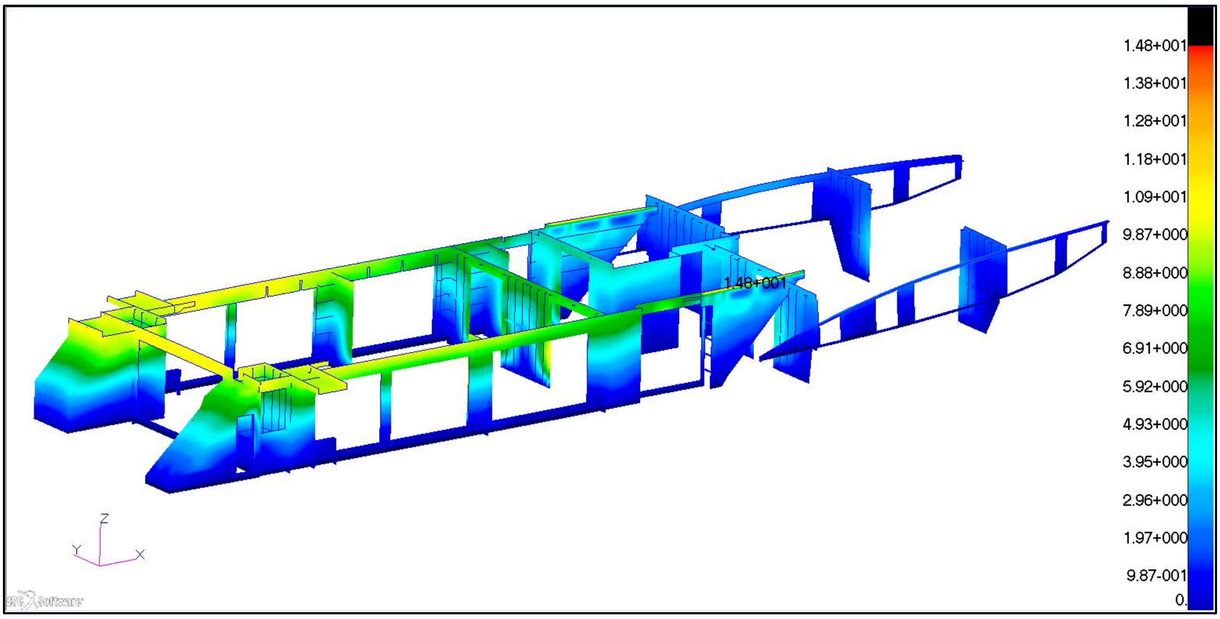


Figure 34 - Detail of side plating deformation

This image clearly shows how the superstructure sides are affected by the transverse acceleration.

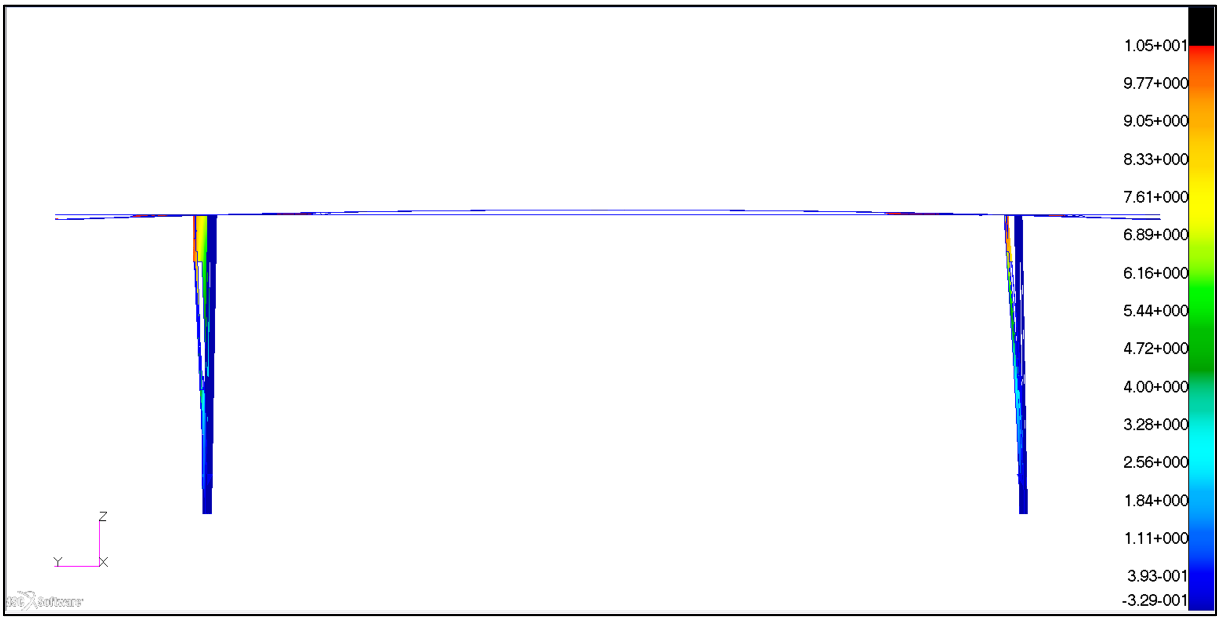


Figure 35 - Section view of the transverse deformation of the side plating

When looking at the side structure alone, the racking effect is clearly visible. Here the side plating deforms by a maximum of 10.5mm where it is welded with the upper deck. It will be interesting to see what the effect will be on the glass windows once they are modelled.

5.4.1.7. Summary

To verify whether the plate deformation is within the requested limits first the maximum allowable deformation is defined according to HSC Rules. To calculate this limit the shortest width of the global plate that is be evaluated must be taken.

Load Case 1: Limit is equal to 1 per cent of the shortest width of the corresponding global plate. A deformation above this value may cause stability issues.

- Saloon interior: 0.01 x 6.5m = 65mm
- Exterior Deck stern:
  - Dining area: 0.01 x 5m = 50mm
  - Aft stern area: 0.01 x 2.1m = 21mm
- Exterior Deck Bow: 0.01 x 3.3m = 33mm

Load Case 3a, 3b, 4: The limit was defined by the Azimut-Benetti R&D office, and was taken as 0.75 per cent of the shortest edge. The reason being to be a bit more conservative since we are now dealing with real loads.

- Saloon interior: 0.0075 x 6.5m = 48.8mm
- Exterior Deck stern:
    - Dining area: 0.0075 x 5m = 37.5mm
    - Aft stern area: 0.0075 x 2.1m = 15.8mm
- Exterior Deck Bow: 0.0075 x 3.3m = 24.8mm

Table 24 - Limit and Maximum Deformation

Areas	Load Case 1		Load Case 3a		Load Case 3b		Load Case 4	
	mm		mm		mm		mm	
	Max	Limit	Max	Limit	Max	Limit	Max	Limit
Saloon interior	23.4	65	15.6	48.8	15.1	48.8	24.8	48.8
Exterior Deck Dining	20.7	50	13.6	37.5	18.2	37.5	18.4	37.5
Exterior Deck Aft	17.1	21	17.1	15.8	12	15.8	18.3	15.8
Exterior Deck Bow	7.98	33	5.19	24.8	5.3	24.8	10.1	24.8

The two values that are above the 0.0075 per cent can be considered admissible because the relative deformation between the pillars and the extreme deck has been investigated with the RINA deck pressure case (see figure 18).

5.4.2. Von Mises

The von Mises stress is a geometrical combination of all the stresses (normal stress in the three directions, and all three shear stresses) acting at a particular location. If the von Mises stress at a particular location exceeds the yield strength, the material yields. If it exceeds the ultimate strength, the material collapses at that location.

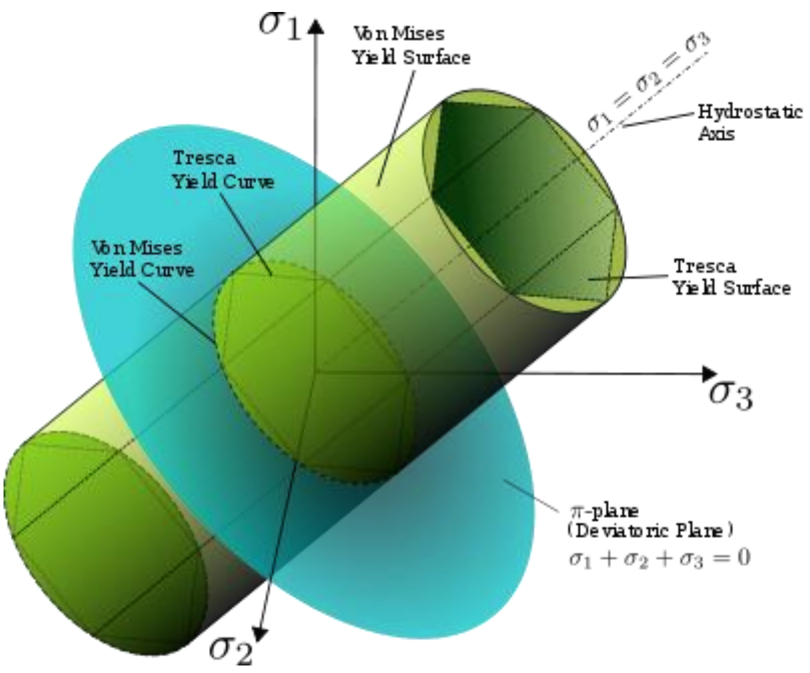


Figure 36 - von Mises stress (http://en.wikipedia.org/wiki/Von_Mises_yield_criterion, n.d.)

$$\sigma_c = \sqrt{\sigma_x^2 + \sigma_y^2 - \sigma_x\sigma_y + 3\tau^2} \quad (28)$$

In this case there are two allowable stress limits for the aluminium structure. The plates are made from aluminium alloy type 5083, and the sections from type 6082.

Table 25 - Minimum guaranteed yield stress

Alloy	Minimum guaranteed yield stress $R_{p\,0.2}$ at 0,2% N/mm^2	Rule limits		
		RINA	**LR**	**ABS**
5083	125	110	93.75	87.5
6082	250	220	187.5	175

5.4.2.1. Load Case 1

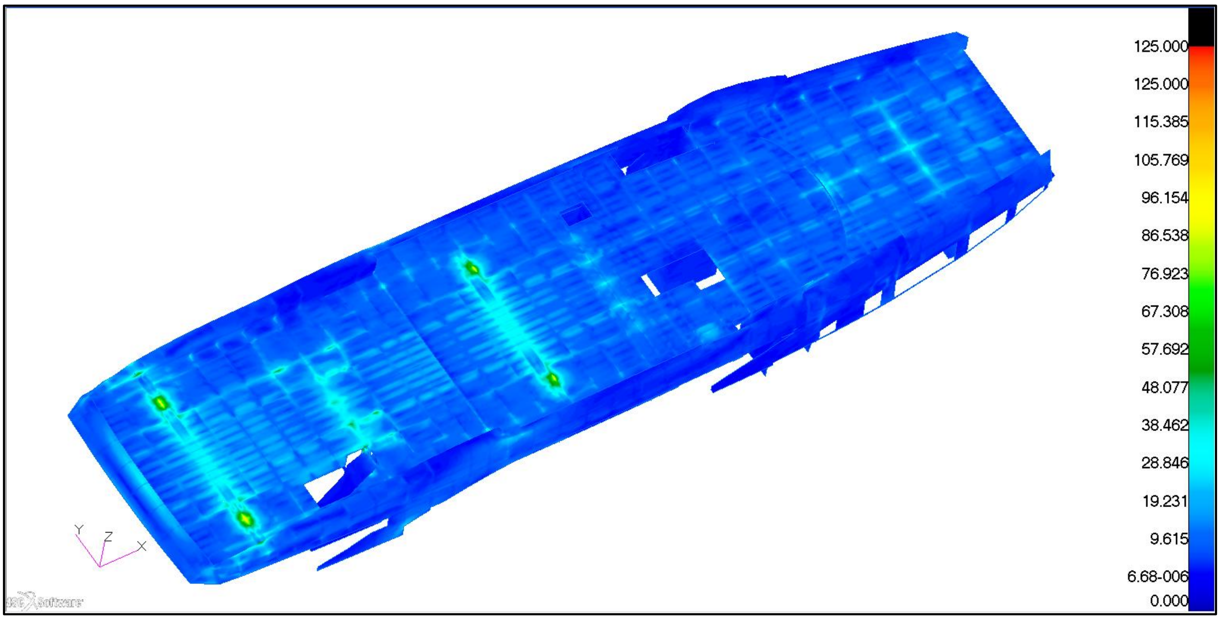


Figure 37 - Stress on the shell – RINA deck pressure

For the shell plating of the deck, side structure and bulwark, globally there are no critical values, apart from a few local areas corresponding to more stressed reinforced beams. The area with the highest stress is on the bulkhead where the saloon double box beam is located.

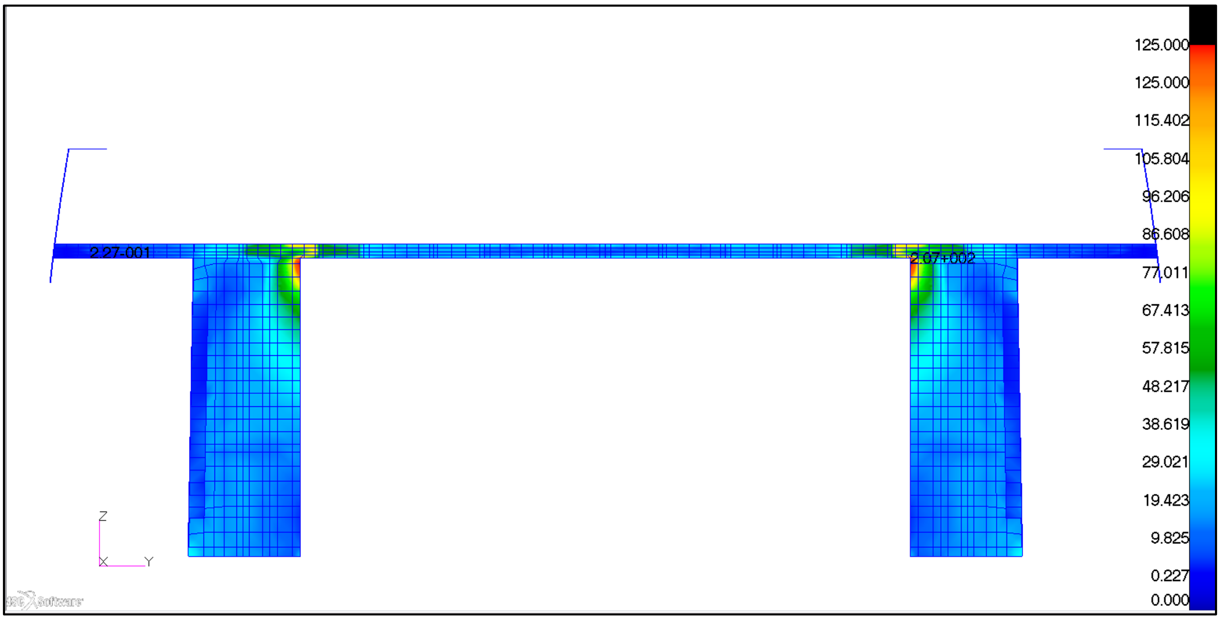


Figure 38 - Saloon double box beam stress peak

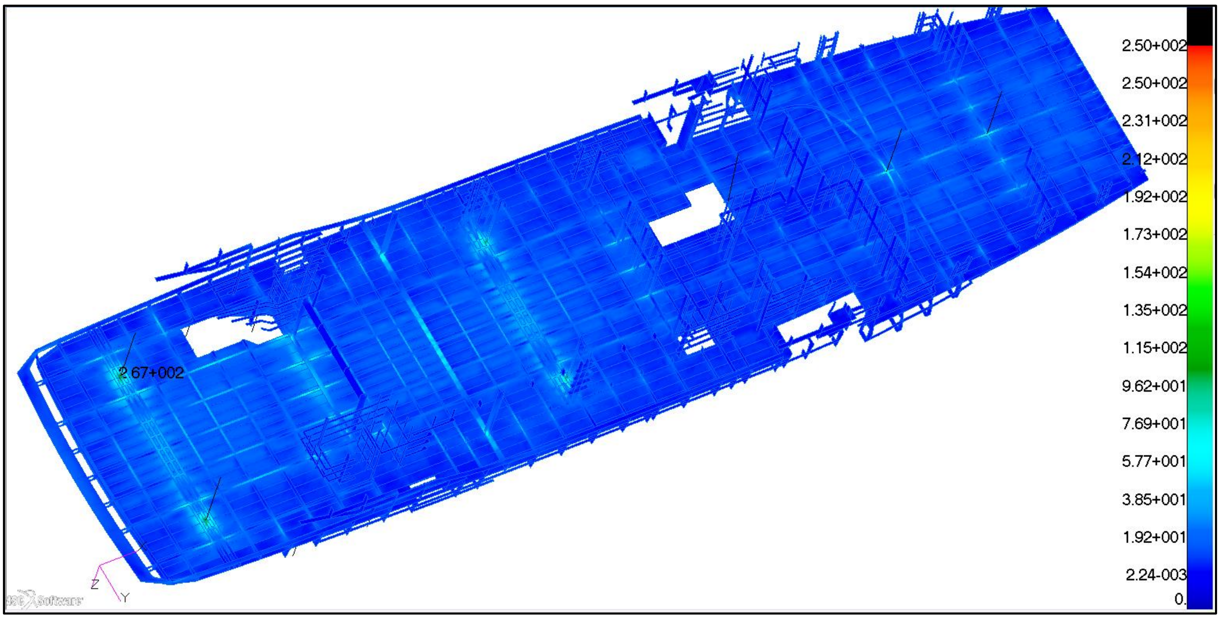


Figure 39 - Stress on the reinforcements

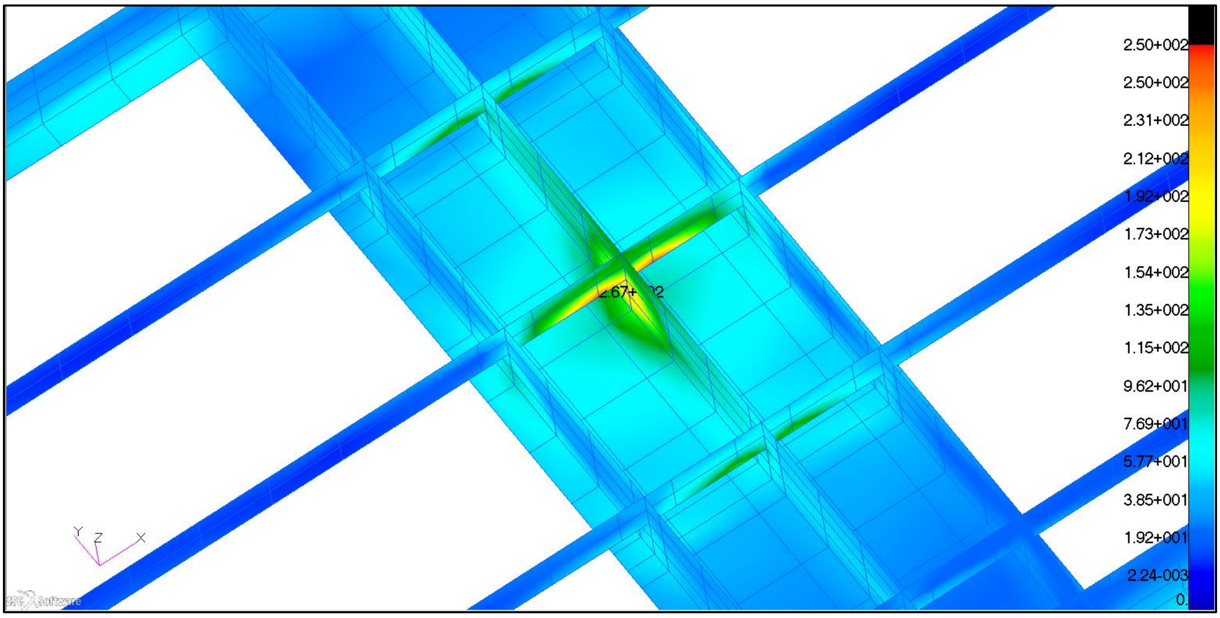


Figure 40 - Peak stress located in aft double box beam box

This stress peak is located where the transverse supporting beam rests onto the pillar. However, the high peak is due to the fact that the load is concentrated into one node, rather than being distributed along the pillar plates and since the stress reduces very quickly within one element this peak can be considered not real.

Nevertheless the yellow zone, which is a bit more dispersed, has slightly higher values but still within the limits of RINA Rules. A possible solution to reducing the stress levels in this area would be to increase the web of the beams.

5.4.2.2. Load Case 2

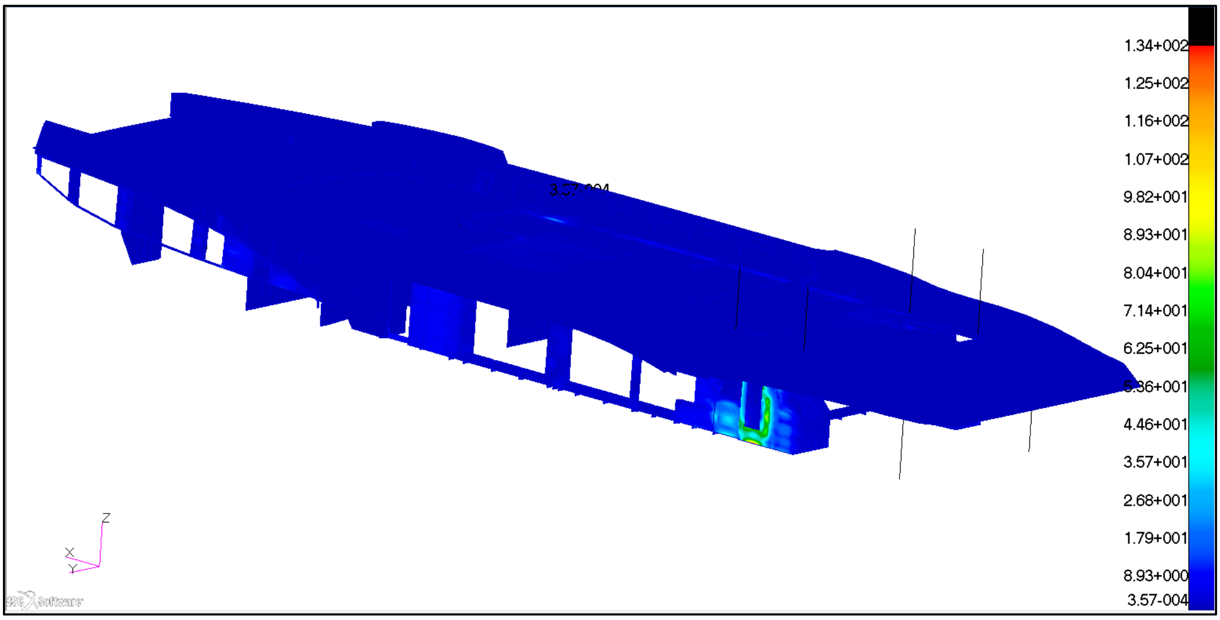


Figure 41 - Stress on the shell plating - RINA side pressure

Globally no critical values. The elevated stressed area is around the door of the trunk zone.

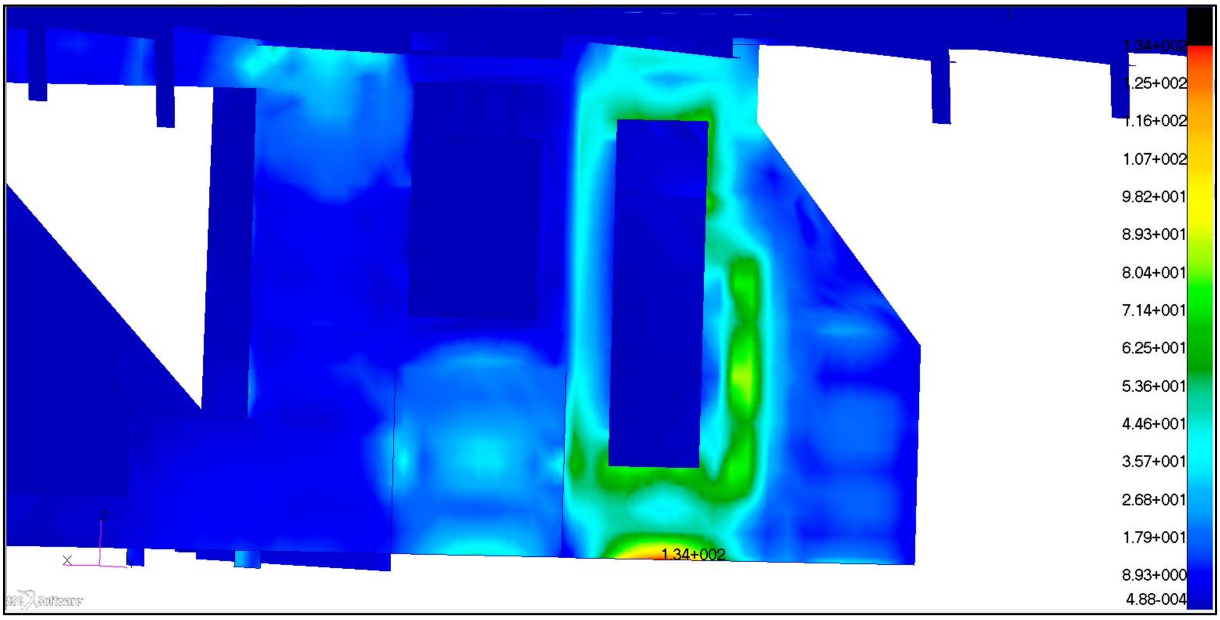


Figure 42 - Trunk detail of the stress on the shell plating - RINA side pressure

Higher stressed area around the door of the trunk, however the values are within the allowable limits. For the peak of 134 MPa, the same consideration applies as mentioned previously in Load Case 1.

5.4.2.3. Load Case 3a

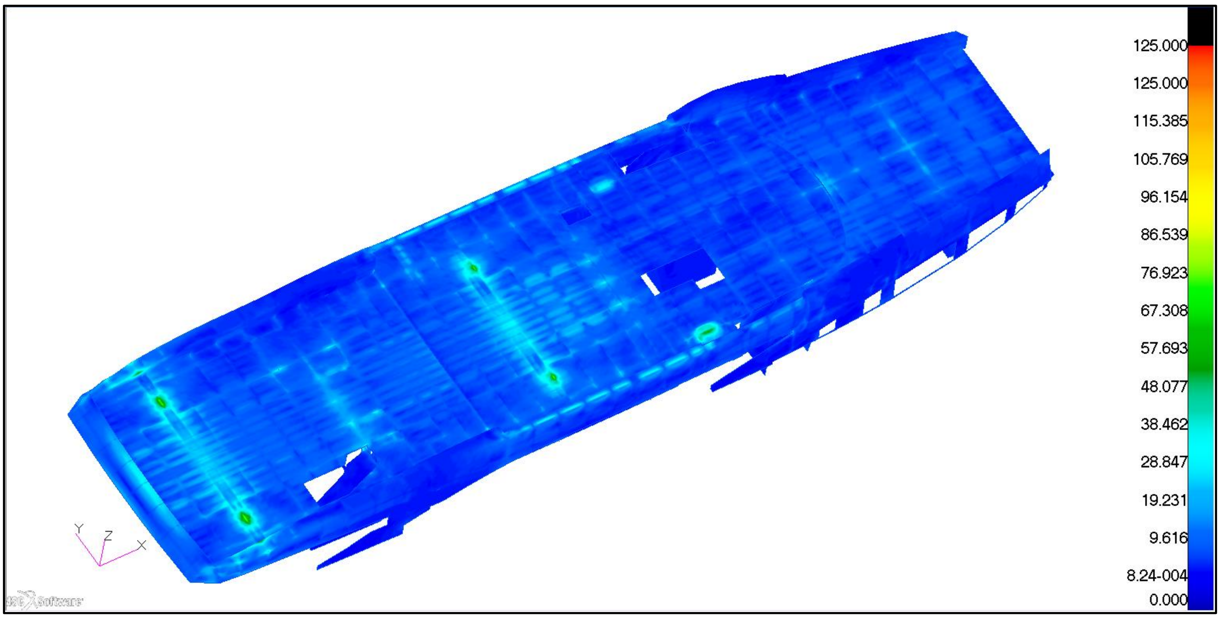


Figure 43 - Stress on the shell – static condition

The areas where the people are located are evidenced by a slightly higher stress (i.e, aft exterior deck and saloon).

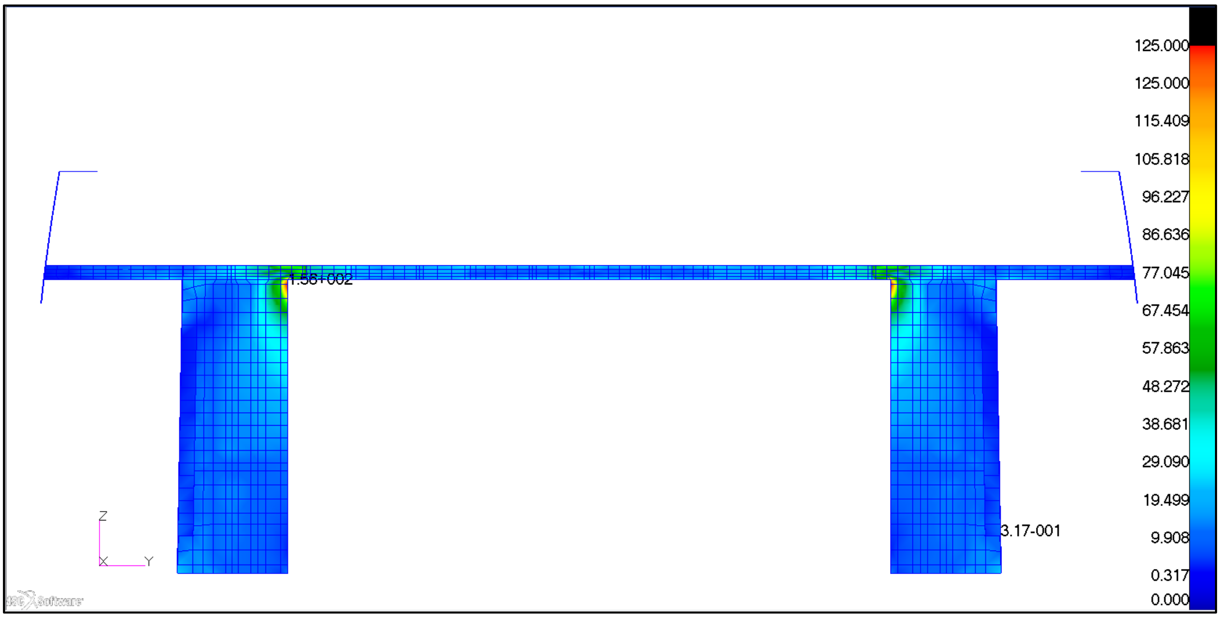


Figure 44 - Saloon double box beam stress peak

The saloon bulkhead is also the location with the highest stress. However in contrary to load case 1, the stress peak is on the opposite bulkhead.

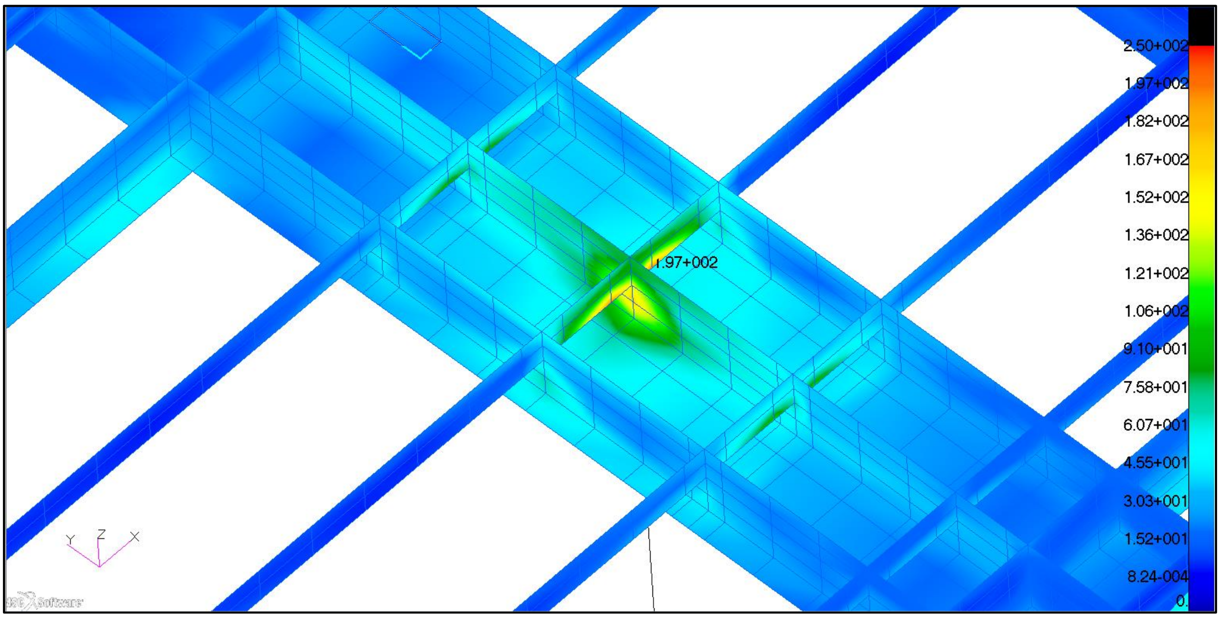


Figure 45 - Peak stress located in aft double box beam box

The highest stress on the reinforcements occurs in the same place as in load case 1, i.e. junction of the double box beam with the pillar.

5.4.2.4. Load Case 3b

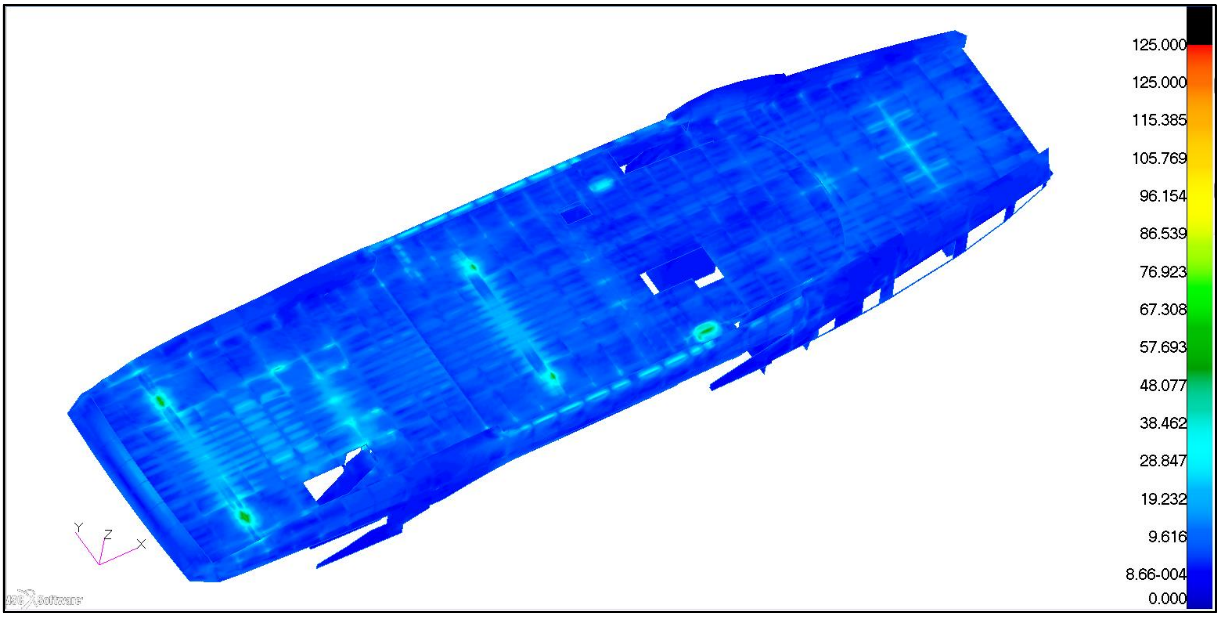


Figure 46 - Stress on the shell – static condition

Slightly enhanced stress values in the areas where the concentrated loads are located, (i.e. aft dining and bow seating area).

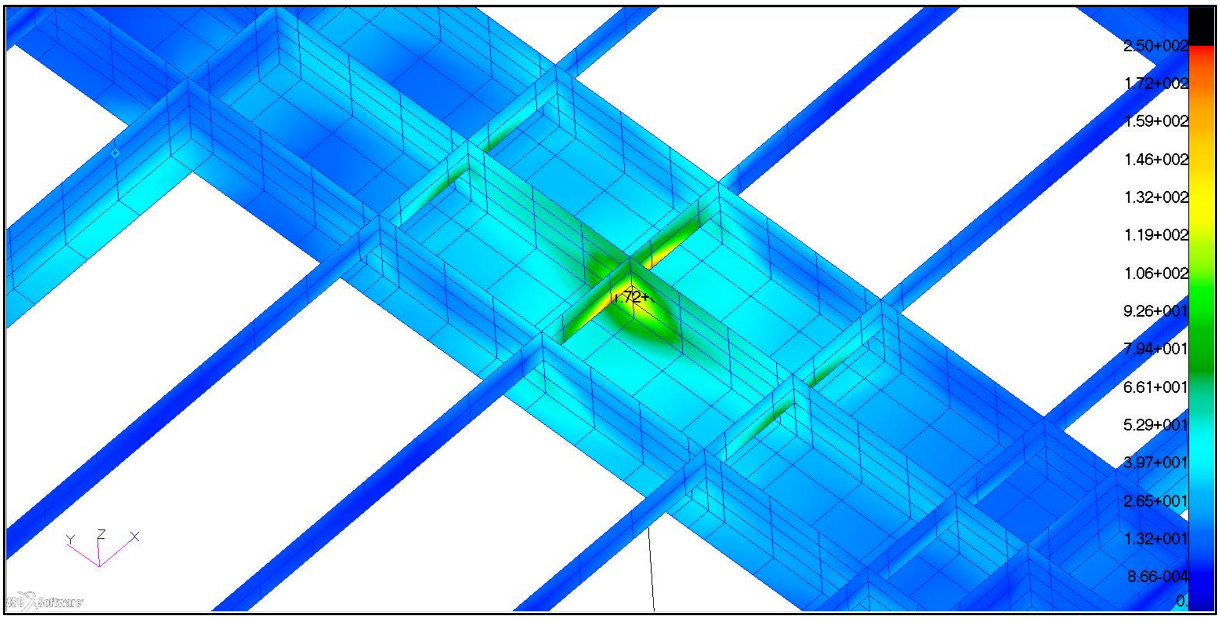


Figure 47 - Peak stress located in aft double box beam box

The highest stress occurs in the same place as in load case 1 and 3a, i.e. junction of the double box beam with the pillar.

5.4.2.5. *Load Case 4*

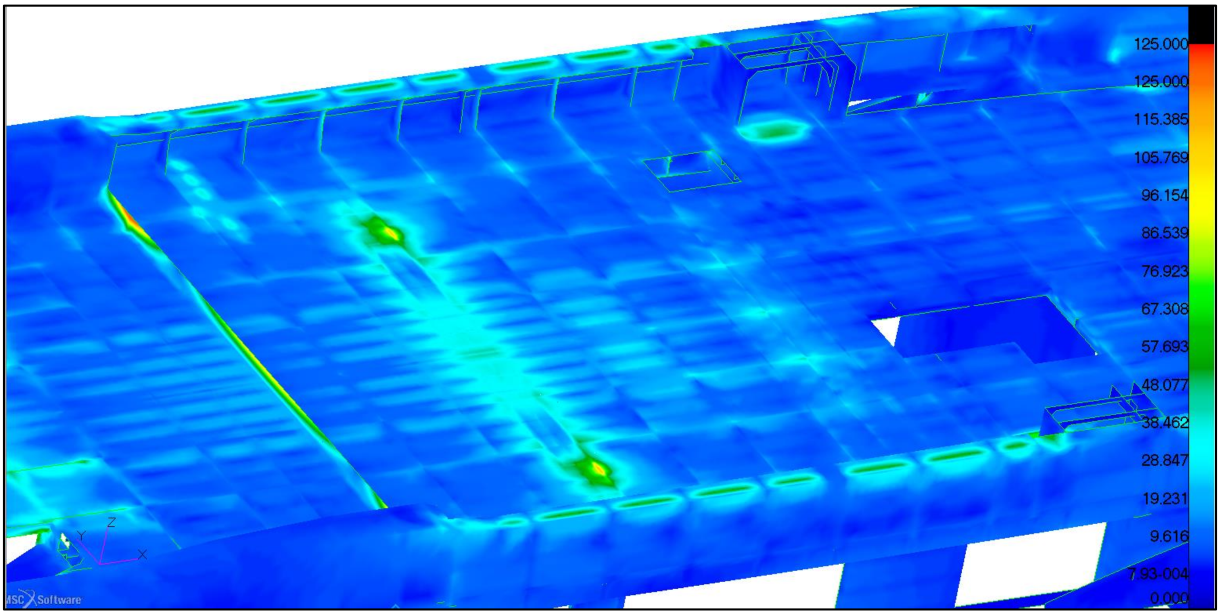


Figure 48 - Stress on the shell - dynamic condition

What is noticeably different in this dynamic condition is the elevated stress on the plates of the side bulwarks where the sun deck structure rests on.

5.4.2.6. *Load Case 5*

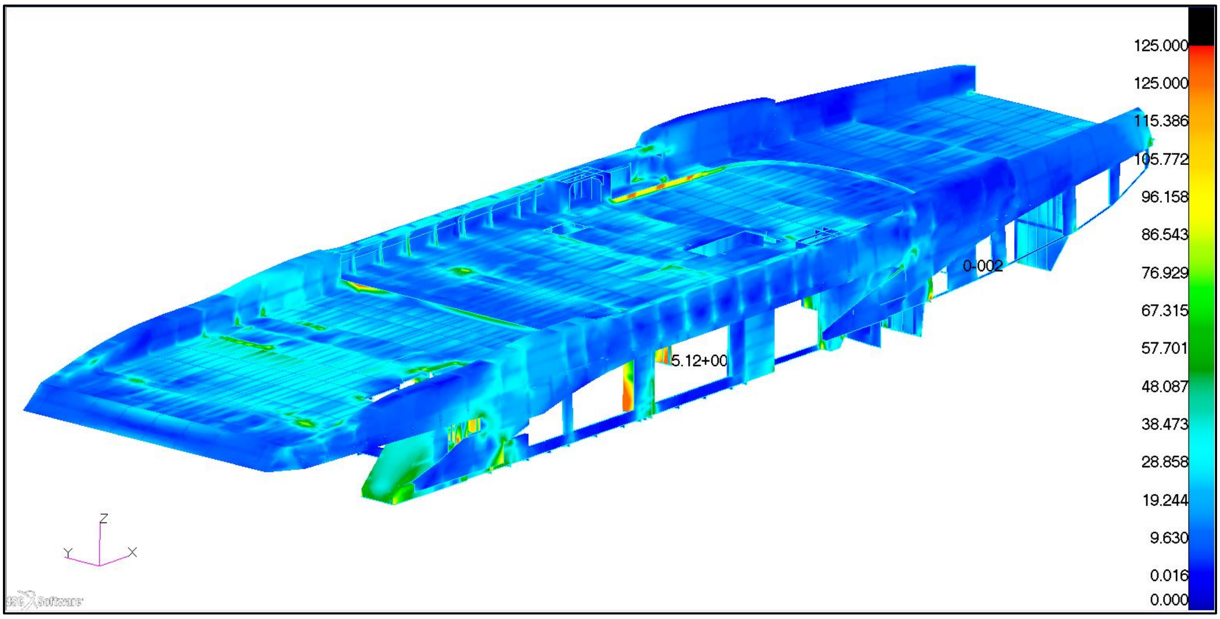


Figure 49 - Stress on the superstructure – racking condition

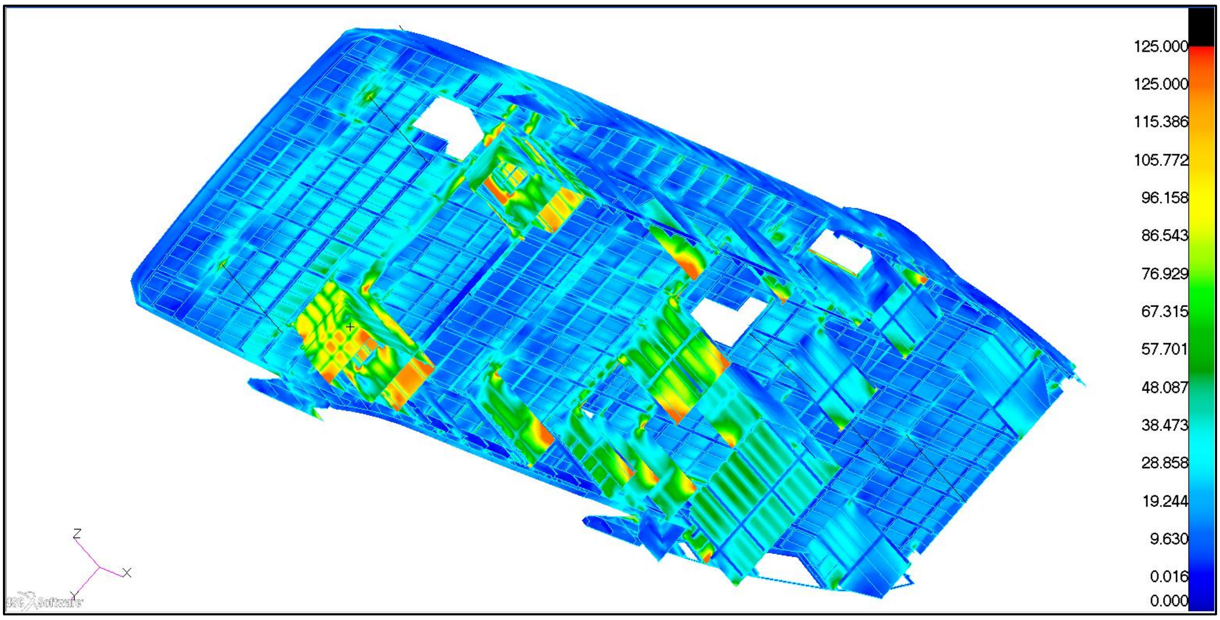


Figure 50 - Stress on the shell – racking condition

Here the stress peak is located on a transverse bulkhead. It is clearly visible that many transverse structures are particularly subject to high stresses throughout the plates, many of which are close, if not above, the required stress limits, thus deforming the plate.

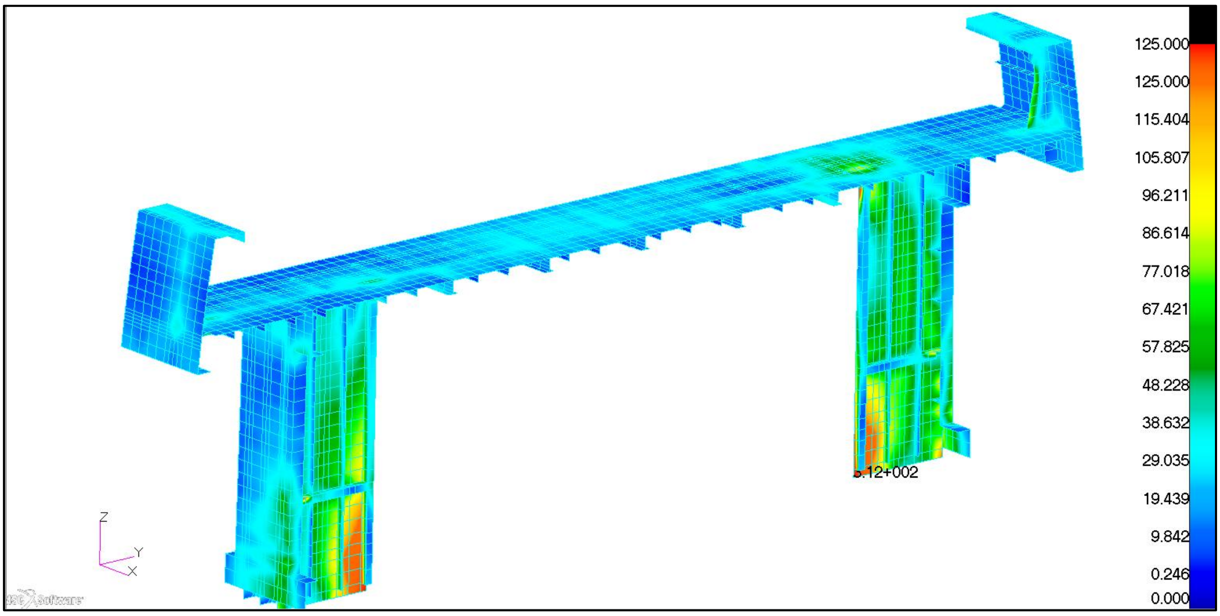


Figure 51 - Stress on the saloon bulkhead

The reinforcements with the highest stress acting upon them are the longitudinal stiffeners and stringers of the transverse bulkheads.

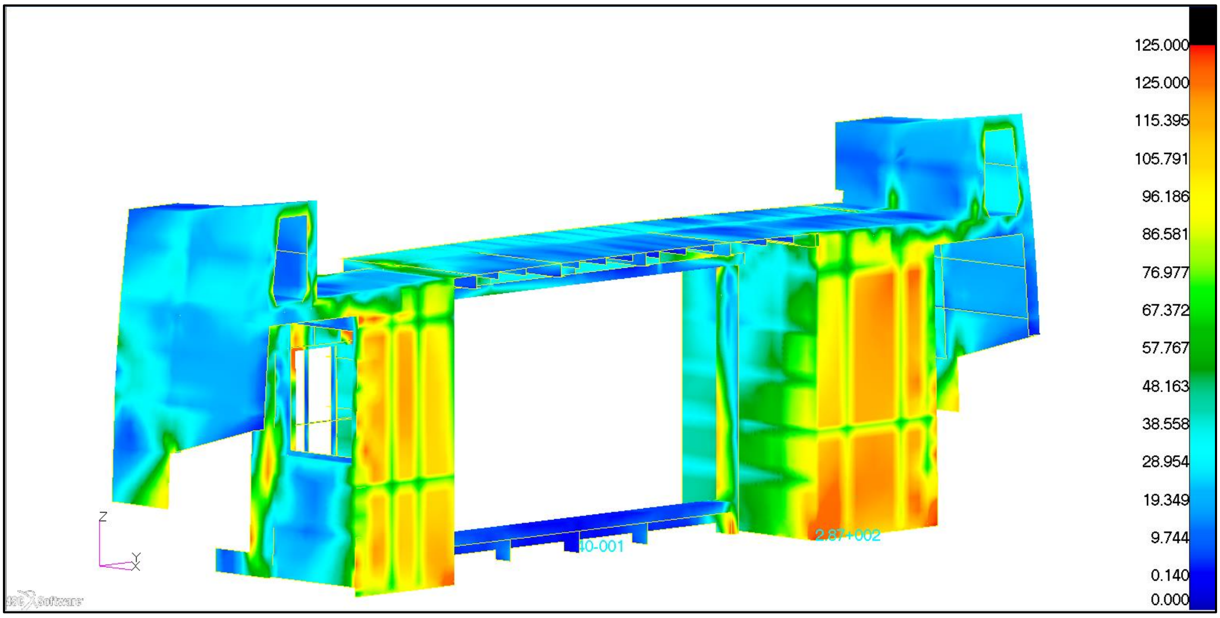


Figure 52 - Stress on the aft saloon bulkhead

5.4.2.7. *Summary*

Table 26 - Maximum von Mises stress σ_c

	Load Case						
Member	**1**	2	**3a**	**3b**	**4**	**5**	**Limit**
	MPa	MPa	MPa	MPa	MPa	MPa	MPa
Aft double box beam	~180		~140	~120	~170		
Aft Trunk Stiffener		~80					250
Bulkhead stringer						~170	
Saloon Bulkhead	~105		~85	~80	~75		
Aft Trunk shell		~95					125
Bulkhead shell						~130	

Analysing these results, it is evident that the stress of most of the shells and reinforcements for cases 1 to 5 are below the maximum allowable limits of the material, apart from the shell plating of the bulkheads in load case 5. Nevertheless some values may be considered in a critical region.

5.4.3. Maximum Shear Stress and Maximum Axial Stress

In this chapter the resulting stresses will be broken down into two components, the axial stress σ and the shear stress τ.

The Rules give formulas to calculate the maximum shear stress as a function of σ_a.

Table 27 - Shear stress values

σ_a	RINA	LR	ABS
	$\tau = 0.577 \times \sigma_a$	$\tau = \frac{\sigma_a}{\sqrt{3}}$	N/A
125	$\tau_a = 72.13\ N/mm^2$	$\tau_a = 72.17\ N/mm^2$	N/A
250	$144.25\ N/mm^2$	$144.34\ N/mm^2$	N/A

5.4.3.1. Load Cases 1, 3a, 3b and 4

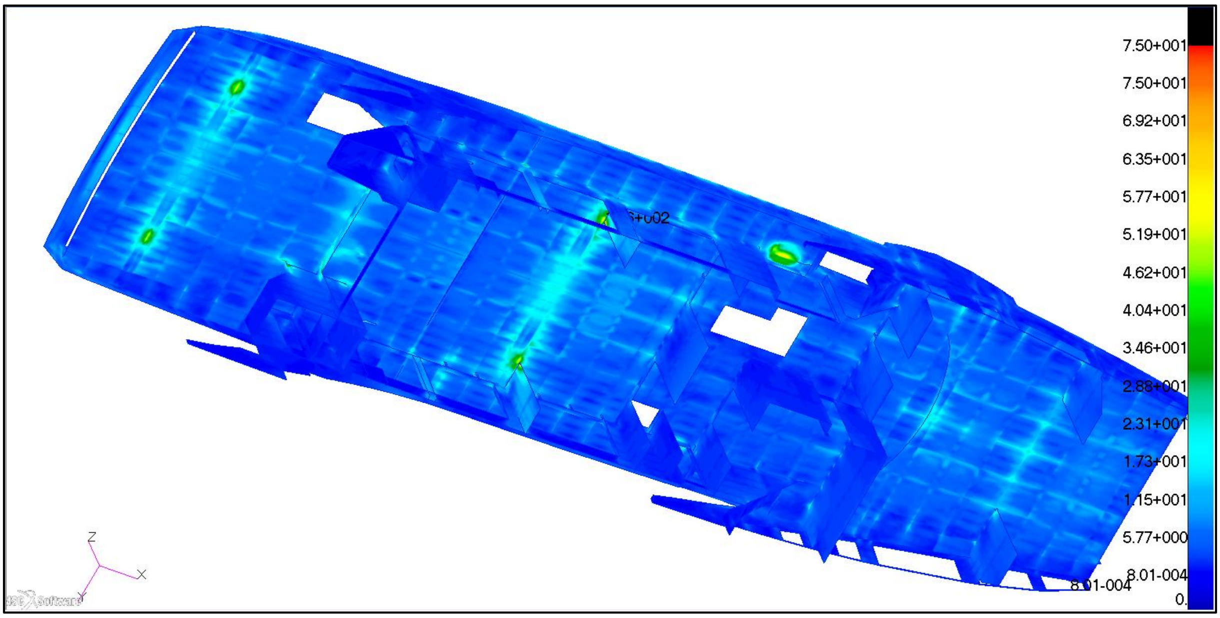


Figure 53 - Shear stress distribution on the shells – Load Case 4

The shear stress τ on the above mentioned cases all had a similar distribution according to the applied loads, however in each case the peak was located at the partial transverse bulkhead of the saloon.

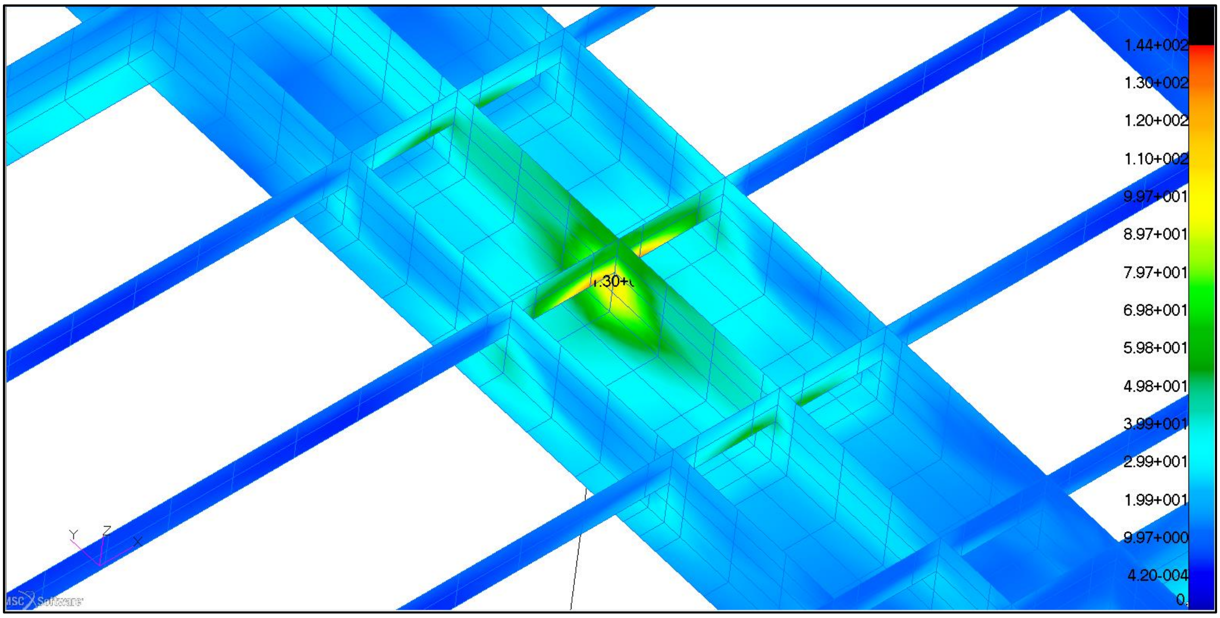


Figure 54 - Shear stress peak on double box beam aft exterior – Load Case 4

On the reinforcements the highest shear stress is located on the aft double box beam supported structure where the pillars support the deck.

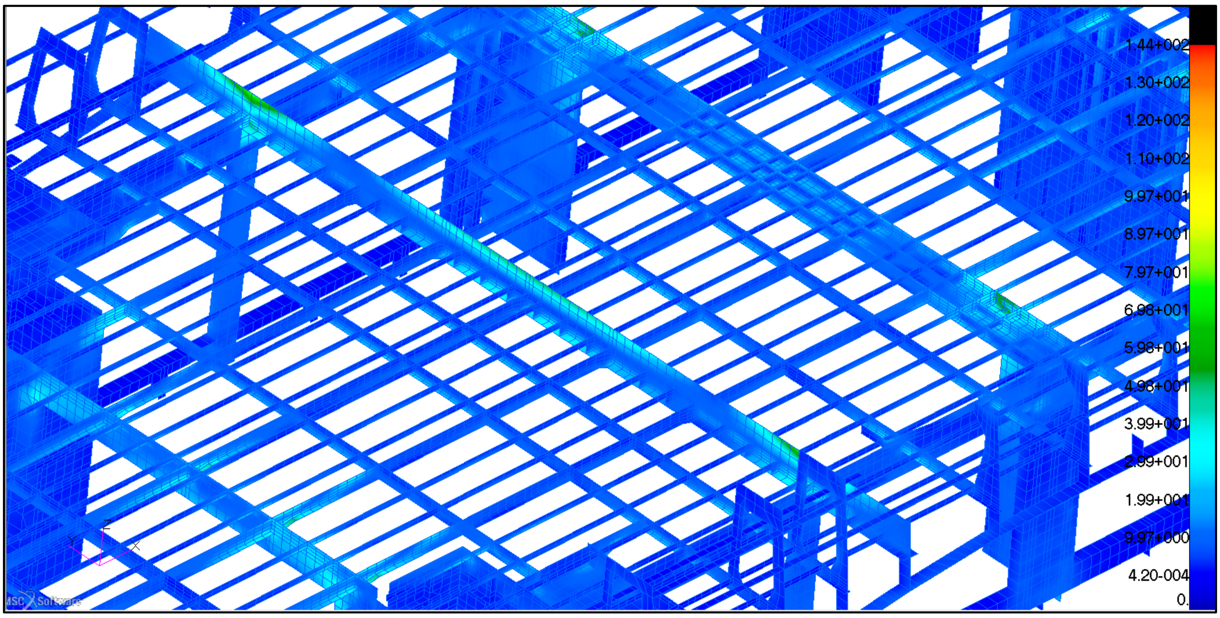


Figure 55 – Shear stress distribution on bulkhead frame, hatch frame and saloon double box beam structure – Load Case 4

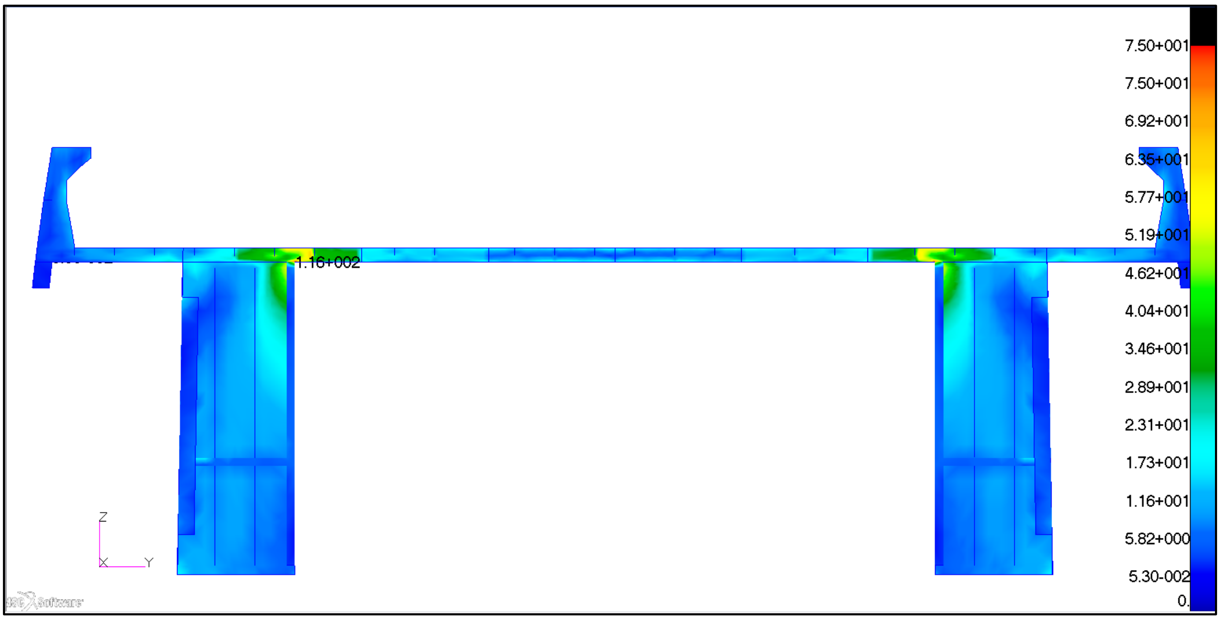


Figure 56 - Shear stress distribution on saloon double box beam structure – Load Case 4

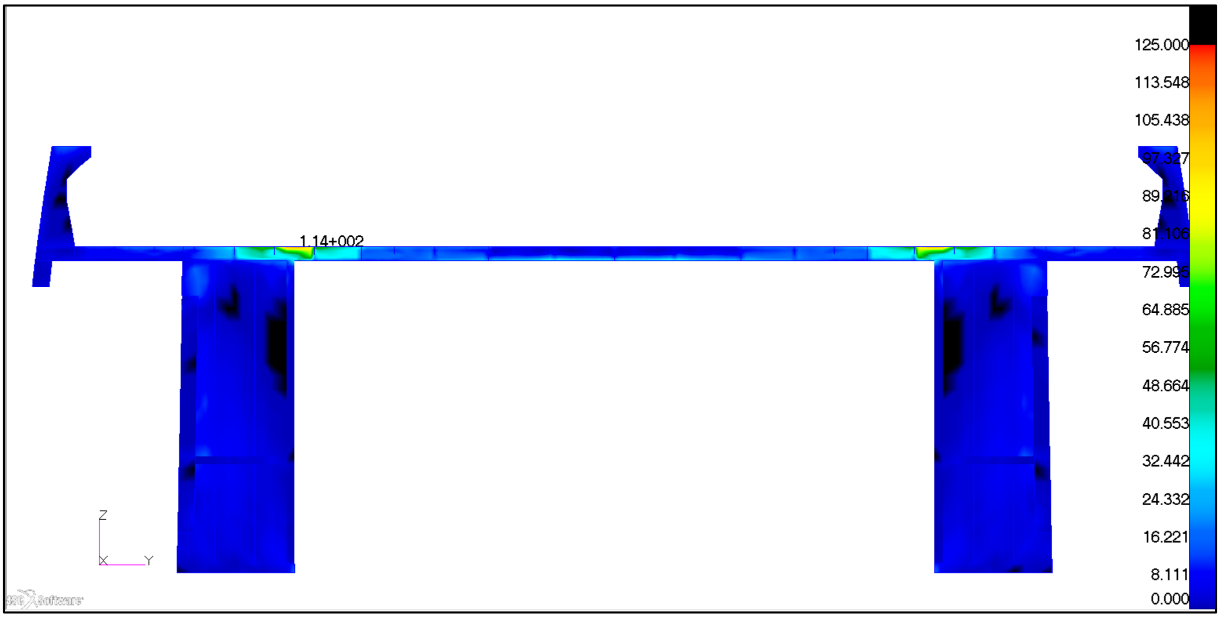


Figure 57 - Normal stress distribution on saloon double box beam structure – Load Case 4

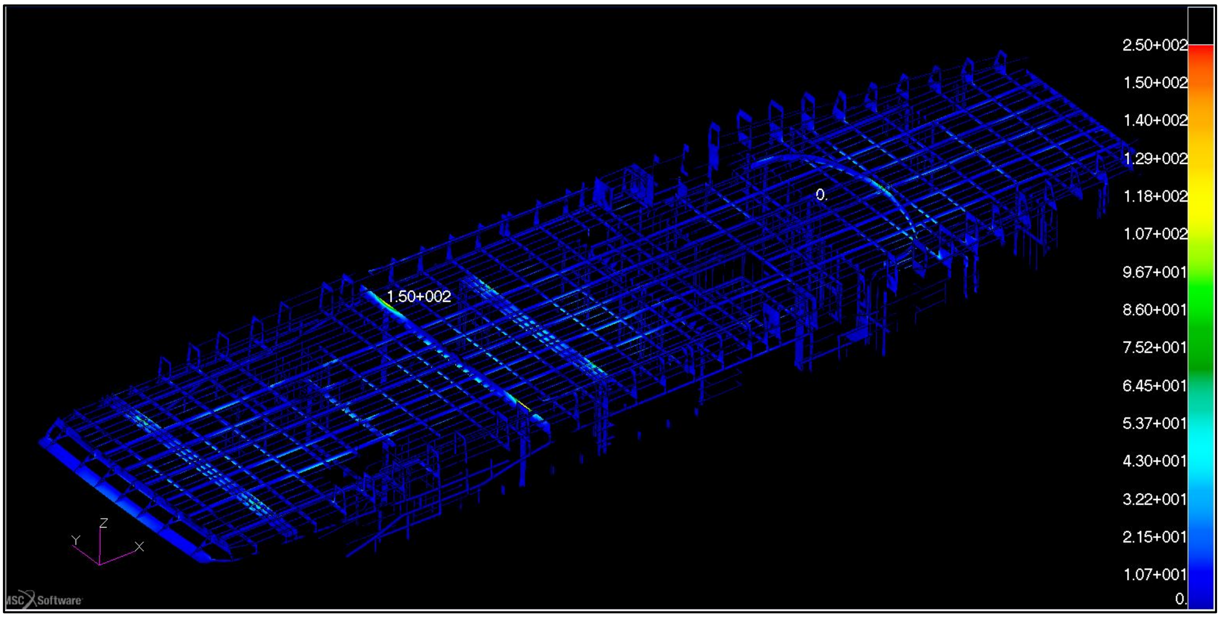


Figure 58 - Normal stress distribution on the reinforcements – Load Case 4

The maximum normal stress occurs for all for load cases (1, 3a, 3b and 4) on the web of the hatch of the aft upper deck saloon door.

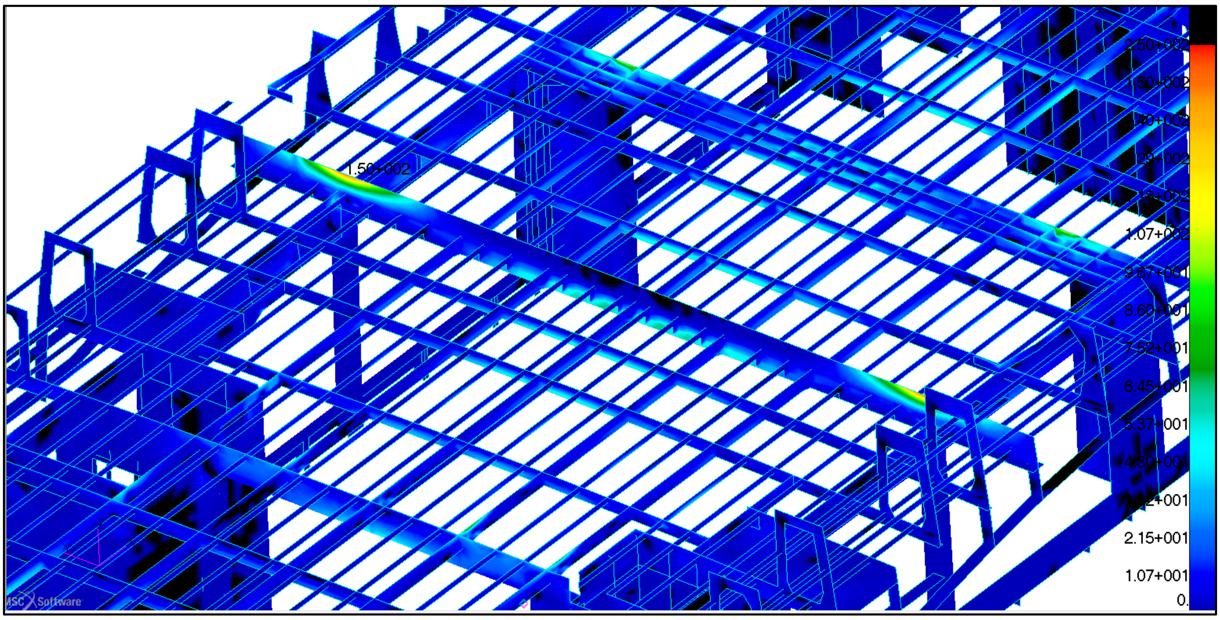


Figure 59 - Normal stress distribution on bulkhead frame, hatch frame and saloon double box beam structure – Load Case 4

5.4.3.2. Load Case 5

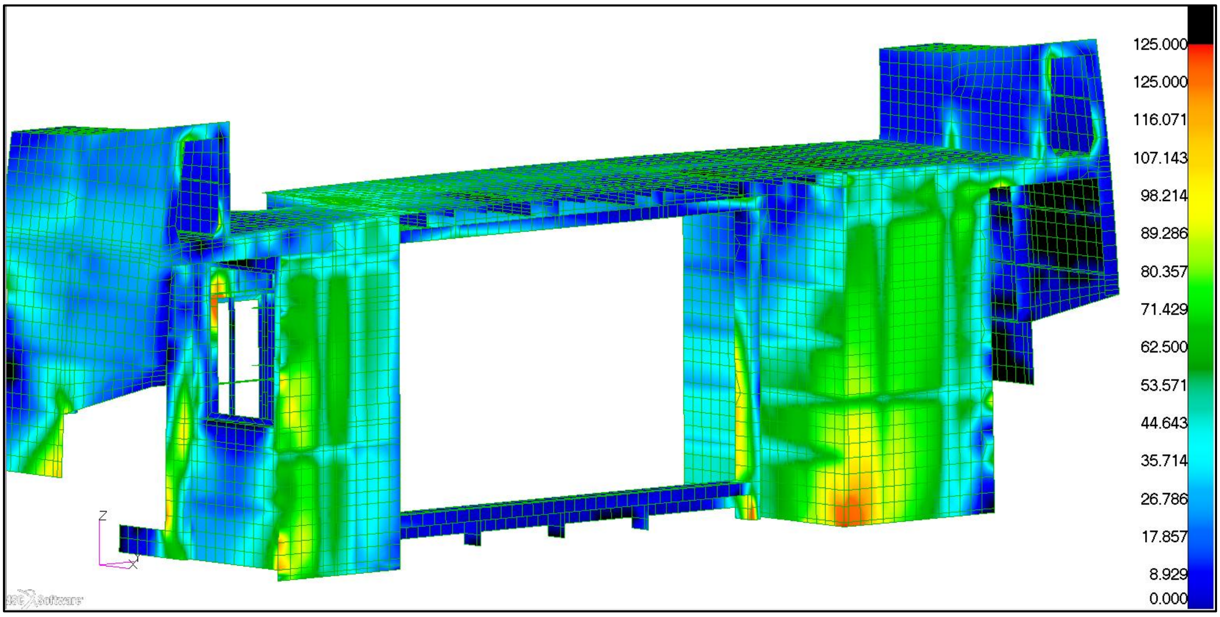


Figure 60 - Normal stress on aft bulkhead of the saloon

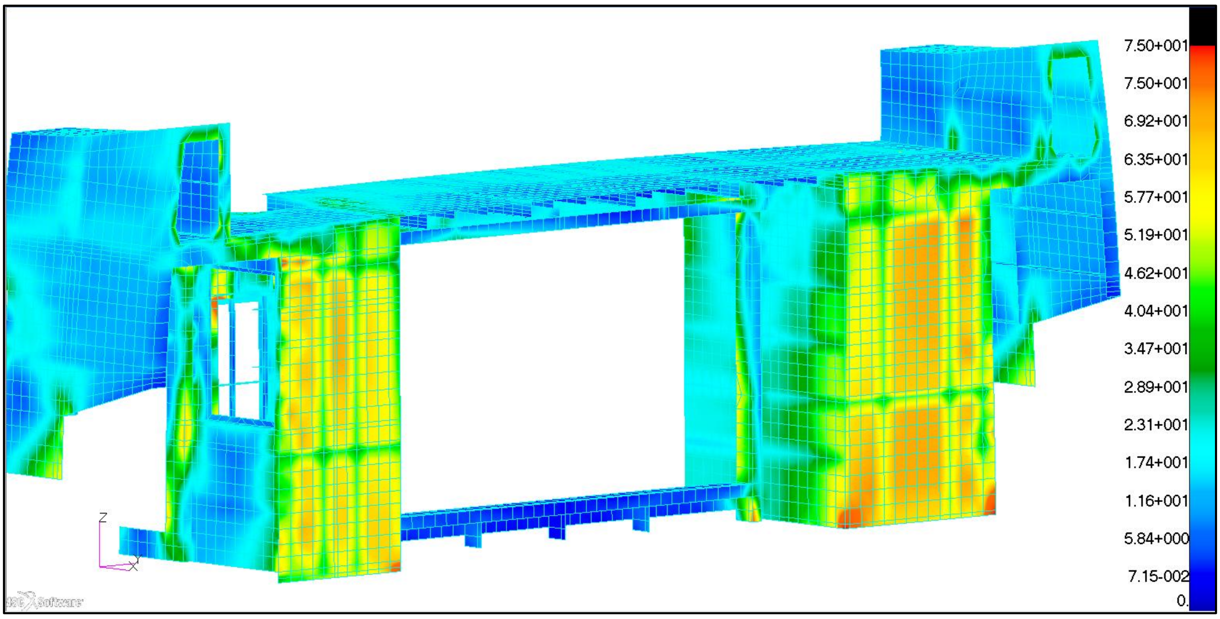


Figure 61 - Shear stress on aft bulkhead of the saloon

When breaking down the resulting stress on the shells, it is made clear that the transverse plates are close to yielding due to the elevated shear stress, which maximum values is at a 45° angle of the normal stress.

5.4.3.3. *Summary*

Table 28 - Maximum Shear stress τ

Member	Load Case					
	1	2	**3a**	**3b**	**4**	**5**
	MPa	MPa	MPa	MPa	MPa	MPa
Aft double box beam	~100		~70	~65	~90	
Aft Trunk Stiffener		~30				
Bulkhead stringer						~90
Saloon Bulkhead	~50		~40	~35	~50	
Aft Trunk shell		~50				
Bulkhead shell						~70

Table 29 – Maximum axial stress σ

Member	Load Case					
	1	2	**3a**	**3b**	**4**	**5**
	MPa	MPa	MPa	MPa	MPa	MPa
Aft double box beam	~180		~140	~120	~170	
Aft Trunk Stiffener		~80				
Bulkhead stringer						~170
Saloon Bulkhead	~105		~85	~80	~75	
Aft Trunk shell		~95				
Bulkhead shell						~130

6. COMPARISON OF RESULTS FEM vs RULES

Table 30 - Maximum Shear stress

Member	Load Case						Rule Limits		
	1	2	**3a**	**3b**	**4**	**5**	**RINA**	**LR**	**ABS**
	MPa	MPa	MPa	MPa	MPa	MPa	MPa	MPa	MPa
Aft Triple T-beam	~100		~70	~65	~90				
Aft Trunk Stiffener		~30					144	144	N/A
Bulkhead stringer						~90			
Saloon Bulkhead	~50		~40	~35	~50				
Aft Trunk shell		~50					72	72	N/A
Bulkhead shell						~70			

Table 31 - Maximum Axial stress

Member	Load Case						Rule Limits		
	1	2	**3a**	**3b**	**4**	**5**	**RINA**	**LR**	**ABS**
	MPa	MPa	MPa	MPa	MPa	MPa	MPa	MPa	MPa
Aft Triple T-beam	~105		~90	~85	~130				
Aft Trunk Stiffener		~70					220	187	175
Bulkhead stringer						~180			
Saloon Bulkhead	~100		~80	~65	~110				
Aft Trunk shell		~105					110	94	88
Bulkhead shell						~90			

Although some values are high, all shear and axial stresses are within the allowable limits that the materials provide.

Table 32 - Maximum Stress comparison with the Rules

Member	Load Case						Rule Limits		
	1	2	**3a**	**3b**	**4**	**5**	**RINA**	**LR**	**ABS**
	MPa	MPa	MPa	MPa	MPa	MPa	MPa	MPa	MPa
Aft Triple T-beam	~180		~140	~120	~170				
Aft Trunk Stiffener		~80					220	187	175
Bulkhead stringer						~170			
Saloon Bulkhead	~105		~85	~80	~75				
Aft Trunk shell		~95					110	94	88
Bulkhead shell						~130			

Although some stresses may be deemed high, for load cases 1 to 4, the resulting stresses on the various members are still within the Rule limits. Nevertheless if a racking condition is analysed (load case 5) then we can see that especially the shell plating of the interior bulkheads might not withstand the load acting on them. However it has to be reminded that σ_{max} for the reinforcements was considered as 250 N/mm^2 and 125 N/mm^2 for the shells.

Table 33 - Maximum deformation comparison with HSC Rule

Areas	Load Case					Limit	
	1	**3a**	**3b**	**4**	**5**	**HSC**	**R&D**
	mm	mm	mm	mm	mm	mm	mm
Saloon interior	23.4	15.6	15.1	24.8		65	48.8
Exterior Deck Dining	20.7	13.6	18.2	18.4		50	37.5
Exterior Deck Aft	17.1	17.1	12	18.3		21	15.8
Exterior Deck Bow	7.98	5.19	5.3	10.1		33	24.8
Racking							
Upper deck bulwark					14.3	7.5	5.6
Side plating					10.5	23.7	17.8

Analysing the plate deformation of load case 1 to 4, all are within the limits, however the plating at the extreme aft deck deforms substantially. Once again the racking condition shows that the upper deck bulwark deforms a lot too, however the material does not fail as the stresses in that zone are low. On the other hand, this transverse movement may cause implications to the above structures resting upon the bulwark.

7. CONCLUSION

The comparison of the three Classification Rules has shown that a yacht classified according ABS Rules will have a heavier, thus more robust, structure. On the other hand, a RINA classified yacht will have a lighter structural layout which may be prone to more critical areas and higher buckling risks of the interior frames. However from a purely scantling calculation point of you, all supporting structures apart from one met the required Rule limits.

Looking at the FEM model from a static and global point of view of the superstructure, it also did not show any critical deformations or stresses. Nonetheless, locally there were some areas which showed elevated stress and deformation that could be re-evaluated and strengthened, for example by increasing the web heights of the primary beams and girders. Also, the supporting beam that did not meet the Rule requirements showed no concerns in the FEM analysis.

However, it was the racking phenomenon that caused the most problems to the entire superstructure. This can be due to two facts, one being that since the transverse acceleration is derived from HSC (High Speed Craft) Rules the values may be higher than what a pleasure yacht would be subject to. Secondly, so far the Classification Societies have not addressed this issue in detail by not setting any limits. Therefore it remains up to the individual yards and their engineers to evaluate the results. Following the current trend of the ever increasing length of yachts and superyachts, which subsequently means more tiers and higher superstructure, racking could become a valid problem. Another aspect to consider is the racking effect on the large glass windows, which if too high can cause the glass to break. The fact that some Rules give formulas to calculate the transverse acceleration that is then to be used in direct calculations brings us to the final point.

A FEM analysis is a very lengthy procedure, so is it worth applying to a superstructure? The answer, in my opinion, is yes, especially when considering transverse acceleration. It is clearly visible that when dealing with highly complex and irregular structures (i.e. superstructures with large windows) a direct calculation analysis is advised to be done in order to evaluate and verify the scantling dimensioning and to possibly optimise the structure. A further step with such an analysis could be to analyse the racking effect with glass panels, and check for buckling problems, which tends to be an issue where the loads must be supported by relatively small pillars or frames in the large open spaces of today's yachts.

8. AKNOWLEDGEMNTS

I would like to express my gratitude to my supervisor Prof. Dario Boote, for his expertise and guidance throughout my post-graduate experience and for advising me to take part in the EMSHIP program. I would also like to thank Prof. Philippe Rigo for his ship structure teachings which turned out to become the essence of my thesis.

I would like to thank all of the professors and assistants at ULG, ECN and UNIGE for their teachings and assistance over the past 18 months.

A special thanks goes to the entire R&D Department of Azimut-Benetti, especially to Dr. Carlo Ighina and Matteo Lasagna for their guidance and patience throughout the past 7 months.

I would also like to thank my family for the support they provided me throughout the years and all my EMSHIP friends with whom we have experienced so much in so little time!

This thesis was developed in the frame of the European Master Course in “Integrated Advanced Ship Design” named “EMSHIP” for “European Education in Advanced Ship Design”, Ref.: 159652-1-2009-1-BE-ERA MUNDUS-EMMC.

9. REFERENCES

Rules	RINA Rules for the Classification of Pleasure Yachts, Part B, Ch.1 Sec.5; Ch.3 Sec.1, Sec.3, Sec.9, Sec.11, 2013
	Lloyds Register Rules and Regulations for the Classification of Special Service Craft, Volume 3 Part 5; Volume 5 Part 7, 2013
	ABS Guide for Building and Classing Motor Pleasure Yacht, Sec.2, Sec.8, Sec.9, February 2000
	DNV High Speed, Light Craft and Naval Surface Craft Part 5 Chapter 5, Special Service and Type – Additional Class Yachts, 2012
	GL Rules for the Classification and Construction, Ship Technology, Special Craft, Yachts ≥ 24m, 2003
	MCA Large Commercial Yacht Code LY3, 2012
Journal	SSC-439 Comparative Structural Requirements for High Speed Crafts, 2005
	Schade HA. The effective breadth concept in ship-structure design. Trans SNAME 1953;61:410–30
Thesis	Vergassola, Gianmarco 2015. *Finite Element Models for Naval Buckling*. Master Thesis. Università degli Studi di Genova.
Technical Report	Prof. Boote Dario and Dr. Ighina Carlo, 2004, *Verifica del Dimensionamento della Sezione Maestra con i Regolamenti RINA, ISO, DNV e ABS*, DINAV Università degli Studi di Genova.
Manuals	MSC Patran 2013 User's Guide, MSC Software

APPENDICES

APPENDIX A1 – Vertical and Transverse Acceleration Calculations

Vertical acceleration a_{CG}		
S		0.29
V	kn	14.5
L	m	37.21
C_F		0.45
a_{CG} (in g)		0.70

Longitudinal distribution of vertical acceleration									
Component		6 People load		Sun deck Weight			Distributed Outfitting		
Location		upper deck stern	interior saloon	stern	mid	fore	stern	mid	fore
kv		0.8	1.00	0.80	1.10	1.47	0.80	1.10	1.66
x/L		0.11	0.50	0.23	0.55	0.74	0.23	0.55	0.83
a_v (in g)		0.56	0.70	0.56	0.77	1.03	0.56	0.77	1.16
new a_v factor		1.56	1.70	1.56	1.77	2.03	1.56	1.77	2.16
a_v effective	mm/s^2	15296	16669	15296	17329	19909	15296	17329	21162

Transverse acceleration a_t			
H_{sl}	m	18.28	
V	kn	14.5	
L	m	37.21	
r		4.65	6.15
a_t (in g)		2.72	3.21
a_t effective	mm/s^2	26723	31457
Z_{deck}	m	4.5	4.5
$Z_{upper\ deck}$	m	6.9	8.4

APPENDIX A2 – Rule Scantling Calculations

RINA

Superstructure Deck

			Deck plate location					
			Aft deck exterior	Interior saloon	Interior saloon	Interior	Interior	Bow exterior
Plating								
$t = 3.9 \times s \times \sqrt{K \times h}$	t	mm	1.10	1.10	1.10	1.10	1.10	1.10
s: stiffener spacing	s	m	0.3	0.3	0.30	0.30	0.30	0.30
h: conventional scantling height	h	m	1	1	1	1	1	1
$K = \frac{110}{(\eta \times R_{p0.2})}$	K		0.88	0.88	0.88	0.88	0.88	0.88
	η		1	1	1	1	1	1
	$R_{p0.2}$	N/mm²	125	125	125	125	125	125

			Double Box Beam Aft deck Exterior	Hatch Frame Saloon	Double Box Beam Saloon	Beam (4)	Beam (5)	Beam (6)
Reinforced Beams								
$Z = 9 \times b \times S^2 \times K \times h$	Z	cm³	**416**	**494**	**335**	**175**	**93**	**44**
h: conventional scantling height	h	m	0.9	0.9	0.9	0.9	0.9	0.9
b: average width of the strip of deck resting on the beam	b	m	3.57	3.3	3.25	1.75	2.72	3.4
S: conventional span of the reinforced beam, equal to the distance between two supporting members	S	m	5.72	6.48	5.38	5.3	3.1	1.9
$K = \frac{110}{}$	K		0.44	0.44	0.44	0.44	0.44	0.44
$(\eta \times R_{p0.2})$	η		1	1	1	1	1	1
	$R_{p0.2}$	N/mm²	250	250	250	250	250	250

Minimum plate thickness
$t_{min} = 1.5\, L^{1/3} K^{0.5}$
4.70

LR

Superstructure Deck

			Deck plate location					
			Aft deck exterior	Interior saloon	Interior saloon	Interior	Interior	Bow exterior
Plating								
$t_p = 22.4 s\gamma\beta \sqrt{\frac{p}{f_\sigma \sigma_a}} \times 10^{-3}$	t	mm	2.07	1.85	1.85	1.85	1.85	2.44
s: stiffener spacing	s	mm	300					
γ: convex curvature correction factor	γ		1					
β: panel aspect ratio correction factor	β		1					
p: design pressure	p	kN/m²	8.92	7.13	7.13	7.13	7.13	10.71
f_σ : limiting bending stress coefficient	f_σ		0.75	0.75	0.75	0.75	0.75	0.65
σ_a: guaranteed minium 0.2% proof stress of the alloy in welded condition	σ_a	N/mm²	125					

			Double Box Beam Aft deck Exterior	Hatch Frame Saloon	Double Box Beam Saloon	Beam (4)	Beam (5)	Beam (6)
Reinforced Beams								
$Z = \Phi_Z \frac{p s l_e^2}{f_\sigma \sigma_a}$	Z	cm³	**534**	**507**	**344**	**180**	**96**	**67**
Φ_Z section modulus coefficient	Φ_Z		0.08					
f_σ limiting bending stress coefficient	f_σ		0.65	0.65	0.65	0.65	0.65	0.65
p: design pressure	p		8.92	7.13	7.13	7.13	7.13	10.71
s: stiffener spacing	s	mm	3570	3300	3250	1750	2720	3400
l_e effective span length	l_e	m	5.72	6.48	5.38	5.30	3.10	1.90
σ_a: guaranteed minimum 0.2% proof stress of the alloy in welded condition	σ_a	N/mm²	250					

Pressure on weather decks								
$P_{wh} = f_L(6 + 0.01 L_{WL})(1 + 0.05\Gamma) + E$	P_{wh}	kN/m²	8.92	7.13	7.13	7.13	7.13	10.71
f_L: location factor for weather decks	f_L		1	1	1	1	1	1.25
$E = \frac{0.7 + 0.08 L_{WL}}{D - T}$	E	kN/m²	1.79	0	0	0	0	1.79
D: depth	D	m	4.45					
T: draught	T	m	2.40					
Γ: Taylor coefficient	Γ		2.38					
V: design speed	V	kn	14.50					
L_{WL}: waterline length	L_{WL}	m	37.21					

Design Pressure								
$P_{dhp} = C_1 \times P_d$	P_{dhp}	kN/m²	8.92	7.13	7.13	7.13	7.13	10.71
C_1			1	1	1	1	1	1

Strength/Main deck plating			
$t_{min} = \omega\sqrt{k_m}(0.5\sqrt{L_R} + 1.4)$		Plate thickness of FB701	
4.45		4	
ω	1.00	σ_A	125
k_m	1	σ_U	260

ABS

Superstructure Deck			Deck plate location					
			Aft deck exterior	Interior saloon	Interior saloon	Interior	Interior	Bow exterior
Plating								
$t = s\sqrt{\frac{pk}{1000\sigma_a}}$	t	mm	1.80	1.80	1.80	1.80	1.80	2.21
s: stiffener spacing	s	mm	300					
p: design pressure	p	kN/m^2	9.01	9.01	9.01	9.01	9.01	13.53
k:	k		0.5					
σ_a: guaranteed minium 0.2% proof stress of the alloy in welded condition	σ_a	N/mm^2	125					

			Double Box Beam Aft deck Exterior	Hatch Frame Saloon	Double Box Beam Saloon	Beam (4)	Beam (5)	Beam (6)
Reinforced Beams								
$SM = \frac{83.3 \times psl^2}{\sigma_a}$	SM	cm^3	**501**	**595**	**404**	**211**	**112**	**79**
p: design pressure	p	kN/m^2	9.01	9.01	9.01	9.01	9.01	13.53
s: stiffener spacing	s	m	3.57	3.3	3.25	1.75	2.72	3.4
l: effective span length	l	m	5.72	6.48	5.38	5.30	3.10	1.90
σ_a: design stress	σ_a	N/mm^2	175					

σ_y	250

Minimum plate thickness
$t_{min} = 0.012 \times s$
3.60

APPENDIX A3 – Effective Breadth Calculations

Effective Breadth

		Double Box Beam Aft deck Exterior	Hatch Frame Saloon	Double Box Beam Saloon	Beam (4)	Beam (5)	Beam (6)
B	*m*	3.57	3.30	3.25	1.75	2.72	3.40
L	*m*	5.72	6.48	5.38	5.30	3.10	1.90
b_e/B		0.35	0.45	0.36	0.69	0.21	0.06
effective breadth b_e	*mm*	1241	1487	1181	1199	567	199

APPENDIX A4 – Transverse Beam Scantlings Calculations

Double Box Beam Aft Deck Exterior (1)

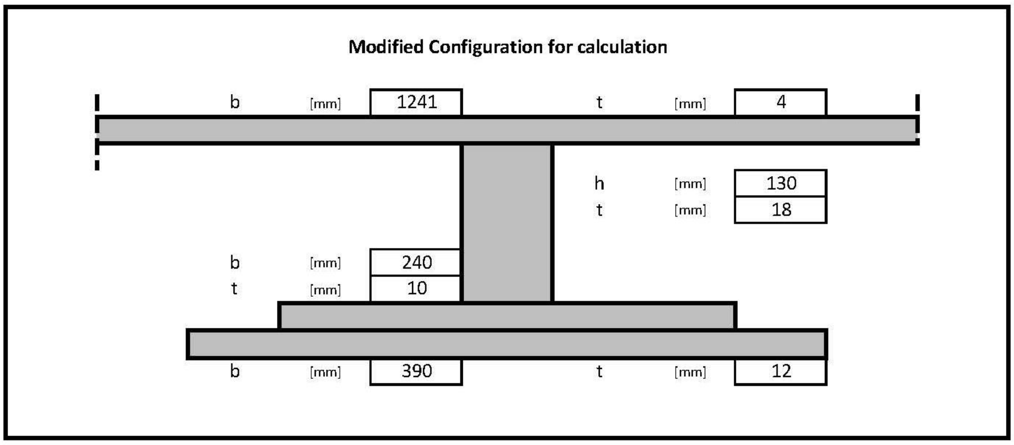
Element	a_i	b_i	A_i	d_i	A_i*d_i	I_o	d'_i	$A_i*(d'_i)^2$
	mm	mm	mm^2	mm	mm^3	mm^4	mm	mm^4
Plate	1241	4	4964	2	9929	6619	-81.91	33307222
Girder Web	18	130	2340	69	161460	3295500	-14.91	520136
Girder Flange	240	10	2400	139	333600	20000	55.09	7284025
Additional flange	390	12	4680	150	702000	56160	66.09	20442291
TOTAL			**14384**		**1206989**	**3378279**		**61553675**

Zg	I
(Ai * di)/Ai	(Ai * di^2) + Io
mm	mm^4
83.9	**64931954**

minimum Z required	cm^3	416

d_plate	mm	72.1
d_flange	mm	83.9
Wplate	cm^3	901
Wflange	cm^3	774

Wmin	cm^3	774	**OK**



Hatch Frame Saloon (2)

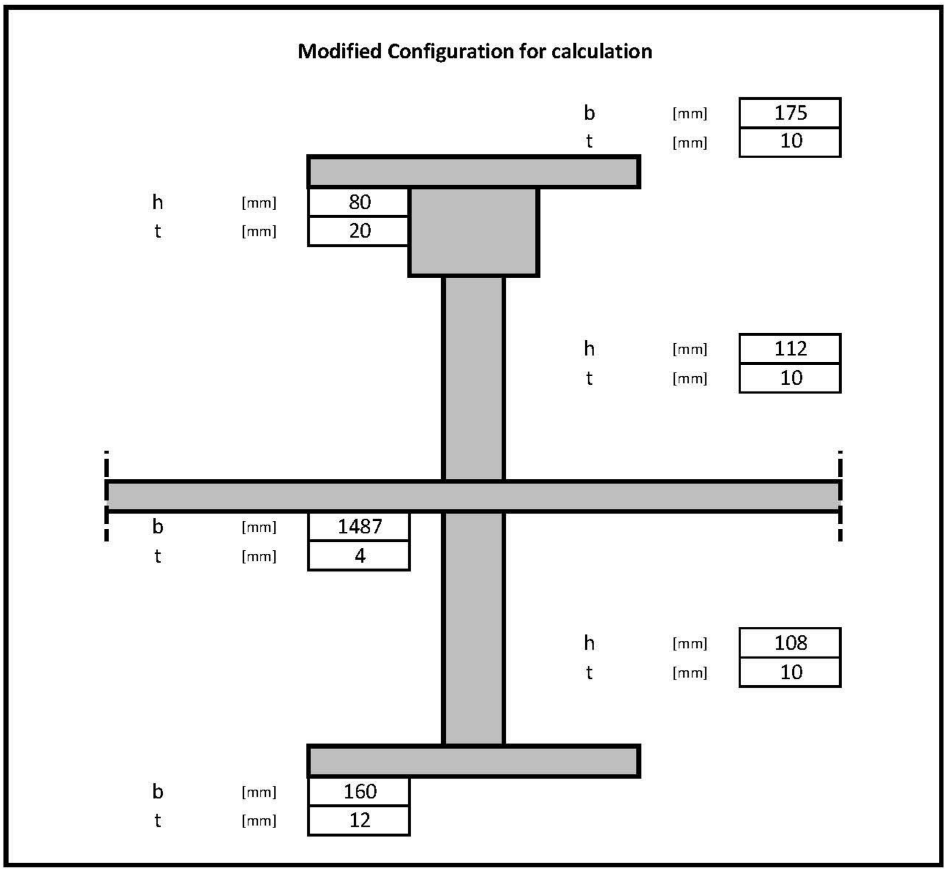
Element	a_i	b_i	A_i	d_i	A_i*d_i	I_o	d'_i	$A_i*(d'_i)^2$
	mm	mm	mm²	mm	mm³	mm⁴	mm	mm⁴
Additional Flange	175	10	1750	5	8750	14583	170.95	51141335
Additional Web II	20	80	1600	50	80000	853333	125.95	25381111
Additional Web	10	112	1120	146	163520	1170773	29.95	1004587
Plate	1487	4	5949	204	1213567	7932	-28.05	4680851
Girder web	10	108	1080	260	280800	1049760	-84.05	7629705
Girder flange	160	12	1920	320	614400	23040	-144.05	39841230
TOTAL			13419		2361037	3119422		129678818

Zg	I
(Ai * di)/Ai	(Ai * di^2) + Io
mm	mm⁴
175.9	132798240

minimum Z required	cm³	494

d_plate	mm	150.1
d_flange	mm	175.9
Wplate	cm³	885
Wflange	cm³	755

Wmin	cm³	755	OK



Double Box Beam Saloon (3)

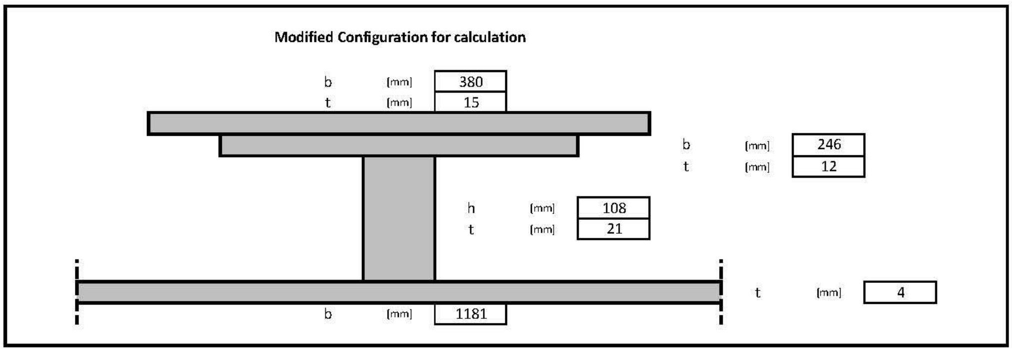
Element	a_i	b_i	A_i	d_i	$A_i * d_i$	I_o	d'_i	$A_i *(d'_i)^2$
	mm	mm	mm^2	mm	mm^3	mm^4	mm	mm^4
Plate	1181	4	4724	2	9447	6298	-77.19	28147420
Girder Web	21	108	2268	58	131544	2204496	-21.19	1018742
Girder Flange	246	12	2952	118	348336	35424	38.81	4445459
Addit flange	380	15	5700	132	749550	106875	52.31	15594798
TOTAL			**15644**		**1238877**	**2353093**		**49206420**

Zg	I
(Ai * di)/Ai	(Ai * di^2) + Io
mm	mm^4
79.2	**51559513**

minimum Z required	cm^3	335

d_plate	mm	59.8
d_flange	mm	79.2
Wplate	cm^3	862
Wflange	cm^3	651

Wmin	cm^3	651	**OK**



Reinforced Beam (4)

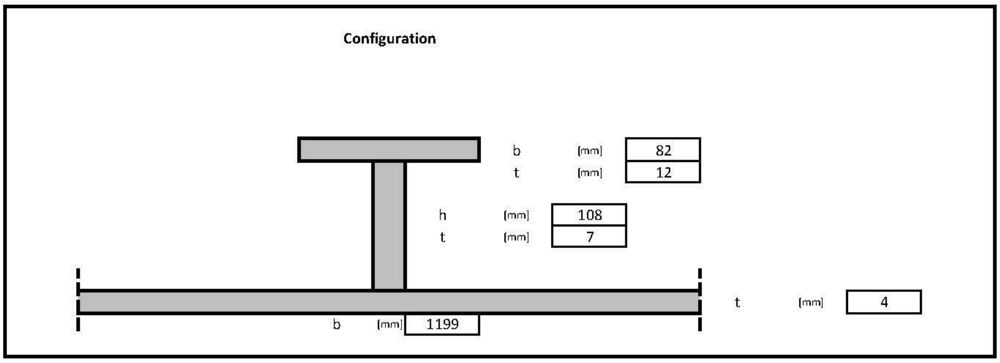
Element	a_i	b_i	A_i	d_i	A_i*d_i	I_o	d'_i	$A_i*(d'_i)^2$
	mm	mm	mm^2	mm	mm^3	mm^4	mm	mm^4
Plate	1199	4	4795	2	9591	6394	-23.94	2749138
Girder Web	7	108	756	58	43848	734832	32.06	776890
Girder Flange	82	12	984	118	116112	11808	92.06	8338845
TOTAL			6535		169551	753034		11864873

Zg	I
(Ai * di)/Ai	(Ai * di^2) + Io
mm	mm^4
25.9	12617906

minimum Z required	cm^3	175

d_plate	mm	98.1
d_flange	mm	25.9
Wplate	cm^3	129
Wflange	cm^3	486

Wmin	cm^3	129	Failed



Reinforced Beam (5)

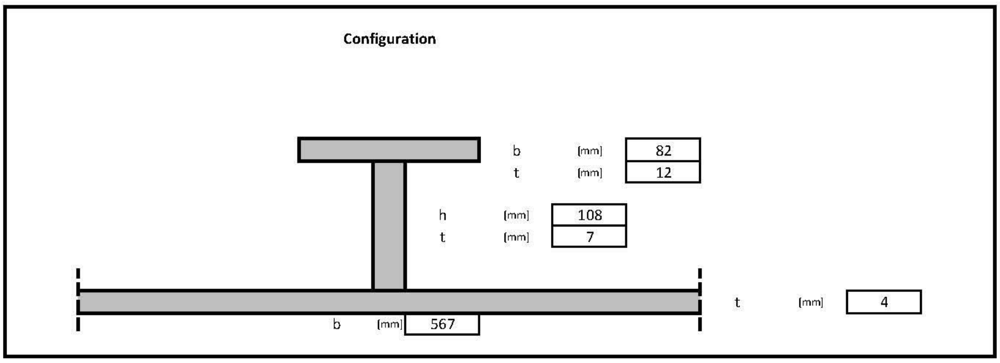
Element	a_i	b_i	A_i	d_i	A_i*d_i	I_o	d'_i	$A_i*(d'_i)^2$
	mm	mm	mm^2	mm	mm^3	mm^4	mm	mm^4
Plate	567	4	2268	2	4536	3024	-39.04	3457058
Girder Web	7	108	756	58	43848	734832	16.96	217394
Girder Flange	82	12	984	118	116112	11808	76.96	5827703
TOTAL			**4008**		**164496**	**749664**		**9502156**

Zg	I
(Ai * di)/Ai	(Ai * di^2) + Io
mm	mm^4
41.0	**10251820**

minimum Z required	cm^3	93

d_plate	mm	83.0
d_flange	mm	41.0
Wplate	cm^3	124
Wflange	cm^3	250

Wmin	cm^3	124	OK



Reinforced Beam (6)

Section Modulus								
Element	a_i	b_i	A_i	d_i	A_i*d_i	I_o	d'_i	$A_i*(d'_i)^2$
	mm	mm	mm^2	mm	mm^3	mm^4	mm	mm^4
Plate	199	4	796	2	1592	1062	-61.70	3030858
Girder Web	7	108	756	58	43848	734832	-5.70	24558
Girder Flange	82	12	984	118	116112	11808	54.30	2901371
TOTAL			2536		161552	747702		5956787

Zg	I
(Ai * di)/Ai	(Ai * di^2) + Io
mm	mm^4
63.7	6704488

minimum Z required	cm^3	44	
d_plate	mm	60.3	
d_flange	mm	63.7	
Wplate	cm^3	111	
Wflange	cm^3	105	
Wmin	cm^3	105	OK