Structural scantling of yachts: different direct calculations vs. numerical analysis

Auteur : Sipauba Rocha Coelho Santos, Marianna
Promoteur(s) : Rigo, Philippe
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by

SIPAUBA ROCHA COELHO SANTOS Marianna
Via Sant' Agostino 24
19121 La Spezia
marianna.sipauba@poli.ufrj.br
Student ID No.: 222 202 279

Supervisor:
Beatrice Zolesi
Sanlorenzo S.p.A.

First Reviewer:
Prof. Dr. Eng./Hiroshima Univ. Patrick Kaeding
Chair of Ship Structures
Albert-Einstein-Str. 2
18059 Rostock
Germany

Second Reviewer:
Dr. Gianmarco Vergassola, PhD
Researcher of Ship Structures
Via Montallegro 1
16100 Genova
Italy

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MASTER THESIS

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List of Abbreviations

2T	Second Tier
3T	Third Tier
ABS	American Bureau of Shipping
CB	Cantilever Beam
CL	Centerline
DH	Deckhouse
DOF	Degree of Freedom
FEA	Finite Element Analysis
LR	LLoyd's Register
LT	Lowest Tier
O	Opening
SLSQP	Sequential Least Squares Programming
SP	Superstructure
SQP	Sequential Quadratic Programming

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ABSTRACT

Nowadays yacht's superstructures represent a real complex problem to structural engineers. Ship's structural calculations already constitute a difficult task, but when it comes to yachts the level of compromise for this design field is increased. Since the main purpose of these type of ships is usually leisure, the general arrangement, aesthetics and clients requirements are prioritized. Therefore, the yacht structure needs to fulfill these constraints and, actually, enable most of them. This fact is amplified for the superstructure area. The most common desired large windows, open spaces, pools and jacuzzi are only possible because of the complex structure behind it.

In this work, the superstructure of a real yacht is analyzed in terms of two different classification societies: Lloyd's register and ABS. The first part consisted into performing rule-based calculations in order to verify and compare both register's requirements. To achieve that two python codes were created based on each classification society rules. In the end, it was also possible to implement an optimization procedure in order to obtain the lighter structural design possible for the study case. The comparisons shown that LR is more severe for safety coefficients, but ABS compensates that with higher requirements for design loads.

Finally, the second part of the study was to perform a finite element analysis for the optimized structure. The idea was to evaluate the proposed design in terms of its structural reliability and to comprehend if there was space for further improvements. The FEA was performed for the deck pressures load case. The results were positive for most locations, and shown some localized problems. Specific locations appear to need local reinforcement, while other would require geometrical smoothing. At last, it was possible to state that a satisfactory design was proposed. Future works could involve, however, other load cases to evaluate possible different weak locations.

Keywords: classification society, direct calculation, finite element method, finite element analysis, python, rule-based design, yacht structural design.

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1. INTRODUCTION

The design of a ship consists in the development of several aspects to originate the final product. Moreover, the compromise of theses aspects in relation to one another. The structural design is one of the most important of these aspects, since will be the part responsible to enable the hull's form conceived. And also to sustain the loads under which the ship is subjected. In fact, since the early phases, most of the ship design aspects will be influenced by the structural design (Motta, Caprace, Rigo, and Boote 2011). Therefore, it is very important to provide an accurate design from the early phases of the ship design. However, the structural design can be a very complex task to perform, to estimate the loads acting on the ship and how the structures are interacting to each other. For yachts design, even more, the degree of complexity is increased by the fact that the general arrangement will be a restraining aspect. This means that the structural design will be limited by the conceived design in order to satisfy the client requirements.

Accordingly to Boote, Vergassola, Pais, and Kramer (2017), nowadays trend markets determine open spaces, natural light from large windows and big stairwells. All theses requirements will influence and limit the structure calculations. Besides that, light structures are required in order to make room in the weight displaced for more gadgets and devices for the client. Because of the limitations in dimensions and in weight, an optimized structural design from the early phases becomes a crucial factor to be studied.

1.1. Background and Motivation

For the purpose of discuss about structural design and analysis, it is important to have a short review about some basic concepts. In the ship building industry, the structures are composed by plates and stiffeners in longitudinal and transversal directions, composing a grid to sustain and transfer the loads. The main framing system can be of longitudinal or transversal types. A longitudinal framing system consists of bigger longitudinal stiffeners called girders intercalated by smaller simple longitudinal stiffeners. And of bigger, more spaced, transversal stiffeners that forms transversal rings in the ship cross-section, called web frames. In other hand, a transversal framing system consists of the transversal stiffeners closer to each other and a few of longitudinal stiffeners. It is also possible to have a combined framing system, which possess components from both types of framing systems. The choice of the framing system depends mainly on the majority of loads that the ship will face in its lifetime. But, the most common type applied in the ship building is the longitudinal framing system (Rigo and Rizzuto 2003 and Ayyub and Assakkaf 2003). Figure 1 illustrates the longitudinal type of framing system.

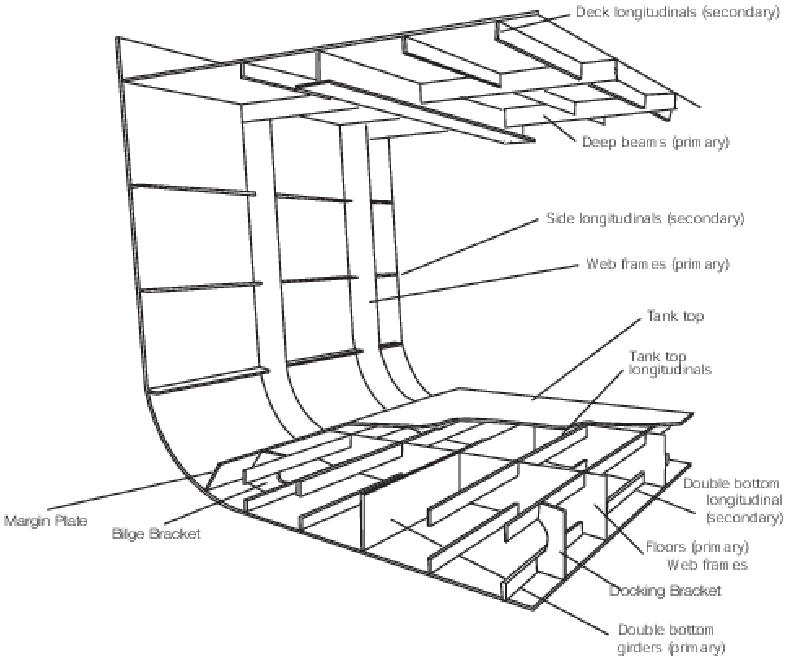


Figure 1: Exemplification of a longitudinal framing system with main components. Available from: `https://www.imorules.com/NSR_V1_PT3_CH1_5.html`

In both types of framing systems, the different components will be responsible to provide strength for the plates in the distinct loading conditions. The smaller stiffeners called secondary stiffeners will compose within the plate the called panels, which sustain for local loads and avoid plate deformations. These elements will transfer the stresses to the bigger stiffeners, called primary stiffeners. These type of reinforcements are in charge of resisting the global loads from the ship. The girders sustain for the global longitudinal bending moment from waves and the transverse web frames for transversal torsional moments.

The structure erected above the ship's maindeck is called superstructure or deckhouse and it is composed by the same type of framing than the hull. The nomenclature applied in this report is the same adopted by ABS (2022). Therefore, a superstructure is an enclosed structure which the sides are an extension of the shell plating, while a deckhouse is an enclosed structure in which the sides are set inboard the hull more than 4% of the breadth of the ship. Usually, superstructures/deckhouses will not be a complex part of the structural definition, since they are not subjected to the complex loads from the sea. However, the scenario changes when it comes to yacht design. In yachts, the superstructures/deckhouses are more challenging once they usually are covering most of the maindeck and need to comply to several aesthetics requirements, with larger openings for windows and stairs or even sustain loads from small pools for example (Boote, Vergassola, Pais, and Kramer 2017).

Accordingly to Rigo and Rizzuto (2003), there are two possible approaches to perform the structural design of a ship: rationally based and rule-based design. The rationally based design consist on the direct analysis of the structure and it is performed by the use of numerical methods. For the early stages design, the rule-based is the most common approach. In this report, direct calculation is used as a synonym to rule-based design. This is the design guided by the classification societies. The general approach is to perform the design of its midship cross-section by the application of the hull girder theory. In this theory, the hull is seen as a beam and the classic Euller-Bernoulli Beam Theory can be applied to determined the response under the global bending moment. From the beam theory assumptions of sections remaining plane and elastic material behavior, the stresses assume a linear behavior and define the cross-section section modulus. The section modulus consists in the cross-section inertia divided by the distance from the neutral axis to one of its extremities. Therefore, the midship design will depend on the required section modulus for the ship to resist the global longitudinal bending loads from the sea. Usually, the midship section is considered the determinant aspect for the main structural design since the maximum bending moment occurs at or very close to the midship section. Besides that, the classification societies required the extension of the midship section scantlings through 0.4 of the ship's length in order to ensure the requirement at the maximum bending moment location (possible fluctuations) and maximum shear location.

The midship scantlings will also be determined by required section modulus. But, in this case, considering as criteria the local loads dictated by the classification societies. These local loads will vary accordingly with the scantling position and consists typically of lateral pressure loads added by the hull-girder loads. The section modulus is, thus, calculated for each stiffener in the design and to the cross-section as a whole. Then, these values are compared to the requirements of the classification society. Typically, the limit state applied to the scantling design is the yielding strength, which means that the allowable stress is defined by the material yield strength under some safety margin coefficient. But, it is also important to perform later verification of buckling, ultimate strength and in some cases vibration and fatigue failures modes.

Since initially the structure is designed to comply within the section modulus requirement, this is a good stage to include an optimization process in order to achieve the better dimensions which still assure the safety of the project. The application of optimization process in the ship's structural design is a field broadly studied. Raikunen, Avi, Remes, Romanoff, Lillemäe-Avi, and Niemelä (2019), for example, performed an optimization in a cruise ship structural design. Their method study the optimization through a coarse mesh finite element analysis. And it pursuits to avoid the overdimensioning due to discontinuities typical for this type of ships by a relaxation of constraints. For yachts, some examples of optimization application are done by Mancuso, Saporito, and Tumino (2022) and Motta, Caprace, Rigo, and Boote (2011).

Mancuso, Saporito, and Tumino (2022) apply topology optimization method to a sailing dinghy in order to obtain internal reinforcements with a better response. They considered two types of analysis, the structural analysis using dynamic loads and a modal analysis. In the end, the authors could obtain improvements for deformations in relevant areas and reductions of moment of inertia to improve manoeuvrability and seakeeping.

Motta, Caprace, Rigo, and Boote (2011) perform the optimization of a mega yacht hull by the use of the LBR-5 software. Their idea is to extend the applicability of this software also to yachts and to show that it is possible to accomplish an optimization process in an early phase of the design process. The authors highlight that this procedure is usually done only in the final design phases to refine the structure, which can lead to several changes and re-work. Therefore, the benefits of bringing the optimization to an early phase are significant. Their work achieved optimized structural designs for both weight and costs objective functions.

The finite element analysis (FEA) is also a tool largely used in the ship design studies. Indeed, Hoque and Islam (2022) state that is the dominant discretization method applied in structural analysis. In their article, they proposed their own developed finite element tool and evaluate the stress discontinuities in common ship structures sections. Doan, Liu, Garbatov, Wu, and Guedes Soares (2020) perform a non-linear FEA to evaluate the difference between the ultimate strength of aluminium and steel panels. By considering a yacht deck panel and equivalent panels between the materials, they concluded that aluminium is a good replacement for the steel panels. It is also studied the influence of openings and the results show their essential part in the stress distributions. Moreover, it is interesting to visualize the different applications that a FEA model can provide.

Pei, Zhang, Cai, Wu, Chen, and Hu (2015) applied FEA to study the structural response of a mega yacht under waves excitation. They analyzed the multi-deck mega yacht in terms of stress distribution, variation of dynamic stress in the maindeck and comparison of structural response for superstructures with different materials. They interestingly found that the stress distribution do not vary linearly in the vertical direction, as expected by beam theory, because of additional local tensile stresses caused by the outbound water pressure. Also, the article states that the superstructure do not present an important contribution for resisting the longitudinal global bending moment from waves for both materials. But, steel superstructures will have a bigger contribution with higher stresses.

In the yachts superstructures subject, Boote, Vergassola, and Matteo (2017) evaluate the interaction of the hull-superstructure of a modern mega yachts through FEA. They conclude the contributions to the stress distribution for these large superstructures and also analyzed the influence of the glazing to it. In their work it is explained the importance of checking for buckling failure around windows frame. Even when not subjected directly to compressive loads, the stresses that arouse from the global bending moment flow in a manner to create locally compressive stresses in these areas.

In addition to that, Boote, Vergassola, Pais, and Kramer (2017) studied specifically the structural response of the superstructure by FEA. They explain the level of complexity that yacht's superstructures are achieving due to the different criteria involved. And, because of that, how a FEA is the best approach to safely assess its structural behavior. In their work, besides local loads, they considered the racking phenomena that occurs in high superstructures. The authors point out that it is important to remember about this type of loads, since it is not yet well documented, but a possible phenomena in these structures.

Meanwhile, Andric, Prebeg, Palaversa, and Zanic (2021) propose a different approach to the structural design of superstructures parts. Trough generic 3D FEM model, they apply exploration of design variants and some techniques to select the most significant topological parameters as a first step. Then, an optimization step to define near optimal design options based on the different selected objectives. Their idea was to propose a method to improve the design efficiency of these complex structures in the early design phase.

The industry interest of accelerating the early design phases is well know and common for different type of ships. Cui and Wang (2013), for example, proposes an knowledge-based engineering tool for the structural design of container ships. Which shows that even for more well-established ships, the pursuit for time decrease and better solutions is still relevant.

Indeed, the shipyard that contributes to this work makes use of its know-how and expertise to accelerate the structural design in the early design phase. On the other hand, their technique of replication from successful designs means a compromise in terms of optimized design. In the yacht context, however, every gain in weight and space is meaningful to the general arrangement possibilities. Therefore, it is of the shipyard's interest study the available margins from classification societies rules and understand the best means to include optimization in their structural design process.

1.2. Objective

The objective of this work is composed by two main parts. The first part consists in perform a study in relation to the safety margins applied in the calculations from classification societies. The idea is to compare formulations and results calculations from the principal classification societies that work within the shipyard. From the comparison among different registers it is possible to withdraw conclusions about the requirements behind the rules and level of conservatism and/or safety applied on it. Finally, it is possible to propose an optimized structure for the superstructure of the yacht in the study case.

Following the advice from Boote, Vergassola, Pais, and Kramer, the second part is composed by a finite element analysis and posterior comparison with the criteria and results from the registers. The FEA is performed in order to verify the reliability of the proposed structure under a chosen lateral pressure loading case. The final comparison among the results from the FEA and the registers calculations will help to evaluate the possibility of a even further optimization.

The complete study aims to help the shipyard to understand their possible working margins within different classification societies. In addition, if their design approach should change to be more directed to FEA, in order to achieve the best possible structural design for their yachts. Which means, the lighter, but still committed to the structural safety for the different failures modes possible.

1.3. Structure of Document

The first section of this document compiles an introduction of the thesis. It includes a short background from basic concepts theory and literature overview about the topics discussed. It closes by explaining the motivation and objective of this work.

Second section describes the methodology that is followed along the thesis. Section 3 presents the yacht in details that is part of the study case for the analysis.

Section 4 proposes a full explanation about the calculations of each classification society in the study and the initial results from this stage of comparison. The section finishes by the explanation of the optimization theory applied in the calculations and the results obtained for the proposed structural design of the study case.

Section 5 comprises a short overview from the finite element method theory. Then, it presents the FE model of the proposed design shown in section 4. The mesh, constraints and load case considered are explained. Finally, the section shows the model results for an initial analysis.

Section 6 compiles the results from section 4 and section 5 analysis. The FEA results are compared against the classifications societies criteria to evaluate the points of success and/or failure of the proposed design. The section is finished by a verification of margins for further improvements.

Section 7 consists of the conclusion of this work, pointing out the most important discovers and considerations for future works.

2. METHODOLOGY

As stated in the Subsection 1.2, the work is splitted into two main parts: comparison among different classification society and comparison through finite element analysis (FEA). Both parts are performed through the use of a study case that is presented in Section 3. For the first part, the requirements from ABS and LLod's Register are compared with regard to safety coefficients, formula coverage and rigidity between results. The design loads, required thickness and section modulus are calculated and compared to the values from the actual study case's structure. The rules from both registers are coded in *Python*. The whole code and database used in the calculations are presented in the Appendices B-F.

Figure 2 shows a scheme explaining the logistics from the codes. From the database of plates and stiffeners, functions called *Data Access* read the data and create the objects *plate* and *stiffener* accordingly. The term stiffener includes both primary and secondary members. The objects are kept in lists and have attributes such as geometric dimensions, index and specific parameters from each classification society. Then, the design pressure of each object is calculated in the homonyms class and the results are applied in the member *Register* class to obtain the requirements from the rules. For plates, the class compares the obtained required thickness with the actual one and saves the largest value. For stiffeners, the class provides also a function to calculate the actual inertia and section modulus from the stiffener real dimensions. Plates and stiffeners are connected by the attribute *location*, since for the stiffeners calculations is necessary to include the effort from the effective attached plate. The results are compiled in an *.xlsx* output file.

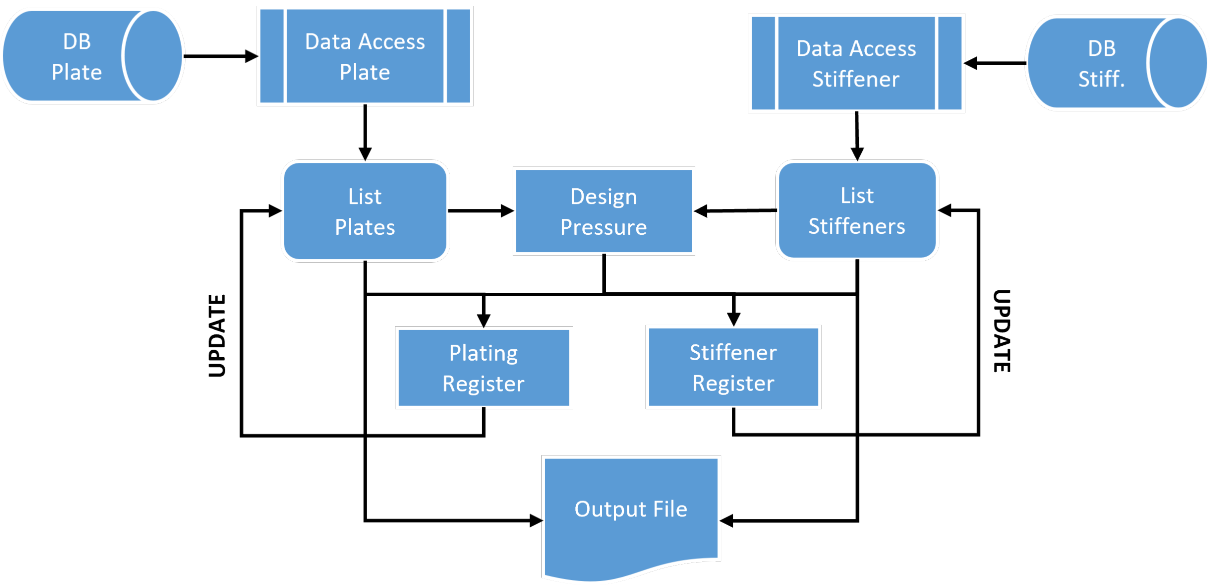


Figure 2: Illustration of methodology applied into python code for the calculation of requirements from registers.

At this step, the classification society that presents a best fit is chosen for an optimization step. The idea is to obtain the lighter structure as possible within the requirements from the selected classification society. For this step, the optimization process is also included in the *Python* code. The method used for the optimization is the Sequential Least Squares method, applicable for minimization problems of multiple variables under constraints. This method is present at the *scipy* module from *Python*, which means a convenient addition to the existent code. Figure 3 below demonstrates how the optimization process works in the code. A new function is included in the *Stiffener Register* class to proceed with the optimization. This function receives the stiffener attributes and access the already existent functions of Section Modulus and Weight calculation constantly to obtain the lighter structure complying with the required section modulus. Geometric constraints are also considered and are detailed in Subsection 4.4. Finally, the stiffener attributes are updated in the end of the process with the optimized dimensions.

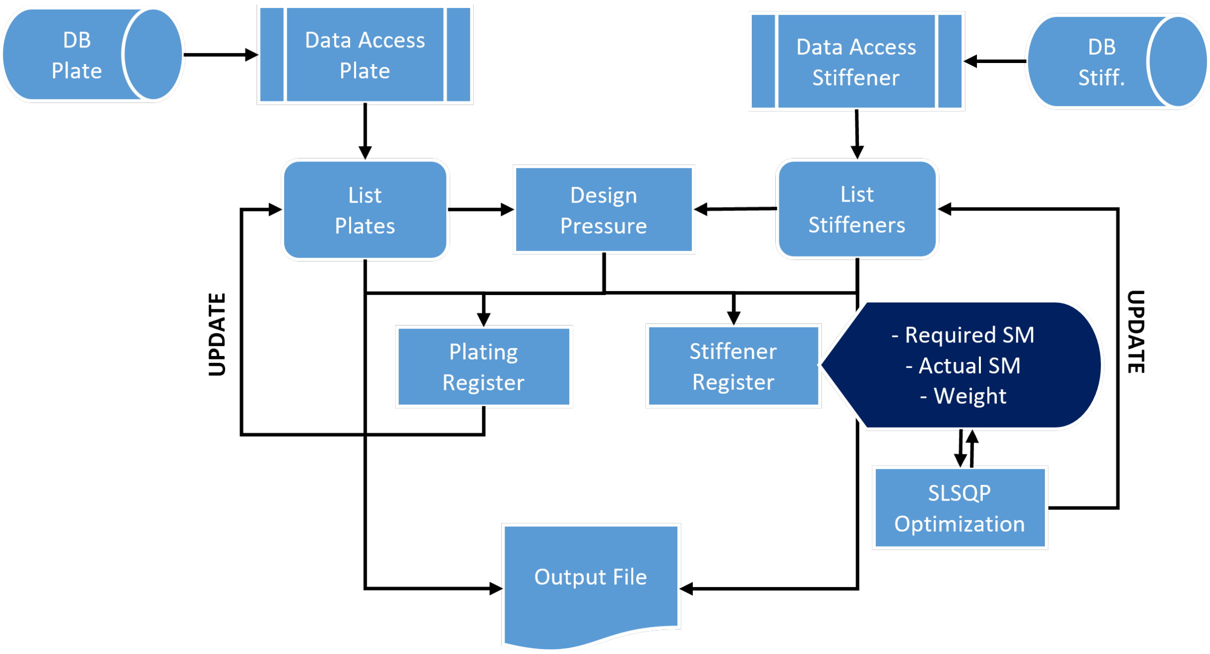


Figure 3: Inclusion of optimization step in the programming of registers' calculations.

The optimization is performed considering the same configuration as the study case design. Therefore, no changes in span, spacing or profiles types are studied under optimization. These approach is taken in order to not influence the yacht's general arrangement.

Finally, the second part is to analyze the optimized structure by finite element method. The first step consists in the modelling, which is performed through *Rhinoceros* 6.0 software. Then, exported to *MSC Apex* 2022.3 software to create the mesh, boundary conditions and load case. The solver *Nastran* 2022.4 is applied to obtain the structural behavior under a linear static loading problem. The results are compared in terms of stresses and displacements. The post-procesing is performing by the use of *MSC Patran* 2022.4.

Figure 4 summarizes the methodology followed in this report.

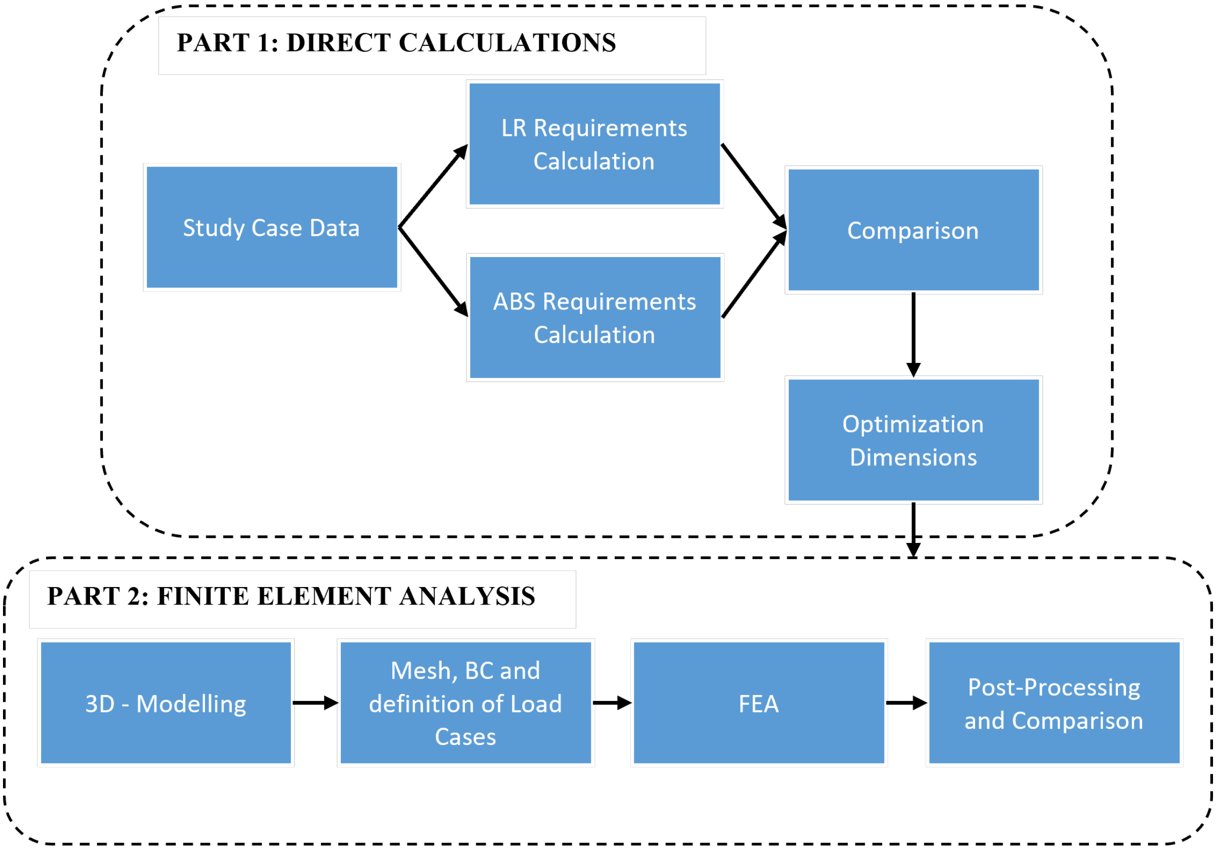


Figure 4: Flowchart followed to produce this work.

3. STUDY CASE

With the objective to perform the tasks proposed by this work, the yacht 57-meter from Sanlorenzo Shipyard is used as a study case. The yacht is shown in Figure 5 for visualization, the superstructure is composed by two decks above the maindeck. The calculations are focus in the yacht superstructure behind 25%L from the forward perpendicular, part that composes the fore plan. The main dimensions are presented in Table 2. It consists of a displacement yacht made of steel AH36 at the hull and aluminium alloy 5083-O at its superstructure. Table 3 presents the material properties from the yacht's superstructure.

Figure 5: 57-meter yacht used as study case. [Reprinted with permission from *General Arrangement Plan - MKK Proposal* provided by Sanlorenzo S.p.A.]

Table 2: Main Dimensions of 57-meter yacht.

Main Dimensions		Units
LOA	56.50	[m]
LWL	54.46	[m]
LPP	52.03	[m]
L_R	52.28	[m]
B	10.50	[m]
D	5.45	[m]
T	2.95	[m]
Cb	0.584	[-]
Δ	970	[ton]
V	16.50	[kn]

Table 3: Material properties from aluminium alloy 5083-O.

Material Properties		Units
ρ	2.70	$[g/cm^3]$
E	69×10^3	[MPa]
σ_y	125	[MPa]
σ_u	275	[MPa]

The yacht's superstructure is composed by a deckhouse and an actual superstructure, using the nomenclature from ABS explained in Section 1. Figure 6 below presents a typical cross-section (Frame 20) of the structural design.

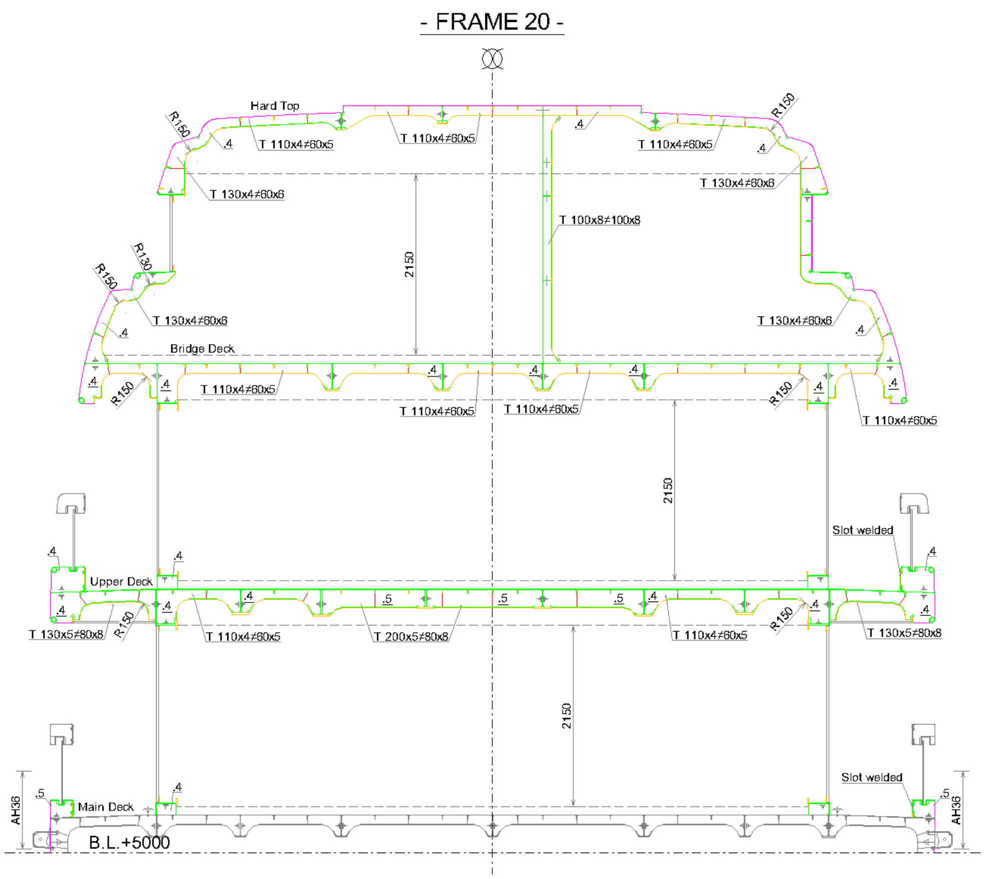


Figure 6: Cross-section of study case at Frame 20 (close to midship position). [Reprinted with permission from *Superstructure Scantling Plan* provided by Sanlorenzo S.p.A.]

For a better comprehension, the structural plan is presented in the Appendix A at Figure 47. The structural plan displayed is composed by the top view and longitudinal views at girders locations.

Table 4 presents the plating thickness for the different parts at the superstructure. Table 5 comprises the dimensions of the structural members to be verified under classification society requirements. More detail information are displayed in the input files present at Tables 47-48 and 51-52 at Appendices D and F.

Table 4: Model thickness in different locations.

Location	t $[mm]$	Location	t $[mm]$
Upper deck	5.0	2nd tier - side deckhouse	5.0
Bridge deck	5.0	2nd tier - shell	5.0
Hard top	5.0	2nd tier - front	5.0
1st tier - aft end	8.0	3rd tier - aft end	5.0
1st tier - side deckhouse	5.0	3rd tier - shell	5.0
1st tier - side superstructure	8.0	3rd tier - front	5.0
2nd tier - aft end	5.0	Internal Bulkheads	5.0

Table 5: Structural members dimensions.

Member	Location	Type	Dimensions [mm]
Transverse Beam	Decks	T-bar	$110 \times 4 + 60 \times 5$
Deck Girder	Upper and Bridge decks	T-bar	$205 \times 12 + 200 \times 20$
Deck Girder	Upper deck	T-bar	$300 \times 12 + 200 \times 20$
Deck Girder	Upper deck	Box Beam	$200 \times 12 + 200 \times 20$
Stiffener	Decks	Flat bar	50×6
Deck Girder	Bridge deck	T-bar	$300 \times 12 + 150 \times 20$
Deck Girder	Hard top	T-bar	$200 \times 5 + 200 \times 8$
Deck Girder	Hard top	T-bar	$150 \times 8 + 150 \times 12$
Web Frame	All tiers - side	T-bar	$150 \times 4 + 60 \times 6$
Web Frame	All tiers - side	Box beam	$120 \times 10 + 100 \times 10$
Side Stringer	1st and 2nd tiers - side	T-bar	$200 \times 10 + 120 \times 10$
Web Frame	1st tier - side	T-bar	$130 \times 6 + 80 \times 8$
Side Stringer	3rd tier - shell	T-bar	$130 \times 6 + 80 \times 8$
Vertical Web	Longitudinal Bulkhead	T-bar	$100 \times 5 + 80 \times 8$
Vertical Web	Transversal Bulkhead	T-bar	$100 \times 10 + 80 \times 12$
Horizontal Stringer	Bulkhead	T-bar	$100 \times 4 + 50 \times 6$

4. PART 1: DIRECT CALCULATIONS

The first part of this work consists of a comparison between the requirements from two classification societies: LLoyd's Register and ABS. The objective is to comprehend how each one is applied for the structure definition and how the requirements vary between them. As explained before, the study case structure was approved by LLoyd's Register. Therefore, it is expected the compliance with its requirements and the results can be used as a base, since the yacht was built and the structure proposed works in the real scenario.

Both registers calculations are programmed into *Python* codes. But, the following subsections will present shortly the requirements from each one and the results obtained by the simulation.

Besides the calculation of the requirements, it is necessary to calculate the actual value of section modulus for each stiffener considered. This part is also computed by the *Python* codes. The section modulus of a stiffener is given by Equation 1, where I is the moment of inertia of the stiffener and y the largest distance to the neutral axis.

$$Z = \frac{I}{y} \tag{1}$$

For a typical stiffener "T", as shown in Figure 7, the neutral axis determination and total moment of inertia are given in Equations 2 and 3. The neutral axis is determined basically by mass-moment equilibrium. While, the moment of inertia needs the application of the Parallel Axis Theorem to consider the contribution of the different parts.

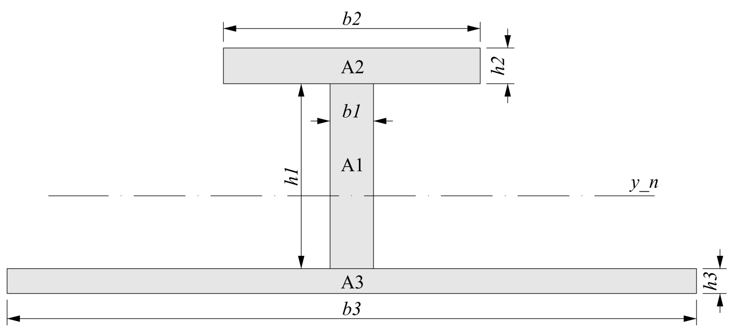


Figure 7: Typical T-bar profile beam with attached plate.

$$y_n = \frac{\sum A_i \cdot y_i}{\sum A_i} \tag{2}$$

$$I = \sum I_{Li} + A_i \cdot d^2 \tag{3}$$

In Equation 2, A_i represent the area of the part "i" of the stiffener and y_i its center of gravity, in consistent S.I. units. In Equation 3, d is the distance between the neutral axis and the part's center of gravity. The term I_{Li} represents the inertia of the element "i" around its own axis, which have well-established formulations for simple geometries. For rectangles shapes, which are of interest for this work, the formulation is $bh^3/12$, where b is the base and h the height of the rectangle.

The main structures of the study case are in T shape for primary elements and flat bar for secondary stiffeners. Box bars are transformed into equivalents T-bar for the computation in the code.

4.1. LLoyd's Register

The procedure and formulations described in this subsection are in accord with the Rules and Regulations for the Classification of Special Service Craft from Lloyd's Register (LR), version of July 2022 .

The first step is to determine the design load applicable to each element (plate or stiffener). This load consists into a pressure that is considered applied to the element for means of the design. Therefore, this value will change accordingly with the position at the ship, representing expected possible loads for the area.

At LR, first it is necessary to calculate the *pressure on weather and interior decks*, P_{wh} for after obtain the pressure for superstructures and deckhouses, P_{dhp}. Equations 4 and 5 demonstrate how to obtain these pressures.

$$P_{wh} = f_L(6 + 0.01LWL)(1 + 0.05\Gamma) + E \ kN/m^2 \tag{4}$$

Where:

- f_L is the location factor for weather decks, defined as equal to 1 to interior decks.
- E is equal to 0 for interior decks and superstructures decks aft of the forward quarter and equal to $min(\frac{0.7+0.08LWL}{D-T}, 3)$ for exposed decks. LWL, D and T are given in Table 2.
- Γ is the Taylor Quotient defined as $\frac{V}{\sqrt{LWL}}$. V and LWL are given in Table 2.

$$P_{dhp} = C_1 \cdot P_{wh} \; kN/m^2 \tag{5}$$

Where:

- C_1 is a factor according with the superstructure location and given in Table 6.
- L_R is the rule length given in Table 2.

Table 6: Factor for superstructure design pressure.

C_1	Location on Superstructure
1.25	Fronts on upper deck within the forward third of L_R
1.15	Fronts on upper deck outside the forward third of L_R
1.0	Fronts above lowest tier
0.8(0.64)	Sides (for deckhouses)
0.5	Elsewhere

Then, finally it is possible to obtain the design load depend on the type of element. For displacement craft, the following pressures are given for plates, P_{DP}, and stiffeners, P_{DS} respectively.

$$\begin{aligned} P_{DP} &= H_f S_f P_{wh} \; kN/m^2 \; for \; interior \; decks \\ &= H_f S_f G_f P_{dhp} \; kN/m^2 \; for \; superstructures \; and \; deckhouses \end{aligned} \tag{6}$$

$$\begin{aligned} P_{DS} &= \delta_f H_f S_f P_{wh} \; kN/m^2 \; for \; interior \; decks \\ &= \delta_f H_f S_f G_f P_{dhp} \; kN/m^2 \; for \; superstructures \; and \; deckhouses \end{aligned} \tag{7}$$

Where:

- $H_f = 1.05$
- S_f is the service type factor and equal to 1.1 for yacht.
- G_f is the service area restriction factor equal to 1.25 for the study case.
- δ_f is the stiffener type factor equal to 0.5 for primary stiffeners and 0.8 for secondary stiffeners.

From the design load of each element, it is possible to obtain the minimum thickness for the plating. Equation 8 presents the formula for aluminium material and mono-hull vessel.

$$t_p = 22.4s \; \gamma \; \beta \sqrt{\frac{p}{f_\sigma \sigma_a}} \times 10^{-3} \; mm \tag{8}$$

Where:

- s is the stiffener spacing in mm.
- γ is the convex curvature correction factor considered equal to 1 because of the majority type of panels analyzed as a simplification.
- β is the panel aspect ratio correction factor defined as $A_R(1 - 0.25A_R)$ for $A_R \leq 2$ or 1 for $A_R > 2$. And A_R is the panel aspect ratio.
- p is the design load calculated before for the element in KN/m^2
- f_σ is the limiting bending stress coefficient. The applicable values are given in Table 7.
- σ_a is the guaranteed minimum 0.2% proof stress of the alloy in the welded condition in N/mm^2, used as equal to σ_y from Table 3.

Table 7: Failure Modes control coefficients for aluminium construction.

Location	f_σ		f_τ	f_δ	
	Plating	Stiffener	Stiffener	Primary Stiff.	Secondary Stiff.
Decks	0.75	0.60	0.60	625	425
Front 1st tier	0.65	0.60	0.60		
Front upper tiers	0.75	0.65	0.65	475	400
Aft and Sides	0.75	0.75	0.75		
House top	0.75	0.75	0.75	400	400
Bulkheads	0.65	0.65	0.65	475	400

Besides the formulation presented in Equation 8 which is general, LR also provides requirements for minimum thickness accordingly to the specific plate location. The final minimum thickness to be considered should be the greater between both formulations. The minimum thickness requirements for the locations relevant for the study case are presented in Table 8.

Table 8: Minimum thickness requirements according to location in superstructure.

Location	Minimum Thickness [mm]
Sides	$\omega\sqrt{k_m}(0.4\sqrt{L_R} + 1.1 \geq 3.0\omega$
Front upper tiers	$\omega\sqrt{k_m}(0.55\sqrt{L_R} + 1.5 \geq 3.0\omega$
Aft	$\omega\sqrt{k_m}(0.25\sqrt{L_R} + 0.7 \geq 2.5\omega$
Bulkhead	$\omega\sqrt{k_m}(0.43\sqrt{L_R} + 1.2 \geq 3.0\omega$

Where:

- ω is the service type correction factor, equal to 1.0 for yachts.
- k_m is equal to $385/(\sigma_u + \sigma_a)$ and σ_u is the minimum ultimate tensile strength in the unwelded condition, given in Table 3 for the aluminium alloy.

It is important to note that the rules do not specify any corrosion margin to be added, as it is stated that is considered negligible loss in strength by corrosion. This happens because for this type of ship, the operation usage is differentiated as well as the maintenance schedule. Therefore, the regular procedures of corrosion protection like coating and cathodic protection, that are applied in the shipyard studied, are enough to avoid the thickness loss due corrosion.

Finally, the section modulus required from each stiffener can be calculated. Equation 9 shows the formula at LR requirements.

$$Z_{req} = \Phi_z \frac{p\ s\ l_e^2}{f_\sigma \sigma_a}\ cm^3 \tag{9}$$

Where:

- p, s, f_σ and σ_a are the same as explained before.
- l_e is the effective span length in meters. At this report, it is taken as equal to the unsupported span l.
- Φ_z is the section modulus coefficient depended on the loading model assumption. Table 9 provide the possible values to be adopted.

At LR requirements, it also necessary to calculate a required inertia and web area for each stiffener. Equations 10 and 11 provide the formulations.

$$I_{req} = \Phi_I f_\delta \frac{p\ s\ l_e^3}{E} \times 100\ cm^4 \tag{10}$$

$$A_{w_{req}} = \Phi_A \frac{p\ s\ l_e}{100 f_\tau \tau_a}\ cm^2 \tag{11}$$

- p, s, l_e are the same as explained before.
- f_δ is the limiting deflection coefficient. The factor consists in the ratio between the member span and the deflections ratios given in Table 7 for relevant locations.
- f_τ is the limiting shear stress coefficient. Table 7 provide the values for relevant locations.
- τ_a is equal to $\sigma_a/\sqrt{3}$.
- Φ_I and Φ_A are the inertia and web area coefficients respectively depended on the loading model assumption. Table 9 provide the possible values to be adopted.

Table 9: Section modulus, inertia and web area coefficients accordingly with the type of support. Note the coefficients vary with the position in the beam model. The table shows the larger coefficient for each type of support condition.

Support	Φ_z	Φ_I	Φ_A
Clamped	1/12	1/384	1/2
Partial clamped	1/10	1/288	1/2
Clamped and simple supported	1/8	1/185	5/8
Cantilever beam	1/2	1/8	1.0
Simple supported	1/8	5/384	1/2

Then, the required values can be compared to the real ones calculated for the existent structure. For this step, it is necessary to consider the attached plate contributing to the stiffener strength. The effective width given by LR needs to respect the following criteria accordingly with the type of stiffener.

$$\begin{aligned} b_e &= min(2t_p\sqrt{E/\sigma_a}, s) \ for \ secondary \ members \\ b_e &= b \cdot 0.3 \left(\frac{l}{b}\right)^{(2/3)} \quad for \ primary \ members \end{aligned} \tag{12}$$

Where:

- b is equal to one-halt of the sum of the spacing between parallel equivalent members, in meters.
- E and σ_a are from the material properties and given in Table 3.

The application of Equation 1 considering the attached plate calculated provide the actual values for the existent structure.

Table 10 compiles the results obtained for the plate's thickness. Table 11 summarizes the results for the reinforcements in different parts of the superstructure. Tables 47 and 48 at Appendix D compiles the complete data used and Tables 49 and 50 at Appendix E the data obtained in the calculations. The inertia and web area are not displayed in this section, since it is perceived that the section modulus is the driving parameter for this study case. Also, only the section modulus will be compared between the classification societies. Note that for general elements, it was considered the largest unsupported span for the calculations. Some specific areas were also selected to be analyzed because of the difference in support and proximity with large openings, such as windows and stairs. The results are shown in Table 12 and the detailed calculations data are in Table 50 in Appendix E.

Table 10: Minimum Thickness Required x Real thickness.

Plate Location		t_{min} $[mm]$	t_r $[mm]$	**Situation**
Decks	Upper Deck	4	5	OK
	Bridge Deck	4	5	OK
	Hard Top	4	5	OK
Superstructure	LT - Aft Ends	4	8	OK
	LT - Sides (DH)	4	5	OK
	LT - Sides (SP)	7	8	OK
	2T - Aft Ends	4	5	OK
	2T - Sides	4	5	OK
	2T - Shell	4	5	OK
	2T - Front	6	5	NOT OK
	3T - Aft Ends	5	5	OK
	3T - Shell	4	5	OK
	3T - Front	6	5	NOT OK
Bulkhead	Transversal	5	5	OK
	Longitudinal	5	5	OK

First of all, it is important to clarify the nomenclatures adopted in this work. In the superstructure location, it is used *LT* for lowest tier, *2T* for second tier and *3T* for third tier. At the lowest tier, the abbreviations *DH* and *SP* stands for deckhouse and superstructure, respectively. It is used since only a part of the superstructure side wall is stepped in to maindeck more than $0.04B$, defined as a deckhouse. Also for the second and third tiers, the side walls are splitted into side and shell. The shell part consists in the most external side plating and the side part consists in the internal side walls delimiting the deckhouse.

Table 10 shows that only for two locations the minimum thickness requirement is not fulfilled. This is an unexpected result, since the LLoyd's Register rules were used to design the structure evaluated. But, it can be explained by the approximation to the upper round number performed in the code. The exact required value for both non-compliant locations is 5.37 mm, which if round down is the exact value used in the design. Also, the requirement is coming from Equations presented in Table 8, not the application of the design load. Therefore, the rounding process applied in the calculations is probably more conservative than used during the structure conception. Nevertheless, it is important to mention that the height between the tiers is larger than the standard superstructure height of 1.8 m determined by the Administration Flag (*Red Ensign Group Yacht Code - Part A*). For this reason, the tiers could be defined as higher tier positions, which could decrease the requirement.

Table 11: Required section modulus and obtained section modulus in the general superstructure scantling.

Member Location		**Member Type**	Z_{req} $[cm^3]$	Z_o $[cm^3]$	**Situation**
Decks	Upper Deck	Transverse	41.74	48.49	OK
		Girder (0.6CL)	448.79	897.69	OK
		Girder (1.8CL)	313.69	420.91	OK
		Stiffener	5.16	5.24	OK
	Bridge Deck	Transverse	45.91	48.53	OK
		Girder (0.6CL)	447.79	897.69	OK
		Girder (1.8CL)	235.81	604.74	OK
	Hard Top	Transverse	45.65	48.52	OK
		Girder (0.6CL)	102.50	217.08	OK
		Girder (1.8CL)	180.56	314.25	OK
Superstructure	LT - Sides (DH)	Transverse	23.61	81.34	OK
		Side Stringer	207.81	349.71	OK
	LT - Sides (SP)	Transverse	26.83	115.51	OK
	2T - Sides	Transverse	13.68	80.72	OK
		Side Stringer	208.14	349.73	OK
	2T - Shell	Transverse	10.91	80.13	OK
	3T - Shell	Transverse	7.82	66.36	OK
		Side Stringer	91.05	113.13	OK
Bulkhead	Transversal	Vertical web	96.48	121.42	OK
		Horizontal Stringer	28.80	42.76	OK
	Longitudinal	Vertical Web	17.07	77.21	OK
		Horizontal Stringer	28.80	42.76	OK

The term *Transverse* is used to refer to both web frames and transverse beams, it is possible to differentiate by the location column. The term *Girder* is used to refer only to deck longitudinal girders. For these members, two types were analyzed because of the different spans. The girders positioned 600 millimeters from the centerline, denoted by *0.6CL*, and the ones at 1800 millimeters from the centerline (*1.8CL*). Finally, stiffener is used to denote the secondary longitudinal reinforcements.

As expected, the obtained section modulus from all the components are in compliance with the required ones from LR. Another point to comment is that for some elements, the obtained section modulus is very large compared to the required one. This is the case for the girders in all decks, side stringer at lowest and second tiers, transverse at all superstructure sides and horizontal stringers at bulkheads. A possible explanation is that the shipyard is used to apply experience and internal know-how in the structural design, replicating successful dimensioning to similar cases. Which means that an optimization is not performed in the design phase. This would indicate that these reinforcements are oversized. Another possibility is that other type of failure mode limited these members designs. These discrepancies are analyzed in more detailed in Subsection 4.3, when comparing with ABS results.

Table 12: Required section modulus and obtained section modulus for selected scantling members.

Member Location		Member Type	Z_{req} $[cm^3]$	Z_o $[cm^3]$	Situation
Decks	Upper Deck	Frame 24 (CB)	122.70	136.07	OK
		Frame 24 (O)	133.67	183.64	OK
		Frame 12+550	506.97	1271.77	OK
		Frame 20	77.94	185.41	OK
		Girder (CB)	1018.92	1213.46	OK
		Girder (Box Beam)	868.46	915.00	OK
	Bridge Deck	Frame 29	227.77	297.04	OK
		Girder (CB)	677.12	719.04	OK
Superstructure	LT - Sides (DH)	Frame 13 (O)	21.95	80.43	OK
	2T - Sides	Frame 15 (O)	74.48	333.36	OK
		Transverse Box Beam	72.34	187.84	OK
Bulkhead	Longitudinal	Vertical Stiffener (O)	21.32	24.37	OK

The selected reinforcements shown in Table 12 are chosen because of their different dimensions in the structural design. The transverse frames in Frame 24 have the extremities with no support, which configures a situation of cantilever beam, and an increase in the middle due to the proximity to the deck opening for stairs. Both parts are analyzed under Frame 24 (CB) and Frame 24 (O) notations respectively. The abbreviations CB and O are also used for other reinforcements in the same situation. The other transverse frames analyzed have a larger span than the general in the model. Therefore, they need to be treated separately.

The cantilever beams type elements are easily treated by changing the parameters Φ_z accordingly in Equation 9. It is interesting to notice that this change have a great effect in the required section modulus. For example, the Z_{req} of the girder at 600 mm from CL at the upper deck is varying from 448.79 cm^3 to 1018.92 cm^3, an increase of almost 130%. This shows the importance of considering the different support conditions realistically in the structural design. For the elements close to openings, besides the possible increase in the span, it is considered the contribution from same type of reinforcements splited by the opening. Therefore, the required section modulus is also elevated. Table 12 shows that every selected component fulfills the requirements.

4.2. ABS

The procedure and formulations described in this subsection are in accord with the Guide for Building and Classing of Yachts from American Bureau of Shipping (ABS), version of January 2022 .

For ABS rules, the first step is also to determine the design load applicable to each element. This is actually the common procedure to follow in any classification society. But, for this case it is calculated a design head, not a design pressure as done before. A design head means that it is considered a water column of determined height at the element, occasioning the design pressure.

For decks, the design head is formulated directly accordingly with the deck location. Equation 13 present the design heads for decks that are included in this study case.

$$\begin{aligned} h_d &= 0.01L + 0.46 \ m \ for \ exposed \ superstructure \ decks \ not \ in \ forward \\ h_d &= 0.01L + 0.15 \ m \ for \ deckhouse \ tops \ above \ 2nd \ tier \\ h_d &= 0.35 \ m \ for \ internal \ accommodation \ decks \end{aligned} \tag{13}$$

Where:

- L is the scantling length defined as the distance at the summer load line from the fore side of the stem to the centerline of the rudder stock. Also, it should not be taken as less than 96% nor larger than 97% than the total length at the summer load line. L was considered as equal to the L_R length in Table 2.

For bulkheads, the design head is shown in Equation 14. It important to note that ABS considers the external superstructure walls as bulkheads, as this formulation needs to be applied for these locations. Also, longitudinal bulkheads must be splited at sizes of maximum $0.1L$ and the formula is applied to the part's midpoint.

$$h_s = ak[(bf) - y]c \ m \tag{14}$$

Where:

- a is a factor related to bulkhead location. The relevant values are given in Table 13.
- k is the service factor, used as equal to 1 at this work.
- b is a factor based on the longitudinal position. Possible values are given in Table 14.
- f is a factor based on the yacht length. The value used for this study is 3.47, calculated from linear interpolation from a table given in the requirements using the length L.
- y is the vertical distance between the design waterline and the midpoint of the stiffener or plate, in meters.
- c is equal to 1 for superstructures and 0.85 for deckhouses.

Table 13: Values for parameter "a" accordingly with bulkhead location.

Bulkhead Location	a
Unprotected front, lowest tier	$2.0 + L/120$
Unprotected front, 2nd tier	$1.0 + L/120$
Unprotected front, 3rd tier	$0.5 + L/150$
Sides of Superstructures	as indicated for fronts
Sides of Deckhouses	$0.5 + L/150$
Aft ends, all tiers	$0.7 + (L/1000) - 0.8x/L$

Table 14: Values of parameter "b" accordingly with the bulkhead's relative longitudinal position x/L.

x/L	b	x/L	b
$0.10L$	1.19	$0.50L$	1.00
$0.20L$	1.10	$0.60L$	1.05
$0.30L$	1.04	$0.70L$	1.15
$0.40L$	1.00	$0.80L$	1.29
$0.45L$	1.00	$0.90L$	1.49

ABS requirements also provide a minimum design head to be considered. Therefore, the final design head to be applied to each element will be the maximum value between Equations 14 and 15, the minimum heads given below.

$$\begin{aligned} h_{min} &= 0.01L + 2.5\ m\ for\ unprotected\ fronts\ on\ lowest\ tier \\ h_{min} &= 0.005L + 1.25\ m\ for\ all\ other\ locations\ on\ lowest\ and\ 2nd\ tier \\ h_{min} &= 1.5\ m\ for\ other\ locations\ from\ 3rd\ tier \end{aligned} \tag{15}$$

From the design head of each element, it is possible to obtain the minimum thickness for the plating. These formulations are also separated by decks and bulkheads. Equation 16 and 17 presents the formulas for decks and superstructure plating respectively, in the case of aluminium material and displacement yachts. ABS rules also establishes that the minimum thickness should not be less than 4 mm for internal decks and superstructures plating in aluminium vessels.

$$t_p = \frac{s\sqrt{qh}}{272} + 2\ mm \tag{16}$$

$$t_p = 0.003s\sqrt{qh}\ mm \tag{17}$$

Where:

- s is smaller dimension of the plate panel in millimeters.
- q is equal to $235/\sigma_y$
- h is the design head calculated for the member in meters.

Finally, the section modulus required from each stiffener can be calculated. Equations 18 and 19 shows the formula at ABS requirements for decks and superstructure stiffeners respectively.

$$Z_{req} = 7.8chsl^2q\ cm^3 \tag{18}$$

$$Z_{req} = 3.43hsl^2q\ cm^3 \tag{19}$$

Where:

- c is a factor equal to 0.64 for deck longitudinals amidships and equal to 0.51 for all other internal deck members.
- s is the spacing of the member in meters.
- l is the unsupported span in meters.
- q and h as stated before.

Then, the required values can be compared to the real ones calculated for the existent structure. As before, it is necessary to consider the attached plate contributing to the stiffener strength. The effective width given by ABS needs to respect the following criteria accordingly with the type of stiffener.

$$b_e = min(s,\ 0.33l,\ 750)\ mm\ for\ primary\ members$$
$$b_e = min(s,\ 60t_p)\ mm\ for\ other\ members \quad (20)$$

The application of Equation 1, considering the attached plate calculated, provide the actual values for the existent structure.

Table 15 compiles the results obtained for the plate's thickness. Table 16 summarizes the results for the stiffeners in different parts of the superstructure. The detailed calculations data are displayed at Tables 51-52 in Appendix F and Tables 53-54 Appendix G. Also, the same selected members results are shown in Table 17. Table 54 in Appendix G present the detailed data also for the selected members. The same spans used before are applied in these calculations.

Table 15: Minimum Thickness Required x Real thickness.

Plate Location		t_{min} [mm]	t_r [mm]	Situation
Decks	Upper Deck	5	5	OK
	Bridge Deck	5	5	OK
	Hard Top	4	5	OK
Superstructure	LT - Aft Ends	5	8	OK
	LT - Sides (DH)	4	5	OK
	LT - Sides (SP)	8	8	OK
	2T - Aft Ends	4	5	OK
	2T - Sides	4	5	OK
	2T - Shell	4	5	OK
	2T - Front	4	5	OK
	3T - Aft Ends	6	5	NOT OK
	3T - Shell	4	5	OK
	3T - Front	4	5	OK
Bulkhead	Transversal	4	5	OK
	Longitudinal	4	5	OK

From Table 15 it is possible to observe that only the plating at the third tier aft end does not comply with the minimum thickness requirement. Once again, the divergence can be explained by the round process. The exact required value calculated is equal to 5.06 mm. The code uses a round up procedure, thus the thickness resultant is 6 mm. But for this case it can be seen clearly that the process was too much conservative and 5 mm is acceptable. Also, the other locations are mostly above the requirement, which contributes for the safety even with this less conservative choice of thickness.

Table 16: Required section modulus and obtained section modulus in the general superstructure scantling.

Member Location		**Member Type**	Z_{req} $[cm^3]$	Z_o $[cm^3]$	**Situation**
Decks	Upper Deck	Transverse	23.04	48.14	OK
		Girder (0.6CL)	315.74	743.43	OK
		Girder (1.8CL)	220.69	412.37	OK
		Stiffener	4.23	5.18	OK
	Bridge Deck	Transverse	25.74	48.30	OK
		Girder (0.6CL)	315.03	743.43	OK
		Girder (1.8CL)	165.90	592.54	OK
	Hard Top	Transverse	48.12	48.36	OK
		Girder (0.6CL)	135.59	213.50	OK
		Girder (1.8CL)	238.86	308.93	OK
Superstructure	LT - Sides (DH)	Transverse	77.00	81.07	OK
		Side Stringer	677.81	332.88	NOT OK
	LT - Sides (SP)	Transverse	70.00	114.86	OK
	2T - Sides	Transverse	44.62	81.07	OK
		Side Stringer	678.88	332.50	NOT OK
	2T - Shell	Transverse	28.46	80.83	OK
	3T - Shell	Transverse	20.26	66.69	OK
		Side Stringer	235.78	109.01	NOT OK
Bulkhead	Transversal	Vertical web	126.00	121.89	NOT OK
		Horizontal Stringer	75.23	42.91	NOT OK
	Longitudinal	Vertical Web	20.69	77.73	OK
		Horizontal Stringer	75.22	42.91	NOT OK

Considering the same reinforcements as before, Table 16 shows several non-compliance problems. Since the structure analyzed is from a real yacht, that did not present structural problems in operation, it is not possible to affirm that the structural design is unsafe. The conclusion from these results is that mostly the loading conditions adopted by ABS are too much conservative for the reality of this yacht in certain areas. These discrepancies are explored deeper in Subsection 4.3. But, one thing to be noted already is that the non-fulfillment occurs in majority for side stringers.

Table 17: Required section modulus and obtained section modulus for selected scantling members.

Member Location		Member Type	Z_{req} $[cm^3]$	Z_o $[cm^3]$	Situation
Decks	Upper Deck	Frame 24 (CB)	25.19	137.71	OK
		Frame 24 (O)	24.98	183.04	OK
		Frame 12+550	260.90	1225.32	OK
		Frame 20	43.70	182.58	OK
		Girder (CB)	262.52	1096.61	OK
		Girder (Box Beam)	223.75	719.71	OK
	Bridge Deck	Frame 29	187.05	293.77	OK
		Girder (CB)	174.46	705.78	OK
Superstructure	LT - Sides (DH)	Frame 13 (O)	71.60	79.97	OK
	2T - Sides	Frame 15 (O)	242.94	336.82	OK
		Transverse Box Beam	235.96	185.72	NOT OK
Bulkhead	Longitudinal	Vertical Stiffener (O)	46.40	23.01	NOT OK

Table 17 shows the results for the same selected reinforcements as before. It is possible to notice two non-compliance for vertical transverse members, both close to openings. The conclusion is again the rigidity of ABS requirements. But, a closer look is done in the next subsection. Also, it is interesting to observe that the components that required a different support condition do not suffer an increased for ABS rules. This happens because support conditions are not included into ABS formulations. Therefore, Equations 18 and 19 are applicable only for clamped conditions. For other support conditions, ABS recommends a finite element analysis for each specific situation. This is also detailed in next subsection. The results in Table 17 are obtained from the Equations for clamped condition.

4.3. Comparison LR x ABS

4.3.1. Analytically

From previous subsections, it is evident that the differences between both registers start in the design load definition. While LR defines a design pressure to be applied, ABS determines a design head. Naturally, both culminate in a load equally distributed over the deck/bulkhead. But, this means that the equations should not be compared directly. It is possible to transform the design heads into design pressures by calculating the hydrostatic pressure originated from the head. In order to achieve that, the density of water is approximated by 1000 kg/m^3 and the gravity acceleration by 10 m/s^2. To obtain the same unit as the design pressure equations (KN/m^2), it is necessary also to divide by 1000. Therefore, equations of design head should be multiply by a factor of 10 to be comparable to the design pressure equations. The cases to be compared are internal decks, exposed decks, superstructures sides and superstructures front.

For internal decks situation, it is necessary to compare Equations 7 and 13. Equation 7 consists of a factor 0.58 over the pressure on weather decks for interior deck and considering primary stiffener. In the case of secondary stiffener, the factor goes to 0.924. From Equation 4, the term f_L is equal to 1 and the term E equal to 0. Therefore, it becomes an equation depending on LWL and V values, starting from a factor of 6. Which means starting from 3.48 for primary stiffeners and 5.54 for secondary. On the other hand, Equation 13 for internal deck and multiplied by the factor of 10 is equal to 3.5 KN/m^2. Clearly, ABS requires a smaller design load in this case.

For exposed decks, same equations should be verified. In Equation 4, the term f_L is also equal to 1, while term E is equal to at maximum 3. Thus, once again it is an equation depending on LWL and V starting from a factor of 6, but that it will be summed by a factor of 3 (in the maximum situation). Consequently, the design pressure will start from a factor around 3.48 and added by the maximum of 1.74 for primary stiffeners in LR formulations. While, Equation 13 multiplied by 10 will depend on L_R, but starting from a factor of 4.6, with no further additions. For that reason, it is difficult to determine which register will result in the larger pressure.

In the case of superstructures sides, Equations 5 and 14 should be analyzed. However, since Equation 14 depends on too many factors to be compared, Equation 15 will be considered, once it provides the minimum values for superstructure design loads. Equation 5 will consist of multiplying a factor of 0.8 in the conclusions taken from the exposed decks case. Therefore, the design pressure will start from a factor of 2.78, varying with LWL and V and will have a final addition of 1.39 in the maximum case. For ABS, Equation 15 multiplied by a factor of 10 starts from a factor of 12.5 for first and second tiers, and it is equal to 15 KN/m^2 for the third tier. Clearly, in this case, LR will require a lower value for the design load.

The case is repeated when considering superstructures front. LR's Equation 5 will start from a factor of 4.35 varying with LWL and V and added by 2.17 at maximum for primary stiffeners. While Equation 15 keeps starting from 12.5 for first and second tiers and it is equal to 15 KN/m^2 for third tier. Even though, LR design pressure increased from the side case, it is still lower than ABS requirements.

From the previous analysis, it is expected that ABS is less rigorous than LR for decks loads, while the opposite is true for superstructure bulkheads.

Concerning the required section modulus, Equations 9 and 18/19 should be analyzed . From Equation 9, it is possible to observe that LR defines the requirement in terms of the design load, a factor depending on the support condition, a safety factor to be multiplied by the material tensile strength, the member spacing and the square of the member span. Looking to Equations 18 and 19, it is concluded that the formulation follows almost the same pattern. It depends on the design head, the material tensile strength, the member spacing, the square of the member span and also some empirical factors. At this time, in order to compare the equations it is simpler to consider to substitute the design pressure in LR equation by its equivalent head. From the same considerations done before, it is considered that $P = 10h$ in Equation 9. Applying the clamped support condition to obtain same scenario applied in ABS formulation and considering the less conservative f_σ value from Table 7, Equation 21 shows the obtained safety factor from LR section modulus equation. The equation is valid for clamped members positioned at superstructure sides, aft and at the house top.

$$Z_{LR} = \frac{1}{12} \cdot \frac{10h\ s\ l^2}{0.75\sigma_y} = 1.11\ \frac{hsl^2}{\sigma_y}\ cm^3 \tag{21}$$

For superstructure members, Equation 19 should be evaluated. Also, in order to compare the safety factors, it is important to remember that in ABS equation the member spacing is used in meters, while in the previous equation from LR is in millimeters. Therefore, the safety factor should be split by 1000 to be compared to the obtained in Equation 21.

$$Z_{ABS} = \frac{1}{1000} \cdot 3.43 \cdot \frac{235}{\sigma_y} hsl^2 = 0.806\ \frac{hsl^2}{\sigma_y}\ cm^3 \tag{22}$$

These results show that ABS section modulus requirement is less conservative than LR's for the condition of clamped reinforcements at superstructure sides, aft and house top. At this scenario, LR would require a section modulus 37.7% larger than ABS, for the same conditions (span, spacing and head). Applying the same reasoning, Table 18 exhibits the comparison for other member's locations.

Table 18: Required section modulus safety factors for LR and ABS formulations in different locations.

Location	Z_{LR} [cm^3]	Z_{ABS} [cm^3]	Difference [%]
Superstructure Fronts (upper tiers)	1.28	0.806	58.8
Decks (longitudinal members)	1.39	1.17	18.8
Decks (other members)	1.39	0.935	48.7

From Table 18, it is possible to observe that LR requires larger safety factors for the other locations as well, with an impressive difference of more than 50% for superstructure fronts. However, it is important to remember that these comparisons are only valid for a situation of same design load application (the term $\frac{hsl^2}{\sigma_y}$ is considered constant). Since the design loads also vary accordingly with the classification society, it is expected that this larger discrepancies will decrease in the actual results calculations for the study case. But, this analysis is relevant to conclude that LR imposes a greater safety factor over the required section modulus of reinforcements.

4.3.2. Numerically

Besides comparing the classification societies' formulations, it is important to analyze the results from the real study case to understand the different approaches in practice. With the objective to visualize the differences between the required section modulus from both registers, Table 19 below compiles the results presented in the previous subsections for the general scantling. The difference is calculated in relation to the ABS result.

Table 19: Comparison between required section modulus from LR and ABS.

Member Location		Member Type	Z_{LR} $[cm^3]$	Z_{ABS} $[cm^3]$	Difference [%]
Decks	Upper Deck	Transverse	41.74	23.04	81.2%
		Girder (0.6CL)	448.79	315.74	42.1%
		Girder (1.8CL)	313.69	220.69	42.1%
		Stiffener	5.16	4.23	22.0%
	Bridge Deck	Transverse	45.91	25.74	78.4%
		Girder (0.6CL)	447.79	315.03	42.1%
		Girder (1.8CL)	235.81	165.90	42.1%
	Hard Top	Transverse	45.65	48.12	−5.1%
		Girder (0.6CL)	102.50	135.59	−24.4%
		Girder (1.8CL)	180.56	238.86	−24.4%
Superstructure	LT - Sides (DH)	Transverse	23.61	77.00	−69.3%
		Side Stringer	207.81	677.81	−69.3%
	LT - Sides (SP)	Transverse	26.8	70.00	−61.7%
	2T - Sides	Transverse	13.68	44.62	−69.3%
		Side Stringer	208.14	678.88	−69.3%
	2T - Shell	Transverse	10.91	28.46	−61.7%
	3T - Shell	Transverse	7.82	20.26	−61.4%
		Side Stringer	91.05	235.78	−61.4%
Bulkhead	Trasnversal	Vertical Web	96.48	126.00	−23.4%
		Horizontal Stringer	28.80	75.23	−61.7%
	Longitudinal	Vertical Web	17.07	20.69	−17.5%
		Horizontal Stringer	28.80	75.22	−61.7%

As it is possible to notice, ABS required section modulus is larger in the majority of locations. This might be odd considering the previous discussion about the safety factors from the formulations. However, these results are related to the design load required for the location. Table 20 shows the design loads calculated for these reinforcements and it is possible to understand the correlation between both results.

Table 20: Comparison between design load by member from LR and ABS for general scantling.

Member Location		Member Type	P_{LR} $[KN/m^2]$	H_{ABS} $[m]$	Difference [%]
Decks	Upper Deck	Transverse	4.20	3.50	20.1%
		Girder (0.6CL)	4.20	3.50	20.1%
		Girder (1.8CL)	4.20	3.50	20.1%
		Stiffener	6.72	3.50	92.1%
	Bridge Deck	Transverse	4.20	3.50	20.1%
		Girder (0.6CL)	4.20	3.50	20.1%
		Girder (1.8CL)	4.20	3.50	20.1%
	Hard Top	Transverse	5.37	6.70	−20.2%
		Girder (0.6CL)	5.37	6.70	−20.2%
		Girder (1.8CL)	5.37	6.70	−20.2%
Superstructure	LT - Sides (DH)	Transverse	3.36	15.10	−77.8%
		Side Stringer	3.36	15.10	−77.8%
	LT - Sides (SP)	Transverse	4.20	15.10	−72.2%
	2T - Sides	Transverse	3.36	15.10	−77.8%
		Side Stringer	3.36	15.10	−77.8%
	2T - Shell	Transverse	4.20	15.10	−72.2%
	3T - Shell	Transverse	4.20	15.00	−72.0%
		Side Stringer	4.20	15.00	−72.0%
Bulkhead	Trasnversal	Vertical Web	3.64	15.10	−75.9%
		Horizontal Stringer	3.64	15.10	−75.9%
	Longitudinal	Vertical Web	3.64	15.10	−75.9%
		Horizontal Stringer	3.64	15.10	−75.9%

As discussed before, LR demands a higher safety factor for the required section modulus. For that reason, in the cases where LR's design load is bigger than ABS', LR will required a greater section modulus. This was expected and it happens for decks locations, as discussed before. Meanwhile, when the opposite is true, it will depend on the difference between the design loads to determine which register requires the larger section modulus. At Table 20, it is possible to conclude that ABS determines a larger Z when its design load exceeds the difference from the safety factor's formulation. For example, in the first tier deckhouse side location ABS' design load is 77.8% bigger than LR's. This consists of applying a decrease of $1 - 0.778 = 0.222$ in the safety factor found before in LR's formulation for this location, which is 1.11. By that, the safety factor in LR's equation becomes 0.246. Comparing with the safety factor in ABS' formulation for same location (0.806), it is clear that ABS required section modulus will be larger. The difference between the new safety coefficients is exactly the difference between the obtained values for Z_{req} in Table 19. The same is repeated for the other locations in the superstructure and bulkheads, once the design loads difference follows the same order.

It is important to comment that the results for the Hard Top location are different because it consists of an exposed deck in the calculations. Therefore, in this case, the ABS' design load becomes larger than LR's. This causes a decrease in LR's safety factor of 20.2%, turning 1.11 (calculated factor for house top) into 0.886. When comparing this value to the calculated safety factor in ABS's formulation for different members present in Table 18, it is comprehensible the results for this location.

For the selected locations, it is not relevant to compare the results for the cases where the support condition is different than clamped. Because ABS formulation underestimated the requirement once it does not give options for different supports conditions. However, it is possible to compare the results for the other selected locations, close to openings for example. Table 21 compiles the results for these reinforcements.

Table 21: Comparison between required section modulus from LR and ABS in selected locations.

Member Location		**Member Type**	Z_{LR} $[cm^3]$	Z_{ABS} $[cm^3]$	**Difference** [%]
Decks	Upper Deck	Frame 24 (O)	133.67	74.94	78.4%
		Frame 12+550	506.97	260.90	94.3%
		Frame 20	77.94	43.70	78.4%
	Bridge Deck	Frame 29	227.77	187.05	21.8%
Superstructure	LT - Sides (DH)	Frame 13 (O)	21.95	71.60	−69.3%
	2T - Sides	Frame 15 (O)	74.48	242.94	−69.3%
		Transverse Box Beam	72.34	235.96	−69.3%
Bulkhead	Longitudinal	Vertical Stiffener	21.32	46.40	−54.1%

Since the openings are treated equally in both calculations, the same pattern observed before is repeated for the results shown in Table 21 from the selected reinforcements. For deck members, LR required section modulus prevails. While, in the superstructure and bulkhead locations, ABS' requirement is more rigorous due to the large design load considered in this areas when comparing to the defined by LR.

To analyze the different supports' members, it is possible to proceed to a direct assessment considering the design load proposed by ABS and the limiting design stress. This procedure is performed for 2 chosen cases: Girder (CB) and Frame 24 (CB) both at the Upper deck.

Since both cases represent a cantilever beam under a distributed load situation in the structural idealization, the sketch in Figure 8 illustrate both.

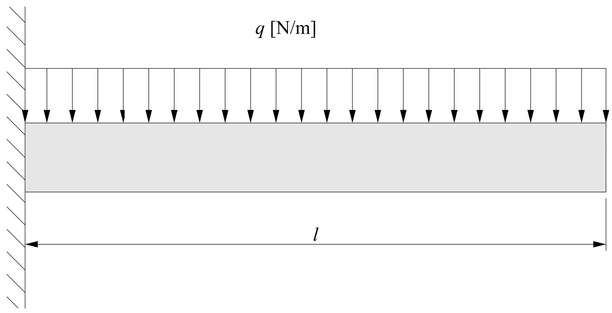


Figure 8: Sketch of cantilever beam under distributed load condition.

In this situation, the maximum bending moment will occur at the clamped edge and from equilibrium of forces will be equal to Equation 23.

$$M = \frac{ql^2}{2} \tag{23}$$

Also, from Euler-Bernoulli beam theory, it is known that the resultant stresses for a beam under bending moment are calculated as express in Equation 24 below.

$$\sigma = \frac{M}{Z} \tag{24}$$

Reorganizing the term from Equations 23 and 24, it is obtained the relation displayed in Equation 25.

$$Z = \frac{ql^2}{2\sigma} \tag{25}$$

From ABS guidelines, the allowable stress should be taken as $\sigma_y/1.67$ considering static loads for bending stresses. Also, Table 22 shows the parameters to be applied in each case.

Table 22: Parameters for two selected cases in Upper deck for required section modulus direct calculation.

Parameter	Girder (CB)	Transverse (CB)
Head [m]	0.98	0.35
Spacing [m]	1.2	1.2
Span [m]	4.87	1.69

Remind that the pressure from the design head consists of $P = \rho g h$, with $\rho = 1000\ kg/m^3$ and $g = 10\ m/s^2$, and that $q = P \cdot s$. Then, the application of Equation 25 leads to the required section modulus shown in Table 23 below. The Table are compiles the results from LR for comparison.

Table 23: Comparison between required section modulus from LR and ABS for different support cases.

Case	Z_{LR} $[cm^3]$	Z_{ABS} $[cm^3]$	Difference [%]
Girder (CB)	1018.92	1863.13	−45.31%
Transverse (CB)	122.70	80.13	53.13

The results are consistently following the same pattern as before. Even though both cases are from Upper deck, the design loads considered for the girder case are for exposed deck because of its position in the end of the deck. Case in which the ABS design load is larger. While, in the transverse from Frame 24, the design loads applied are for internal decks. In this case, LR presents a bigger proposed load.

It is important to comment these results against the obtained section modulus of these members. For the girder in cantilever beam situation, the Z_O from Table 17 is equal to 1096.01 in ABS calculations. This means that this member does not comply with ABS requirement. However, it interestingly fulfills LR's requirement. Also, as explained before, the study case is from a real case. Thus, it is possible to conclude that ABS's design load for this location is too conservative and overestimate the reality. For the transverse in Frame 24 case, by comparison from the value in Table 17, it is possible to observe that the reinforcement is in compliance. But, the obtained required modulus is closer to the requirement from LR.

From the comparisons made in this subsection it is possible to conclude that ABS' rules are more conservative than LR's in several locations of the superstructure because of the design loads considered. In fact, these design loads seem to be over than in reality, since when comparing the requirements with the study case of a successful constructed yacht some reinforcements do not even fulfill the criteria. But also, LR's requirements present larger safety factors when compared to ABS. Therefore, these difference are mainly because of the design loads considered.

4.4. Optimization

From the conclusions withdrawn in the previous subsection about the design loads coming from both classification societies, it is decided to use the requirements from LLoyd's Register for the optimization phase. Other points considered are that the study case was designed by this set of rules and LR provides more flexibility for calculation of different members. This makes the optimization more consistent and easier to be implemented.

As explained in Section 2, the optimization is incorporated in the *Python* code calculations by the addition of another method in the *Stiffener Register* class. The optimization is performed by the use of the package *scipy*, which in the *optimize* module has the function *minimize*. This function can be applied to minimization problems through the use of several methods. The method Sequential Least Squares Programming (SLSQP) is chosen to implement the optimization problem. This method is suitable for minimization non-linearly constrained problems of one or more variables.

Kraft (1988) explains that the SLSQP is a sequential quadratic programming (SQP) type of method. SQP consists in an technique that solves the minimization problem by solving sequentially quadratic sub-problems originated from the quadratic approximation of the Lagrange function and linear approximation of constraints. The Lagrange function of a general minimization problem of the function $f(x)$ is presented in Equation 26, and Equation 27 shows its quadratic approximation. The term "d" consists in the search direction, which is taken as equal to B, the Lagrange function hessian matrix. While "k" is the step index. Equation 28 shows the general form of the linearized constraints.

$$L(x, \lambda) = f(x) - \sum_{j=1}^{m} \lambda_j g_j(x) \tag{26}$$

$$min\ \frac{1}{2} d^T B^k d + \nabla f(x^k) d \tag{27}$$

Subjected to the linearized constraints below.

$$\begin{aligned} \nabla g_j(x^k) dg_j(x^k) = 0 \; j = 1, ..., m_c \\ \nabla g_j(x^k) dg_j(x^k) \geq 0 \; j = m_c + 1, ..., m \end{aligned} \tag{28}$$

In the SLSQP the quadratic sub-problems are replaced by linear least squares sub-problems using a stable factorization process of the matrix B. The SQP-based methods have to fulfill the Karush-Kuhn-Tucker conditions to achieve optimal conditions. The conditions are given in Equation 29 below.

$$\begin{aligned} \nabla L(x, \lambda) &= 0, \\ g_j(x) &= 0, \; j = 1, \cdots, m_c \\ g_j(x) &\geq 0, \; j = m_c + 1, \cdots, m \\ \lambda_j(x) &\geq 0, \; j = m_c + 1, \cdots, m \end{aligned} \tag{29}$$

The specific optimization problem applied in this work is formulated with regards to the structure weight. The idea is to reduce the dimensions of the reinforcements to minimize the structural weight, but keeping the section modulus above the required one, from LLoyd's calculations. Also, from LR requirements, it is necessary to respect the required inertia and web area. In addition to that constraints, LR's also determined some geometric proportions to be followed in order to avoid local buckling and keep the structural stability. Therefore, Equations 30 and 31 below formulate the minimization problem.

$$min \; W(h_w, t_w, w_f, t_f, b_p, t_p) \tag{30}$$

Subjected to the following constraints:

$$\begin{aligned} Z_{req} - Z_o(h_w, t_w, w_f, t_f, b_p, t_p) &\geq 0 \\ I_{req} - I_o(h_w, t_w, w_f, t_f, b_p, t_p) &\geq 0 \\ Aw_{req} - Aw_o(h_w, t_w, w_f, t_f, b_p, t_p) &\geq 0 \\ t_w - max(h_w/15, 3) &\geq 0 \; if \; flat \; plate \\ t_w - max(h_w/50, 3) &\geq 0 \; if \; built \; section \\ 16t_f - b_f &\geq 0 \\ h_w/w_f - 1.5 &\geq 0 \\ h_w - 2h_{op} &\geq 0 \\ h_{max} - h_w &\geq 0 \end{aligned} \tag{31}$$

Where:

- h_w is the web height in millimeters.
- t_w is the web thickness in millimeters.
- w_f is the flange width in millimeters.
- t_w is the flange thickness in millimeters.
- b_p is the plate effective width in millimeters.
- t_p is the plate thickness in millimeters.
- h_{op} is the height of cut-outs in the web section in millimeters.
- h_{max} is the initial web height considered as maximum to not influence the height between decks and spacing availability from the general arrangement.

The optimization problem is applied to all the reinforcements shown in the calculations before. It is important to comment that the weight is calculated approximated by the multiplication of the member section area with the member span. Also, because of the large differences observed in Table 11 between the required and obtained section modulus, some additions were considered for the transverse elements positioned at superstructure sides. Since the limiting factor to determine these elements could be the buckling, the required section modulus of these elements is increased. The process applied to achieve that is to consider an increase in the design load, by the addition of the load coming from the upper deck connected to the side. For a future work, would be interesting to include directly the buckling criteria in the calculations to have a better defined limit. Table 24 displays the results obtained for the optimization process. The required section modulus for transverse elements positioned at the sides locations differ from the previous results presented because of the addition in the design load.

After the optimization process is finished, a round-up procedure is made to provide exact values for the dimensions. Besides that, some dimensions were changed to match among the structural design. The values shown in Table 24 are the final ones used for the model. It is possible to observe that the obtained section modulus is as close as possible to the required one, but still respecting it. Table 55 in Appendix H displays the complete output from the *Python* code.

Table 24: Optimized dimensions with obtained section modulus against required ones.

Member Location		**Member Type**	**Dimensions** $[mm]$	Z_{req} $[cm^3]$	Z_o $[cm^3]$
Decks	Upper Deck	Transverse	$110 \times 4 + 60 \times 4$	41.74	42.08
		Frame 24 (CB)	$160 \times 4 + 98 \times 7$	122.70	137.25
		Frame 24 (O)	$200 \times 4 + 84 \times 6$	133.67	146.55
		Frame 12+550	$300 \times 6 + 158 \times 10$	506.97	517.31
		Frame 20	$168 \times 4 + 64 \times 4$	77.94	78.66
		Girder (0.6CL)	$205 \times 5 + 137 \times 15$	448.79	473.40
		Girder (1.8CL)	$300 \times 6 + 120 \times 8$	313.69	336.67
		Girder(0.6CL-CB)	$300 \times 6 + 200x17$	1018.92	1030.65
		Girder(1.8CL-CB)	$294 \times 6 + 196 \times 15$	954.89	959.84
		Girder (Box B.)	$200 \times 4 + 200 \times 22$	868.46	892.67
	Bridge Deck	Frame 29	$140 \times 4 + 94 \times 16$	227.77	229.89
		Girder (0.6CL)	$205 \times 5 + 137 \times 15$	447.79	473.40
		Girder(1.8CL)	$300 \times 6 + 100 \times 7$	235.81	259.66
		Girder(0.6CL-CB)	$300 \times 6 + 186 \times 12$	677.12	697.36
	Hard Top	Girder(0.6CL)	$200 \times 4 + 66 \times 5$	102.50	115.60
		Girder(1.8CL)	$150 \times 4 + 100 \times 11$	180.56	191.18
Superstr.	LT - Sides (DH)	Frame 13 (O)	$145 \times 4 + 48 \times 4$	53.12	54.34
		Side Stringer	$200 \times 4 + 113 \times 8$	207.81	229.45
	LT- Sides (SP)	Transverse	$130 \times 4 + 60 \times 4$	53.65	54.28
	2T - Sides	Frame 15 (O)	$200 \times 4 + 100 \times 7$	167.60	185.35
		Transverse (Box B.)	$120 \times 4 + 120 \times 10$	162.77	172.82
		Side Stringer	$200 \times 4 + 113 \times 8$	208.14	229.45
Bulkhead	Transv.	Vertical Web	$100 \times 4 + 67 \times 13$	96.48	98.56
		Horizontal Stringer	$100 \times 4 + 40 \times 4$	28.80	29.08
	Long.	Vertical Web	$78 \times 4 + 32 \times 4$	17.07	17.93
		Horizontal Stringer	$100 \times 4 + 40 \times 4$	28.80	29.08
		Stiffener (O)	102×7	21.32	22.45

Table 25 below shows the weight comparison in order to demonstrate the weight reduction. This values are approximated for only one element. Later on, a more accurate weight estimation can be obtained from the 3D model and compared to the old structural weight. But, it is already demonstrated a good percentage of weight reduction, coming to almost 30% for some members.

Table 25: Optimized dimensions with obtained weight and % of reduction from initial dimensions weight.

Member Location		Member Type	Dimensions $[mm]$	W_o $[kg]$	Reduction
Decks	Upper Deck	Transverse	$110 \times 4 + 60 \times 4$	30.60	1.6%
		Frame 24 (CB)	$160 \times 4 + 98 \times 7$	16.36	3.1%
		Frame 24 (O)	$200 \times 4 + 84 \times 6$	34.14	7.0%
		Frame 12+550	$300 \times 6 + 158 \times 10$	158.68	32.2%
		Frame 20	$168 \times 4 + 64 \times 4$	48.95	13.0%
		Girder (0.6CL)	$205 \times 5 + 137 \times 15$	219.42	27.1%
		Girder (1.8CL)	$300 \times 6 + 120 \times 8$	153.97	8.7%
		Girder(0.6CL-CB)	$300 \times 6 + 200x17$	128.53	19.7%
		Girder(1.8CL-CB)	$294 \times 6 + 196 \times 15$	124.98	23.5%
		Girder (Box B.)	$200 \times 4 + 200 \times 22$	138.19	21.3%
	Bridge Deck	Frame 29	$140 \times 4 + 94 \times 16$	65.72	14.9%
		Girder (0.6CL)	$205 \times 5 + 137 \times 15$	219.17	27.1%
		Girder(1.8CL)	$300 \times 6 + 100 \times 7$	123.52	22.2%
		Girder(0.6CL-CB)	$300 \times 6 + 186 \times 12$	86.04	13.2%
	Hard Top	Girder(0.6CL)	$200 \times 4 + 66 \times 5$	60.47	11.2%
		Girder(1.8CL)	$150 \times 4 + 100 \times 11$	89.98	16.0%
Superstr.	LT - Sides (DH)	Frame 13 (O)	$145 \times 4 + 48 \times 4$	27.18	4.8%
		Side Stringer	$200 \times 4 + 113 \times 8$	157.22	16.0%
	LT- Sides (SP)	Transverse	$130 \times 4 + 60 \times 4$	38.96	10.9%
	2T - Sides	Frame 15 (O)	$200 \times 4 + 100 \times 7$	28.07	12.9%
		Transverse (Box B.)	$120 \times 4 + 120 \times 10$	28.43	18.1%
		Side Stringer	$200 \times 4 + 113 \times 8$	158.39	16.0%
Bulkhead	Transv.	Vertical Web	$100 \times 4 + 67 \times 13$	34.67	12.6%
		Horizontal Stringer	$100 \times 4 + 40 \times 4$	22.81	3.8%
	Long.	Vertical Web	$78 \times 4 + 32 \times 4$	8.49	22.9%
		Horizontal Stringer	$100 \times 4 + 40 \times 4$	22.81	3.8%
		Stiffener (O)	102×7	11.70	4.4%

5. PART 2: FINITE ELEMENT ANALYSIS

The second part of this work is composed by the achievement of a detailed structural response to the optimized structure through a finite element analysis. And posteriorly, comparison of the results to the classification society criteria to evaluate the structure reliability. The finite element analysis consists into the application of the finite element method to solve the structural response. The finite element method is defined by the discretization of a complex geometry into subdomains, called finite elements or just elements. The general idea is to use simple geometry elements that allows for the problem solution and then assemble all the elements to extend the approximated response to the main structure.

The initial problem is based in continuum mechanics and defined by a set of partial differential equations and boundary conditions. The differential equations include the equilibrium equations, compatibility equations and constitutive relations. In the finite element method, the problem is transformed to a discrete scenario. The differential equations become algebraic equations and are solved to each element in terms of their nodes. The nodes determine the degree of freedom (DOF) of the problem, which are the main unknowns of the problem. Internal elements values are determined by interpolation of the nodal values through polynomial functions. The number of nodes of each element is defined by the number of vertices and the desired polynomial degree.

The algebraic equations are defined as Equation 32. In which for structural problems, K is the stiffness matrix dependent on the material and geometry. The term q is the vector of the DOF's, the unknowns of the problem. And the term g is the vector of the generalized loads. The stiffness matrix and vector of loads needs to be computed for each element and then, assemble in the global stiffness matrix and global loads vector. The solution of the problem is given in Equation 33. The inversion of the matrix K is not trivial and, therefore, numerical methods are required.

$$K \cdot q = g \tag{32}$$

$$q = K^{-1} \cdot g \tag{33}$$

The elements are connected to each other by their nodes. Therefore, side-by-side elements share DOFs and require boundary conditions. The elements need to be defined as to assure a piecewise continuity among them. This property ensure the continuity of the solution in the discretized structure. The interpolation functions or also called shape functions are used to determine the response within the elements. These functions are polynomials, usually of first or second order. They are defined accordingly with the type of element chosen and level necessary for the analysis.

From the problem solution, the DOFs are obtained, which consists of the generalized displacements on the nodes. Then, it is possible to obtain the strain and stresses from the compatibility and constitutive equations. The method can be used to solve both linear and non-linear problems, as well as static and dynamic load cases.

Therefore, the procedure to follow is:

- Modelling: stage where occurs the translation of the real structure to an idealized one to be analyzed. In this step the structure is simplified and defined accordingly to the goal of the analysis.
- Meshing: phase that the discretization process is performed. It is important to attempt to factors as element choice, mesh size, properties and mesh quality.
- Define boundary conditions and loads: input in the model consistent boundary conditions to provide a trustworthy response and the actual loads that are acting on the body.
- Solve problem: step mainly consists in choosing the solver and type of problem to be solved.
- Post-processing: stage where displacements and stresses can be plotted and evaluated. It is also important analyze the results in order to validate the model and check for consistency.

The pre-processing, which consists of the modelling, meshing and definition of boundary conditions and loads, are performed through the softwares *Rhinoceros* 6.0 and *MSC Apex* 2022.3. The solver applied is the *MSC Nastran* 2022.4 and for the post-processing is used *MSC Patran* 2022.4.

5.1. Modelling

The modelling part consists into translating to the software an idealization of the real structure to be studied. Therefore, it is important to consider simplifications in the geometry to facilitate the solution of the problem. The shipyard provided the 3D block models' of the superstructure in Rhino files. But, since these files are also used in the production department, the structures are constructed in polysurfaces and have many details as cut-outs and spaces for weldings. Therefore, the main part of the work is to transform the polysurfaces into single surfaces and change the dimensions to the optimized ones.

Concerning simplifications, brackets and small parts are removed from the model. As well as the cut-outs for the passage of stiffeners and extra-spacing in plate destined to the welding. The stairs are also modified to a single surface, when possible, in order to make the model simpler. Each block was edited separately and, then, they were united to verify the alignment and import the *.iges* file to *MSC Apex*. Figure 9 and 10 illustrate some of the simplifications performed. It it important to notice that the colours changed between the figures, because the structures are divided by thickness. Therefore, figures at right already applied the optimization changes to the dimensions.

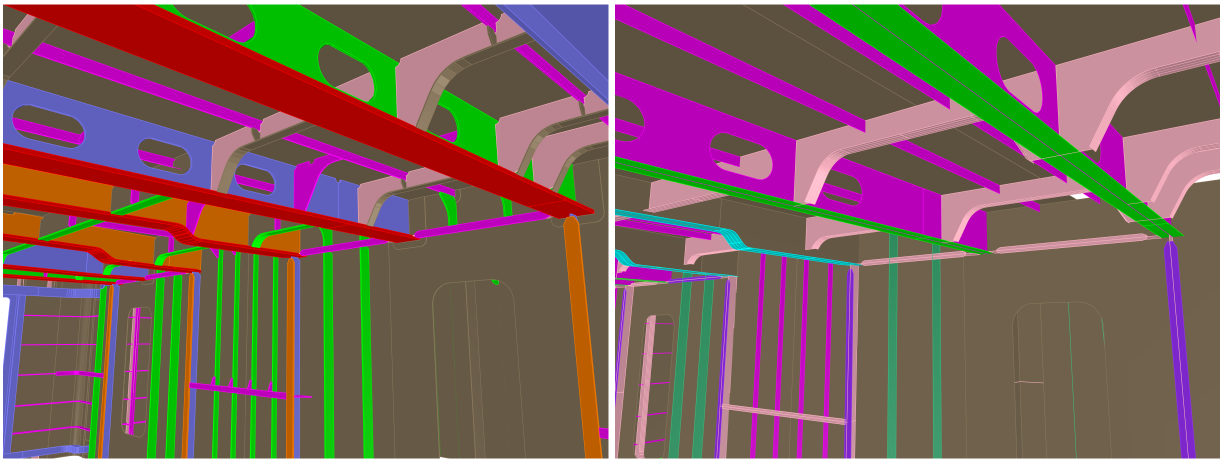


Figure 9: At left, initial structure with thickness and details as cut-outs and brackets. At right, final structure after change to surfaces, remove of details and adjust of dimensions.

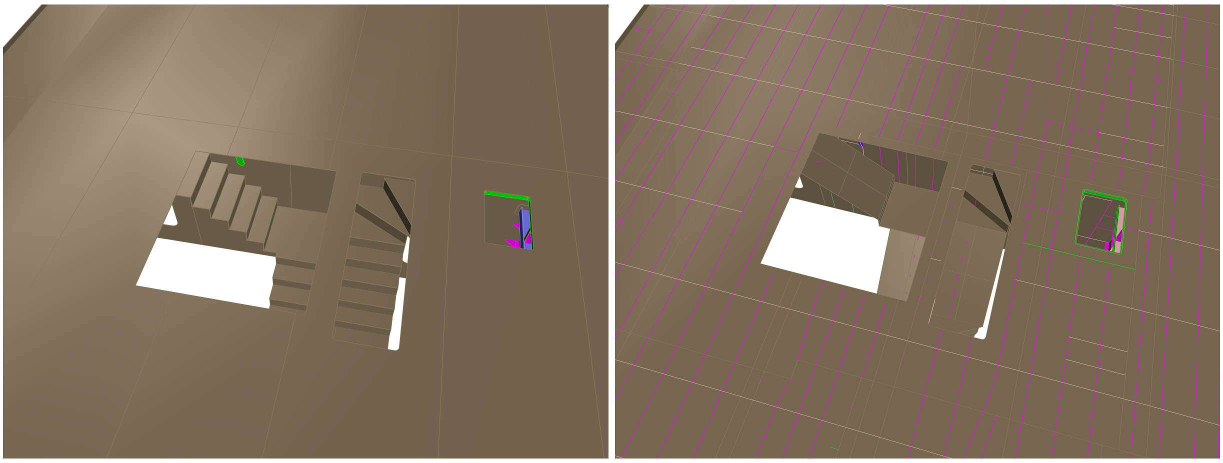


Figure 10: At left, initial stairs structure. At right, simplified stairs to single surface.

The modelling is finalize in *MSC Apex*, same software used for the meshing. This step involved a final geometry clean up, by removing small edges and extra vertices present on the model. Besides that, to verify and ensure the surfaces connections. This part, specifically, was crucial. Because of the different tolerances between the softwares most of the surfaces appear to not be correctly connected, even though they were in the Rhino model. And this would make the meshes from these surfaces to not coincide and create disconnected displacements.

For the connections task, the first idea was to attach all the surfaces from the full model. However, many problems arise with that as deformations in the surfaces, generation of corrupt bodies and also making the model slower to work with. Thus, in the end, it was chosen to attach the surfaces within each block. And then, the interactions among the blocks are ensured after the meshing stage, process explained in the next subsection. Figure 11 shows the block SA01, the aft part of the upper deck. The lines in yellow represent perpendicular connections, in green parallel connections and in red free edges. Figure 12 displays the full model of the superstructure.

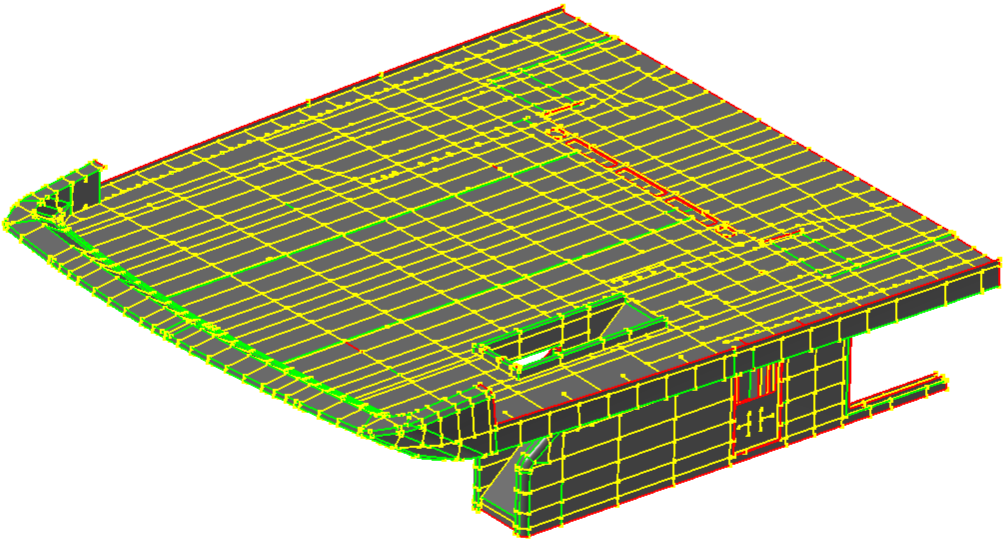


Figure 11: Surfaces connections in the block SA01 (aft part of first tier).

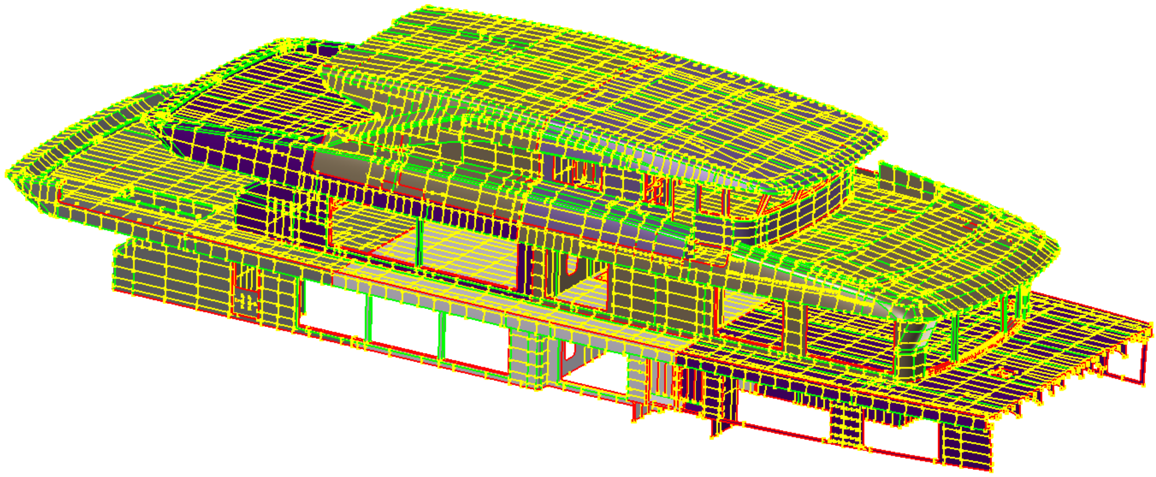


Figure 12: Full superstructure model.

5.2. Meshing

After modelling, the next step is to discretize the geometry in finite elements, which means create the mesh. The first decision to be made is to select the type of elements for each part of the model. Elements can have different shapes, dimensions and degrees and their choice will influence directly in the possible loads that the structure can take it. For example the 1D rod type of element can only take axial or torsional loads, meanwhile the 1D beam type of element can also take bending and shear loads. The dimension depends on the structure to be analyzed and the stress/strain state that it is expected to obtain in the analysis. A plane stress state needs 2D element's type for example.

For the study case, since the structures are composed by panels, it is chosen to apply 2D shell elements of type CQUAD4 and CTRIA3. These are the linear quadrilateral and triangular elements as shown in Figure 13 below. These elements can represent in-plane, bending and transverse shear behavior. The CQUAD4 elements are preferred for accuracy reasons since the CTRIA3 can present excessive stiffness. But the triangular ones are used when the geometry cannot be defined by the quadrilateral elements. It is considered that the linear elements present a good trade-off between accuracy and analysis efficiency, due to the model size which requires a long time for processing.

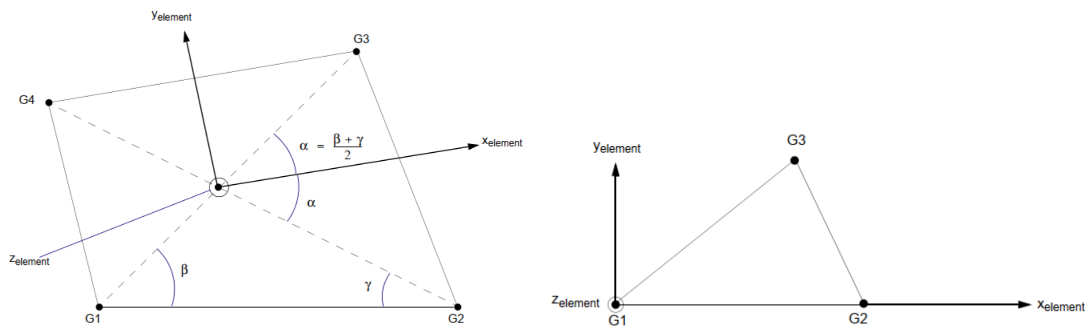


Figure 13: CQUAD4 and CTRIA3 elements with their local coordinates systems.

As mentioned before, the elements are considered linear because of the polynomial degree of its shape functions. For the selected elements, the linear behavior of their shapes functions means a linear approximation of the displacements. Because of that, the approximation of strains and stress inside the elements is constant.

From the shipyard know-how, it is known that a good mesh size is usually taken as half to one third of the smaller dimension of the simple stiffeners for a fine mesh. Since the model is very large to perform a convergence study, the information from the shipyard was applied. Therefore, it was decided to use 30 millimeters as mesh size. Figure 14 and 15 below shows the obtained mesh different parts of the superstructure.

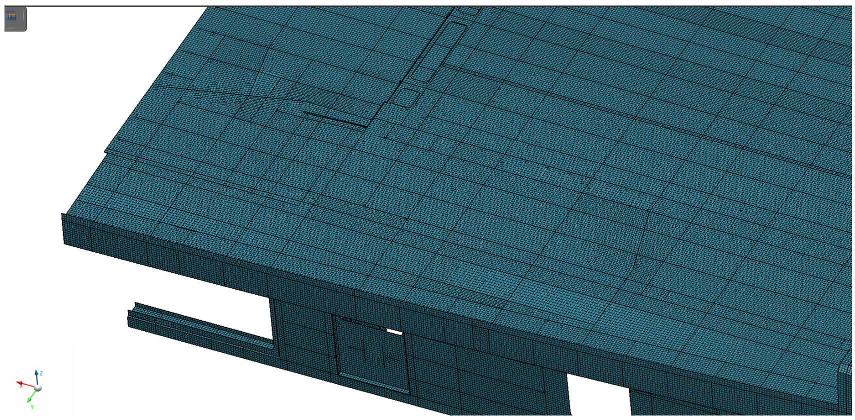


Figure 14: Part of the mesh created in the superstructure model (showing the block SA01).

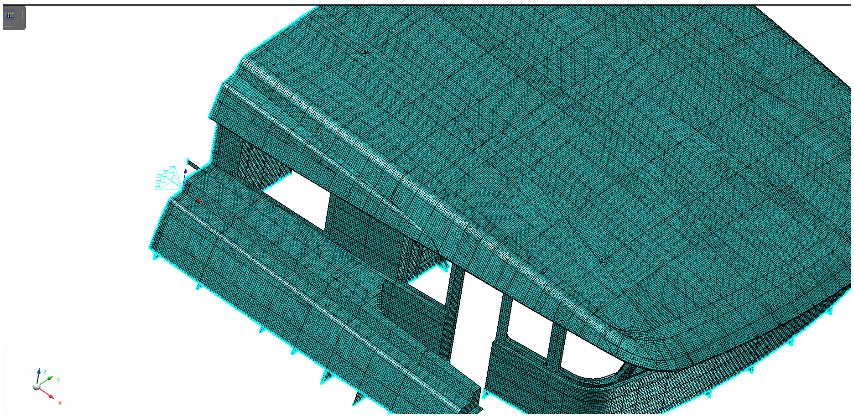


Figure 15: Part of the mesh created in the superstructure model (showing the block SC02).

After the mesh creation, it is necessary to apply the properties to the elements. For this case, it is only necessary to chose the thickness and material. The model comprises 13 different thickness for the parts varying to 4 mm to 22 mm, as defined in the optimization. The material is the same for the whole model, aluminium alloy. The properties inserted in the software are the ones shown in Table 3. Figure 16 below displays the visualization in the software with the elements thickness.

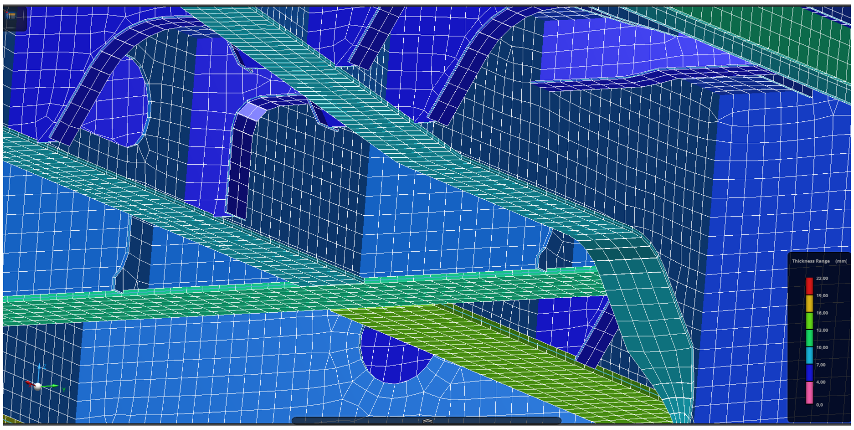


Figure 16: Mesh after application of sections properties, displaying thickness.

It is important to comment that for the two pillars present in the model a different mesh type was selected. For this structure it is applied beam elements with a circular constant cross-section. The diameter is 70 mm and the thickness is 7.5 mm. The mesh size is used the same, 30 mm of length.

Finally, it would be the moment to join the block's meshes. The only possible solution for that besides joining geometrically in the model would be to apply a contact interaction between the blocks. However, this would make the analysis to be non-linear in the block's joining. This fact aligned with such a big model and fine mesh would make the analysis take too long and need too much disk space. Thus, it was chosen to analyzed the model by block focusing on areas further from the boundaries. This choice will influence the boundary conditions and loads applied to each block, which is explained in the next subsection. Because of this decision, the blocks will be referred by their nomenclatures from the shipyard's division. Figure 17 below shows the delimitation of each block along with their labels.

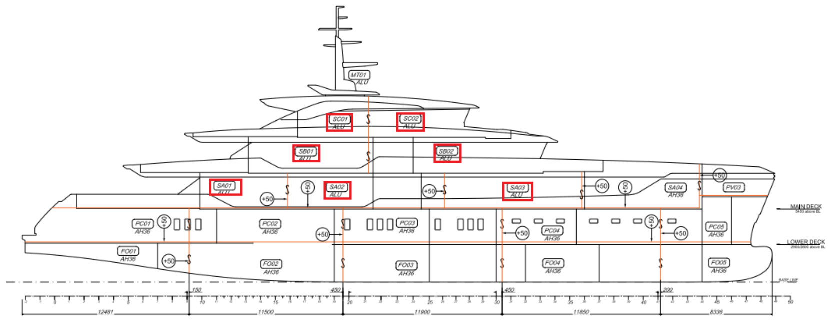


Figure 17: Division of blocks from yacht's superstructure.

In the end, it was generated a mesh with 2846539 elements and 2813754 nodes for the full model. The separated values for each block are detailed along with the results. It is important to check the mesh quality before the next step. The software lists the following parameters for the mesh quality check: aspect ratio, warpage, skew, taper, jacobian and maximum/minimum internal angles. Among these the warpage and taper are only applicable to quadrilateral elements. Table 26 below shows the ranges applied in the software to define good elements from bad ones.

Table 26: Range values for mesh quality parameters check.

Parameter	Good	Poor	Bad	Invalid
Aspect Ratio	1-3	3-5	5-20	>20
Warpage	0-5	5-10	10-15	>15
Quad Skew	0-30	30-60	60-80	>80
Tria Skew	0-10	10-30	30-50	>50
Taper	0-0.30	0.30-0.60	0.60-0.80	>0.80
Jacobian	1-0.70	0.70-0.50	0.50-0	<0
Quad Min Interior Angle	90-70	70-40	40-5	<5
Quad Max Interior Angle	90-110	110-140	140-175	>175
Tria Min Interior Angle	60-45	45-20	20-5	<5
Tria Max Interior Angle	60-80	80-120	120-175	>175

During the mesh quality check, some invalid elements were observed in the blocks' meshes. After some work, these elements could be eliminated completely. In the end the mesh presented 2829117 of good elements, 10427 of poor elements and 6995 of bad elements. Even though it might seem a high number of bad elements, it only corresponds to 0.24% of the total number of elements. Therefore, it is considered that the final mesh present a good quality in overall. Figures 18 to 21 shows the mesh quality plot by block. It is possible to observe that the good quality elements are the majority.

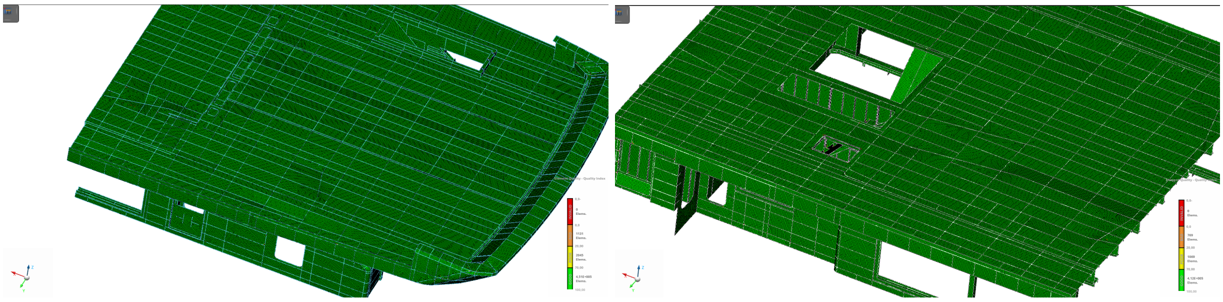


Figure 18: Mesh quality plot of blocks SA01 at left and SA02 at right.

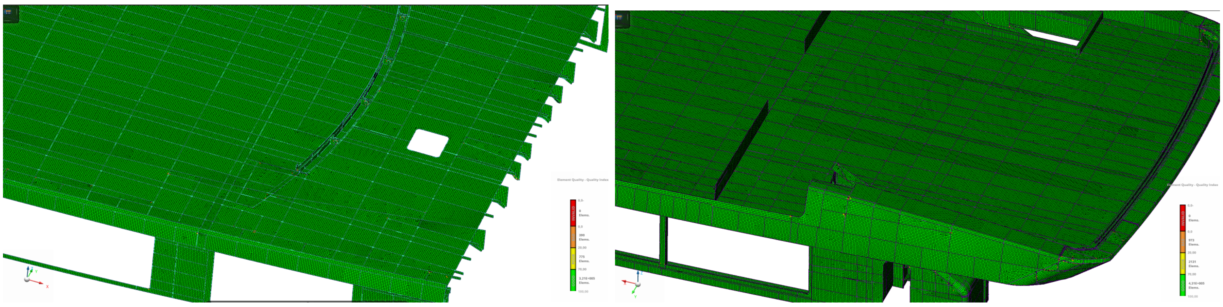


Figure 19: Mesh quality plot of blocks SA03 at left and SB01 at right.

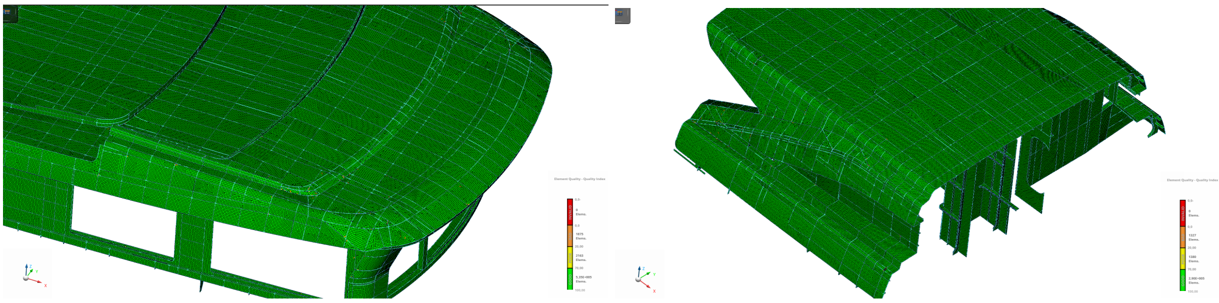


Figure 20: Mesh quality plot of blocks SB02 at left and SC01 at right.

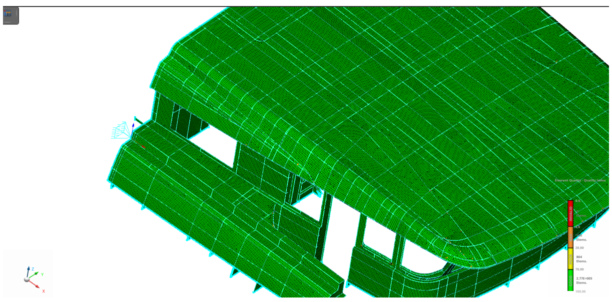


Figure 21: Mesh quality plot of block SC02.

5.3. Boundary Conditions and Loads

The boundary conditions are the constraints necessary to solve the problem. They are responsible to represent the real connection between the model and the external world. Boundary conditions can be classified into essential and natural. The essential boundary conditions are the ones directly related (explicitly) to the DOF's. The natural are other ones, related to the DOF's in an implicit manner. Only essential boundary conditions are considered from this point.

For the study case, since only the superstructure is modelled it is necessary to apply boundary conditions in the edges responsible with the connection to the yacht's hull. Once the superstructure is made of aluminium and the hull of steel, it is considered these nodes as clamped. This means that the nodes are not free to translate or rotate in any direction. Because the steel will represent a high stiffness and is expected to hold for the superstructure. Also, the fore part of the superstructure was not modelled. Since the model stops almost in a bulkhead position, these nodes are also considered as clamped. But, it is important to not use the area close to the edge for the analysis.

After the decision to run the analysis separately by block, extra boundary conditions need to be added in each block to hold for their connections. For each block, the edges which would be connected to another block were considered as clamped. Even though, the relation between some parts would not have a clamped behavior, this is a simplification in order to analyze the model. It is just necessary to remove the results directly near these areas. From these considerations, the boundary conditions could be applied in the software. Figure 22 to 25 shows the model with the clamped boundary conditions.

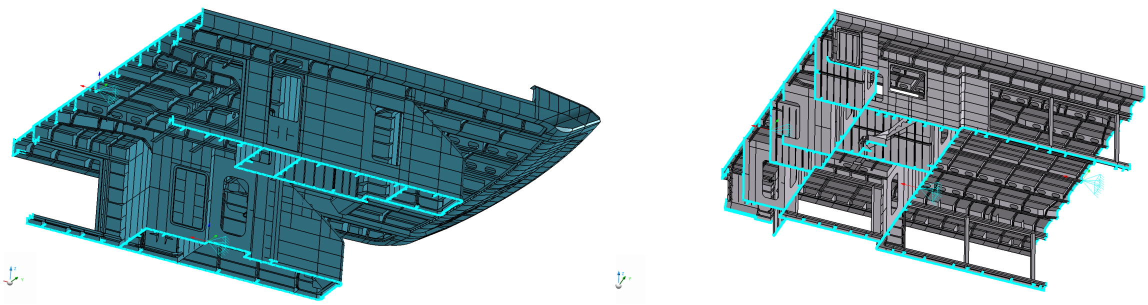


Figure 22: Boundary conditions of blocks SA01 at left and SA02 at right.

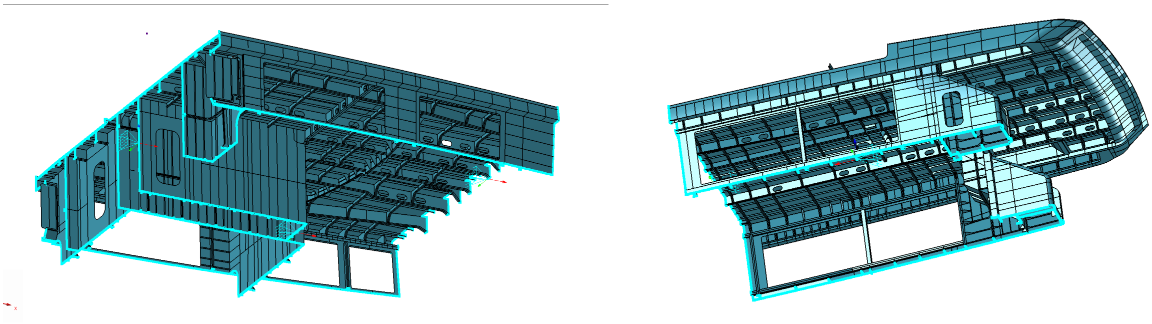


Figure 23: Boundary conditions of blocks SA03 at left and SB01 at right.

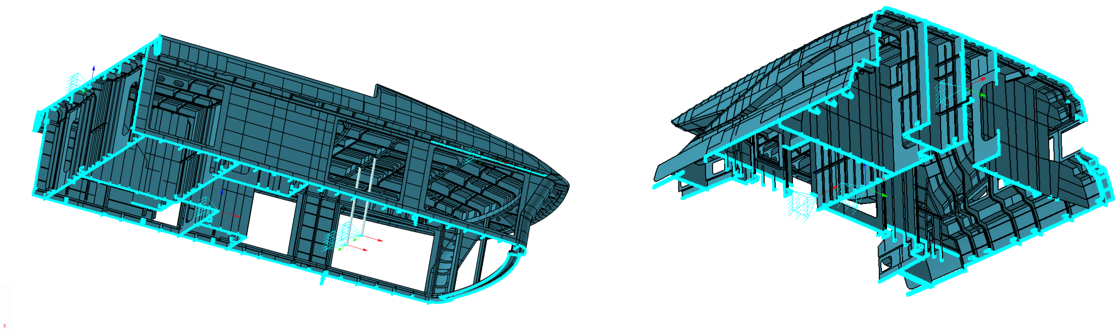


Figure 24: Boundary conditions of blocks SB02 at left and SC01 at right.

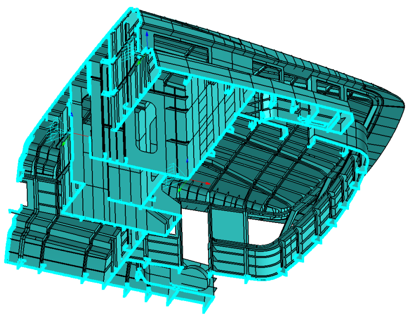
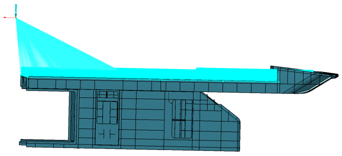
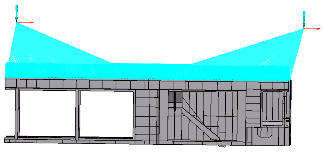
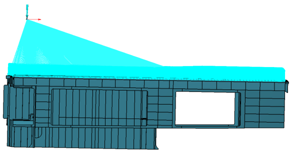
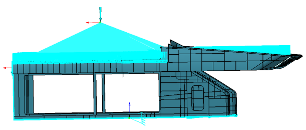
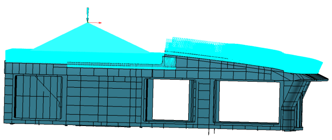
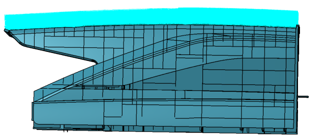
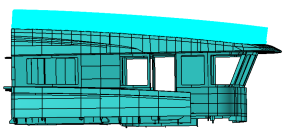


Figure 25: Boundary conditions of block SC02.

Finally, it is necessary to define the load case to be applied and analyze the structure. Since LR do not give specific indication for finite element analysis, it was considered the design loads used for the scantling definition. Because of the time frame, one load case is selected, the deck pressure loads in the upper deck, bridge deck and hard top. In addition, with the choice to pursuit the analysis separately by block, it was also decided to apply the weight of the upper blocks to be closer to the real situation. Thus, for the blocks in the first and second tier, it was added a concentrated load in the center of gravity of the block positioned directly above. The load is connected to the block by rigid links connections spread in the area where the upper block would be supported by. Table 27 shows a complete description for each block and the loads values.

Table 27: Load configuration for each block at the load case chosen.

Block		Loads
SA01		Deck Pressure $[KN/m^2]$
		4.20 (internal) / 5.37 (external)
		Weight from upper block [N]
		35725 at (17.8,-0.03,10.4) m
SA02		Deck Pressure $[KN/m^2]$
		4.20 (internal)
		Weight from upper block [N]
		35725 at (17.8,-0.03,10.4) m
		40765 at (26.7,-0.07,10.3) m
SA03		Deck Pressure $[KN/m^2]$
		4.20 (internal)
		Weight from upper block [N]
		40765 at (26.7,-0.07,10.3) m
SB01		Deck Pressure $[KN/m^2]$
		4.20 (internal) / 5.37 (external)
		Weight from upper block [N]
		48920 at (19.4,0.15,12.7) m
SB02		Deck Pressure $[KN/m^2]$
		4.20 (internal) / 5.37 (external)
		Weight from upper block [N]
		44890 at (26.9,0.03,12.6) m
SC01		Deck Pressure $[KN/m^2]$
		5.37 (external)
		Weight from upper block [N]
		-
SC02		Deck Pressure $[KN/m^2]$
		5.37 (external)
		Weight from upper block [N]
		-

During the application of the loads, it was important to verify the element orientation in order to have the right direction for the loads application. For the problem analysis, the load case is selected as a linear static problem.

5.4. Results

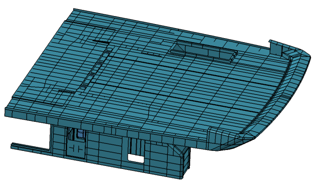
In this subsection the Results from the analysis of each block are displayed. Next section presents the comparison with the classification society criteria and further considerations.

The results shown are related to the nodes displacements and the von mises stress. The von mises stress corresponds to the equivalent stress in the analyzed location. It is the combination of all the normal stresses and shear stresses acting at the point of interest. Equation 34 displays the formulation to obtain this stress.

$$\sigma_{vm} = \sqrt{\sigma_x^2 + \sigma_y^2 - \sigma_x\sigma_y + 3\tau^2} \tag{34}$$

5.4.1. Block SA01

Table 28: Details of block SA01.

Block SA01	Number of Elements
	453814
	Number of Nodes
	447321
	Analysis Time
	15 min

This block positioned in the aft part of first tier is subjected to both external and internal deck pressures. Figure 26 shows the displacement plot along the block for the load case studied. The legend values are in millimeters.

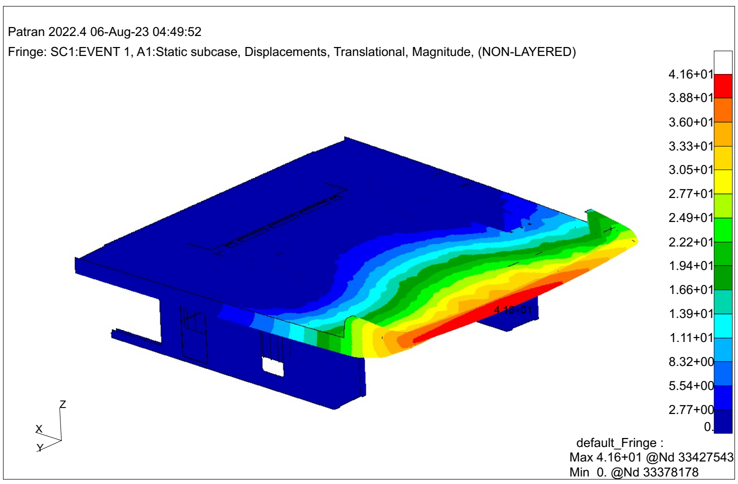


Figure 26: Displacement plot for block SA01.

It is possible to observe that the maximum displacement occurs in the aft part of the deck with a value of 41.6 mm. This result is expected, since the structures in this region are in a situation of cantilever beam, where the maximum displacement occurs in the free edge. The maximum value occurs for both girder and secondary stiffener. For frames, the maximum displacement observed is 27.7 mm.

Considering the stresses, Figure 27 below displays the plot for this block, after disregarding some discontinuities due the sharp edges. It is possible to observe that the maximum occurs in the flange of a frame. This is the frame that is connected to the main frame that holds for the cantilevered structures. Also, this frame is positioned very close to some of the discontinuities mentioned. Therefore, it is consistent that the maximum appears in this location. The value for this location is 116 MPA.

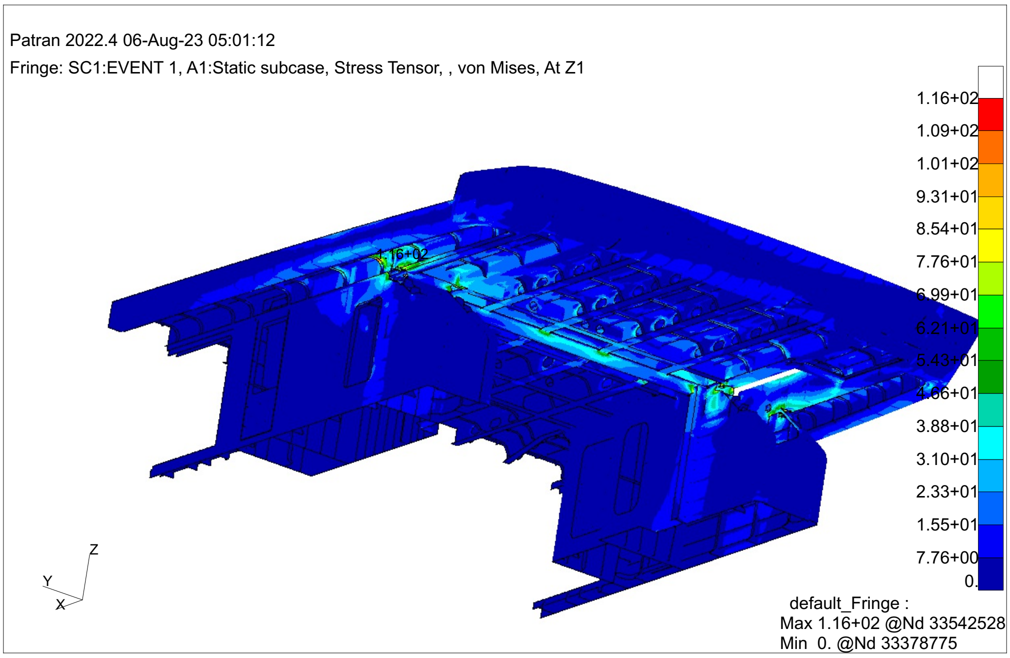


Figure 27: Von Mises stress plot for block SA01.

From the results, the maximum stress for primary members is the actual maximum stress discussed before. For plating, the maximum value found is approximately 70 MPA, in the area close to the frame with maximum stress.

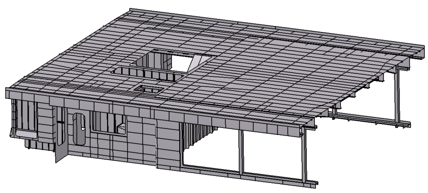
Table 29 summarizes the results for Block SA01. These values are gonna be compared to the defined criteria from LR in the next section.

Table 29: Summary from results obtained at block SA01.

Maximum Displacements		
Girder	41.6	$[mm]$
Frame	27.7	$[mm]$
Stiffener	41.6	$[mm]$
Global	41.6	$[mm]$
Maximum Von Mises Stress		
Primary stiffener	116	$[MPA]$
Plating	70	$[MPA]$
Global	116	$[MPA]$

5.4.2. Block SA02

Table 30: Details of block SA02.

Block SA02	**Number of Elements**
	413697
	Number of Nodes
	412097
	Analysis Time
	6 min

This block positioned in the middle part of first tier is subjected to only internal deck pressure. Figure 28 shows the displacement plot along the block for the load case studied. The legend values are in millimeters.

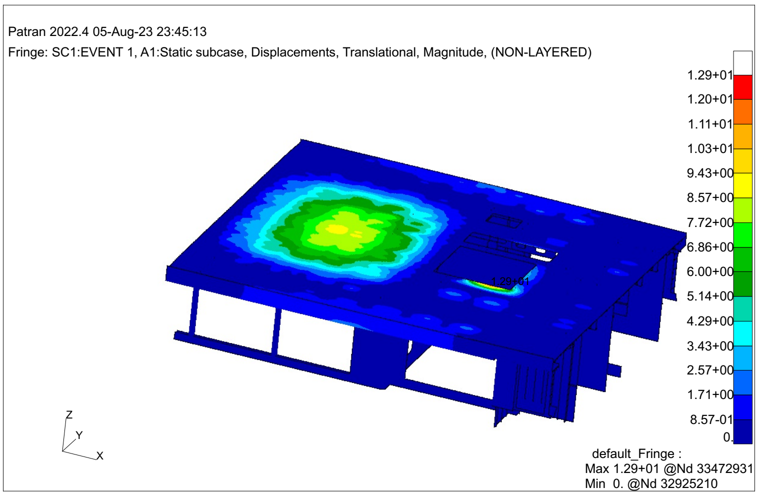


Figure 28: Displacement plot for block SA02.

From the figure, the maximum deflection is happening along the big deck opening for the stairs with a value of 12.9 *mm*. The opening create a free edge on the deck and because of its large size, there is a great span unsupported. The opening was considered during the design and the frames around it are enlarged. But, the result was already expected. In the figure, it is also possible to observe a large area with displacements up to 9 *mm*. These deflections occur because of the large area without support. This bigger span, however, was considering in the design stage. Concerning global results, for a girder, the maximum displacement observed is 7.72 *mm* and for a secondary stiffener is 8.57 *mm*. For frames, the maximum displacement observed is 6.86 *mm*.

Figure 29 shows in more details the area with maximum displacement. In the real structures, there are some transversal stiffeners located between this longitudinal stiffener and the girder. This will probably influence in the value of the displacement. It was a simplification to remove the small transversal stiffeners, but in this case it is important to mention their absence.

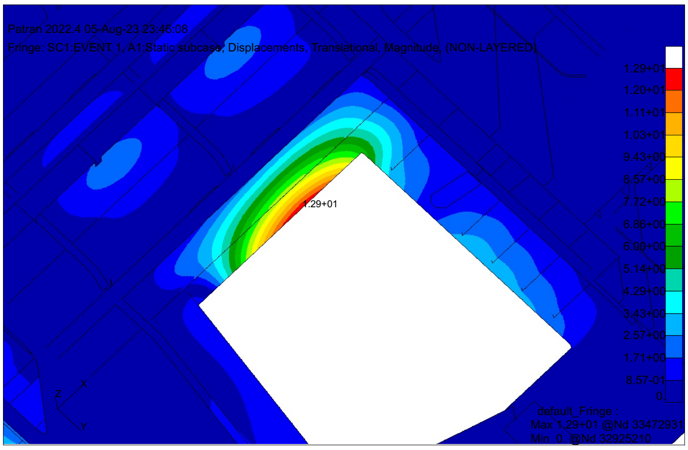


Figure 29: Closer look to maximum displacement at block SA02.

Considering the stresses, Figure 30 below displays the plot for this block. The maximum stress is occurring at the web of the vertical web element, close to the connection with the girder, with a value of 98.9 MPA. This is a area of high stress caused by the junction of different stiffeners in the bulkhead and also close to the discontinuity caused by the deck opening. Besides that, during the modelling the flange of this element was not modelled in the full length of the web, which could cause a weakness in the location. Therefore, it is consistent that a peak is located there. It is important to mention that the stresses arising at the edge of the block should be disregarded due to the boundary conditions applied at this location.

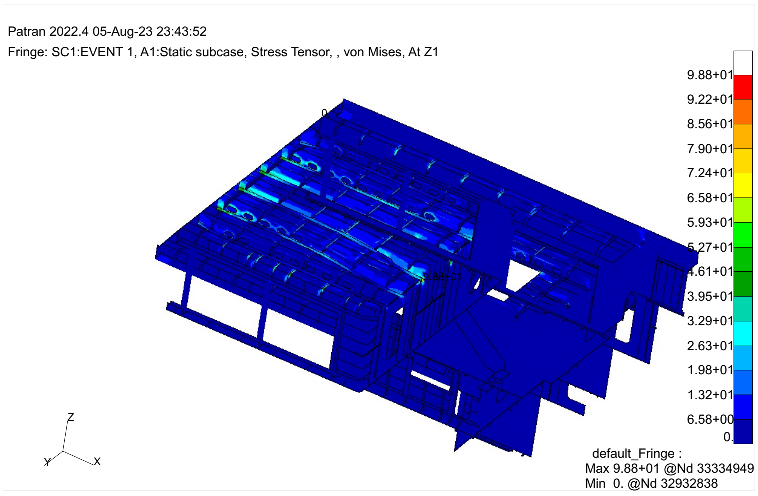


Figure 30: Von Mises stress plot for block SA02.

From the results, the maximum stress for primary members is the actual maximum stress discussed before. For plating, the maximum value found is 39.5 MPA, close to the corner of the deck opening.

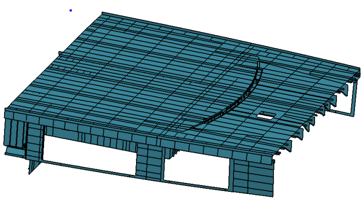
Table 31 summarizes the results for Block SA02. These values are gonna be compared to the defined criteria from LR in the next section.

Table 31: Summary from results obtained at block SA02.

Maximum Displacements		
Girder	7.72	$[mm]$
Frame	6.86	$[mm]$
Stiffener	8.57	$[mm]$
Global	12.9	$[mm]$
Maximum Von Mises Stress		
Primary stiffener	98.9	$[MPA]$
Plating	39.5	$[MPA]$
Global	98.9	$[MPA]$

5.4.3. Block SA03

Table 32: Details of block SA03.

Block SA03	**Number of Elements**
	434060
	Number of Nodes
	426516
	Analysis Time
	3 min

This block positioned in the front part of first tier is subjected to only internal deck pressure. Figure 31 shows the displacement plot along the block for the load case studied. The legend values are in millimeters.

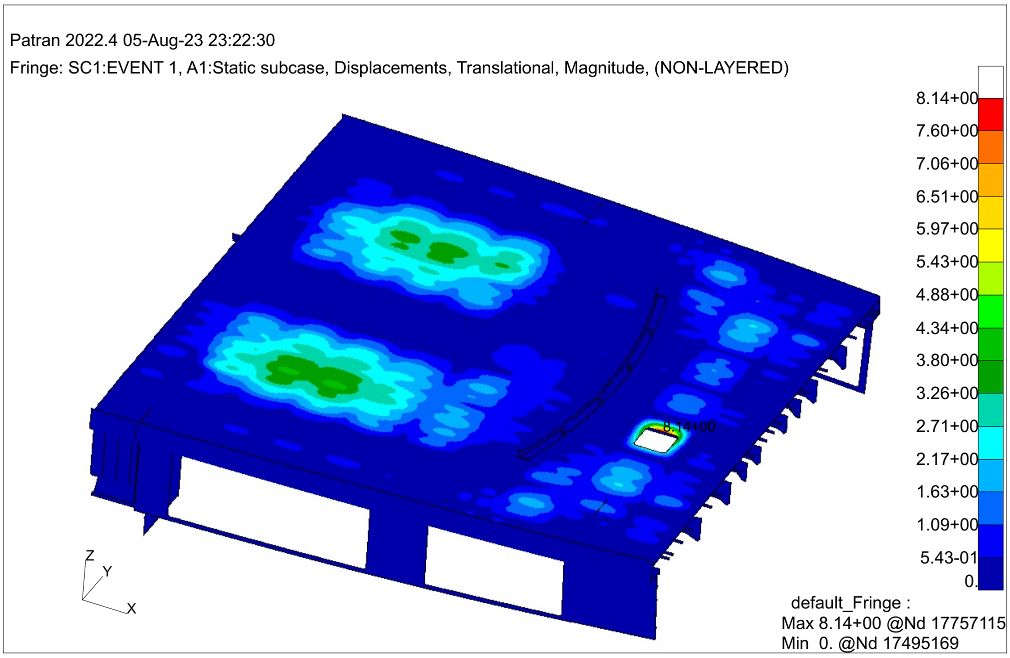


Figure 31: Displacement plot for block SA03.

The maximum displacement occurs for the opening in the deck with a value of 8.14 mm. Once again, the opening creates a free edge. So the maximum location is expected. For a girder, the maximum displacement observed is 2.71 mm and for a secondary stiffener is 3.80 mm. For frames, the maximum displacement observed is also 3.80 mm.

Regarding stresses, Figure 32 below displays the plot for this block. In this block, it was expected that the maximum stress would occur along the opening. Thus, this result was an initial surprise. The maximum stress of 79.1 MPA is in the flange of a frame.

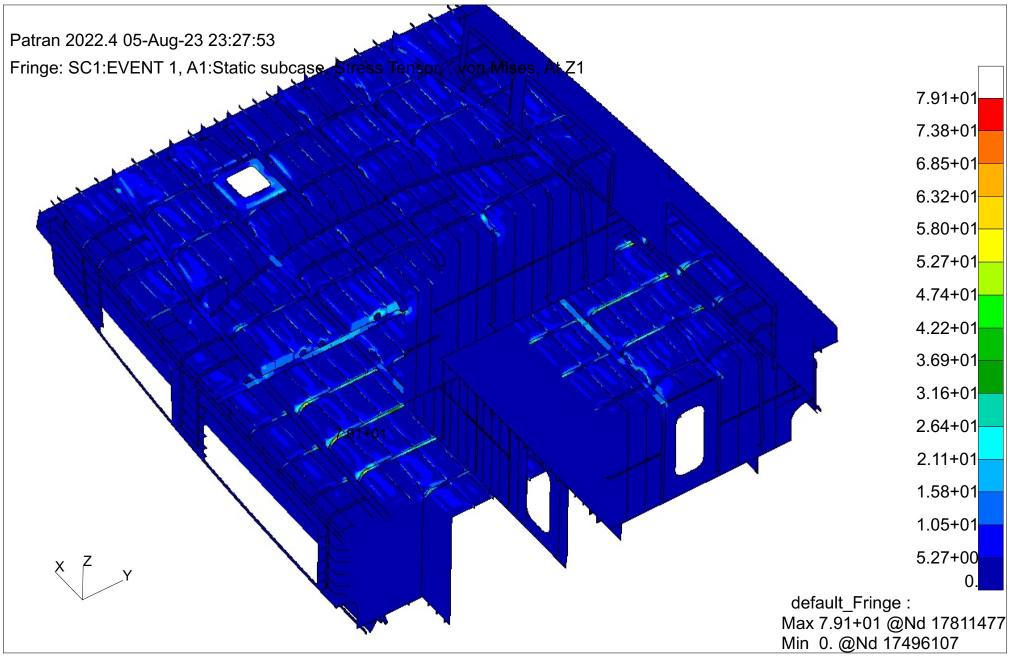


Figure 32: Von Mises Stress plot for block SA03.

Looking closer to the area, Figure 33 shows the exact position of the maximum stress. The maximum arises in the curvature that makes the connection between the frame and the girder. It is also possible to observe that other flange frames in the same region are having peaks. The explanation is, therefore, that the geometry is causing this peak in the stress. The curvature should be smoother to obtain a decrease in this area, which means, increase the radius. This aspect, indeed, was not verified during the modelling. So, this could be a point of improvement.

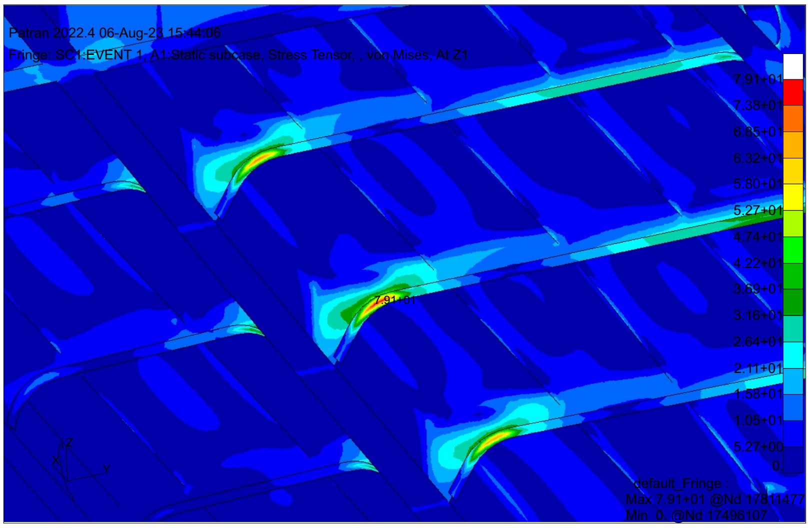


Figure 33: Position of maximum stress at block SA03.

From the results, the maximum stress for primary members is the actual maximum stress discussed before. For plating, the maximum value found is 26.4 MPA.

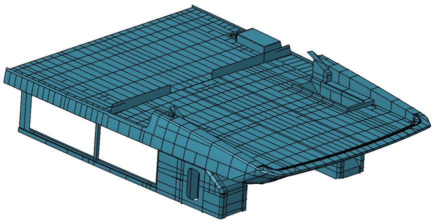
Table 33 summarizes the results for Block SA03. These values are gonna be compared to the defined criteria from LR in the next section.

Table 33: Summary from results obtained at block SA03.

Maximum Displacements		
Girder	2.71	$[mm]$
Frame	3.80	$[mm]$
Stiffener	3.80	$[mm]$
Global	8.14	$[mm]$
Maximum Von Mises Stress		
Primary stiffener	79.1	$[MPA]$
Plating	26.4	$[MPA]$
Global	79.1	$[MPA]$

5.4.4. Block SB01

Table 34: Details of block SB01.

Block SB01	Number of Elements
	434060
	Number of Nodes
	425724
	Analysis Time
	6 min

This block positioned in the aft part of second tier is subjected to both external and internal deck pressures. Figure 34 shows the displacement plot along the plot for the load case studied. The legend values are in millimeters.

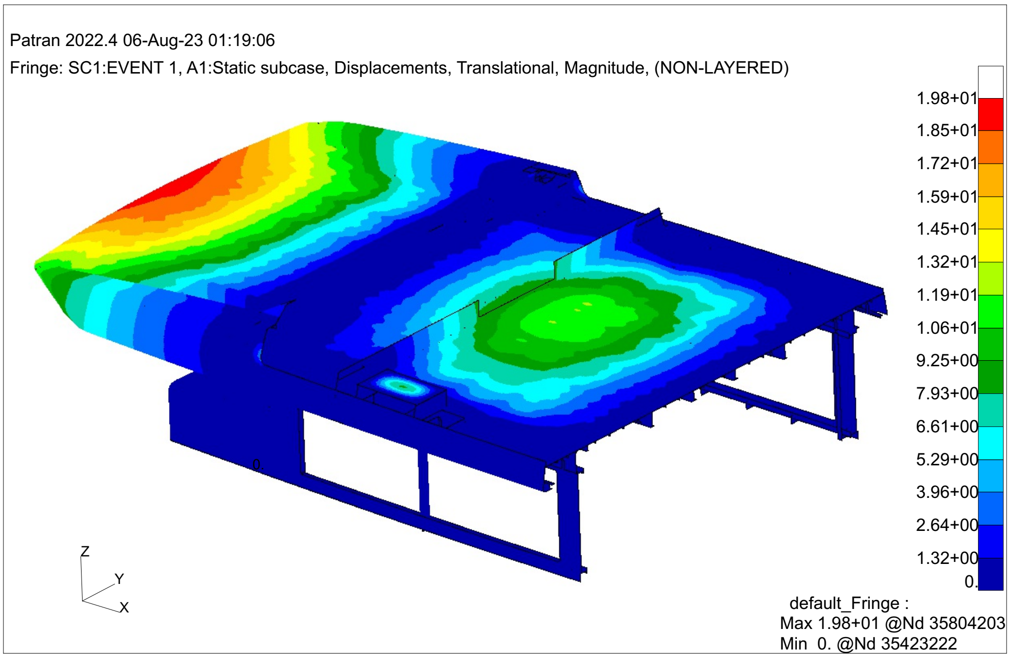


Figure 34: Displacement plot for block SB01.

As for the first tier, the maximum displacement occurs in the aft part of the deck with a value of 19.8 mm. Once again the structures are cantilevered and, thus, the behavior agrees with the theory. The maximum value occurs for all the central region positioned in the most extreme part aft of the deck. Therefore, the maximum displacement for both girder and secondary stiffeners is the maximum value. For frames, the maximum displacement observed is approximately 16 *mm* for the ones positioned closer to the aft area. It is also possible to observe another area in the middle presenting some deflections of around 11 *mm*. This behavior happens because of the large unsupported span in this area.

Concerning stresses, Figure 35 below displays the plot for this block. The maximum value observed, of 99 MPA appears in a region with some sharp edges due to the simplifications for the modelling. Therefore, it is possible to consider this peak as a singularity due to the geometric discontinuity.

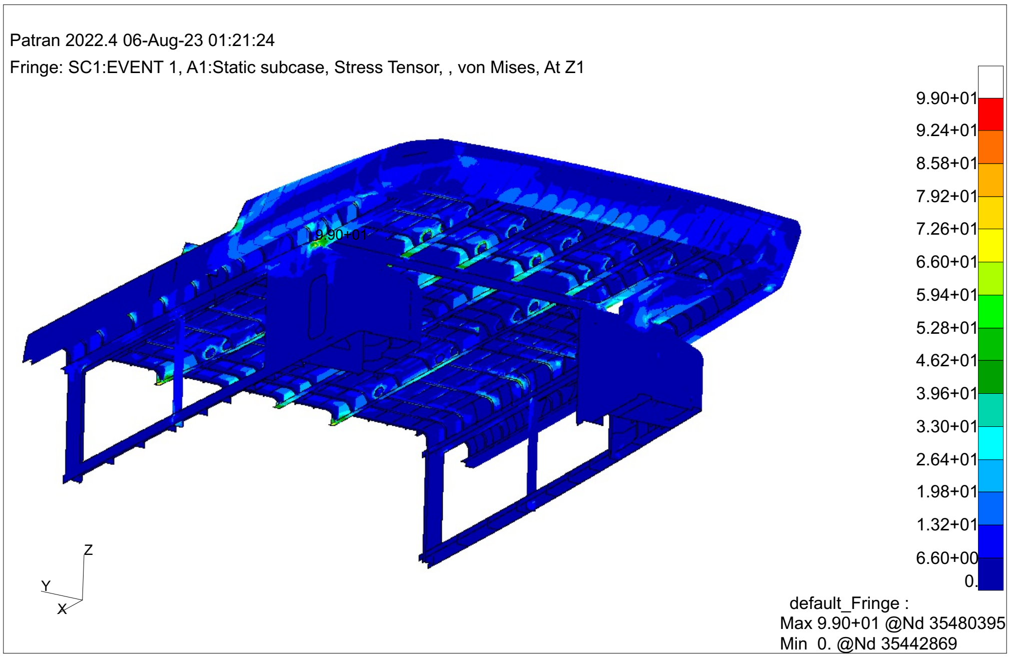


Figure 35: Von Mises stress plot for block SA01.

By removing the area mentioned from the plot, the new maximum occurs in the web opening from the cantilevered girder, near the clamped edge. This result is consistent to the expectations for the structural behavior, due to the loading condition. Figure 36 shows the area, the maximum value is 83.6 MPA.

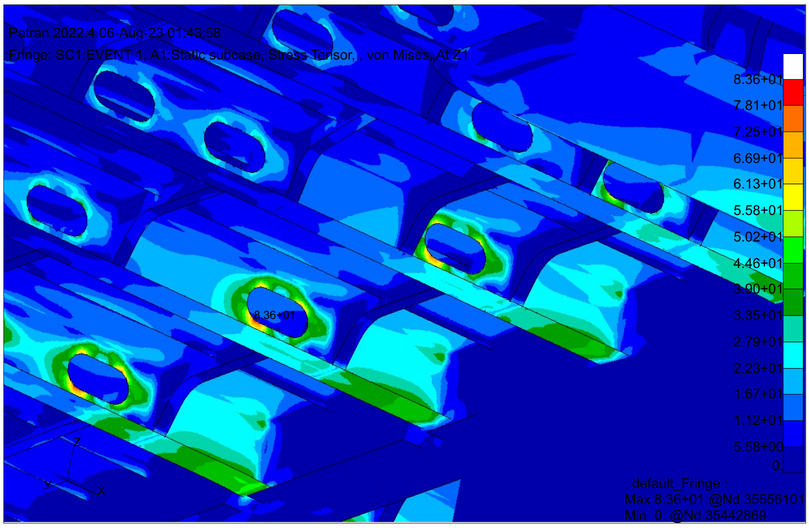


Figure 36: Maximum stress area for block SB01.

From the results, the maximum stress for primary members is the stress occurring around the web openings discussed previously. For plating, the maximum value found is 66 MPA approximately.

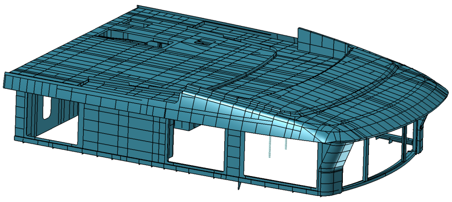
Table 35 summarizes the results for Block SB01. These values are gonna be compared to the defined criteria from LR in the next section.

Table 35: Summary from results obtained at block SB01.

Maximum Displacements		
Girder	19.8	$[mm]$
Frame	16.0	$[mm]$
Stiffener	19.8	$[mm]$
Global	19.8	$[mm]$
Maximum Von Mises Stress		
Primary stiffener	83.6	$[MPA]$
Plating	66.0	$[MPA]$
Global	99.0	$[MPA]$

5.4.5. Block SB02

Table 36: Details of block SB02.

Block SB02	Number of Elements
	539207
	Number of Nodes
	533381
	Analysis Time
	19 min

This block positioned in the front part of second tier is subjected to both external and internal deck pressures. Figure 37 shows the displacement plot along the block for the load case studied. The legend values are in millimeters.

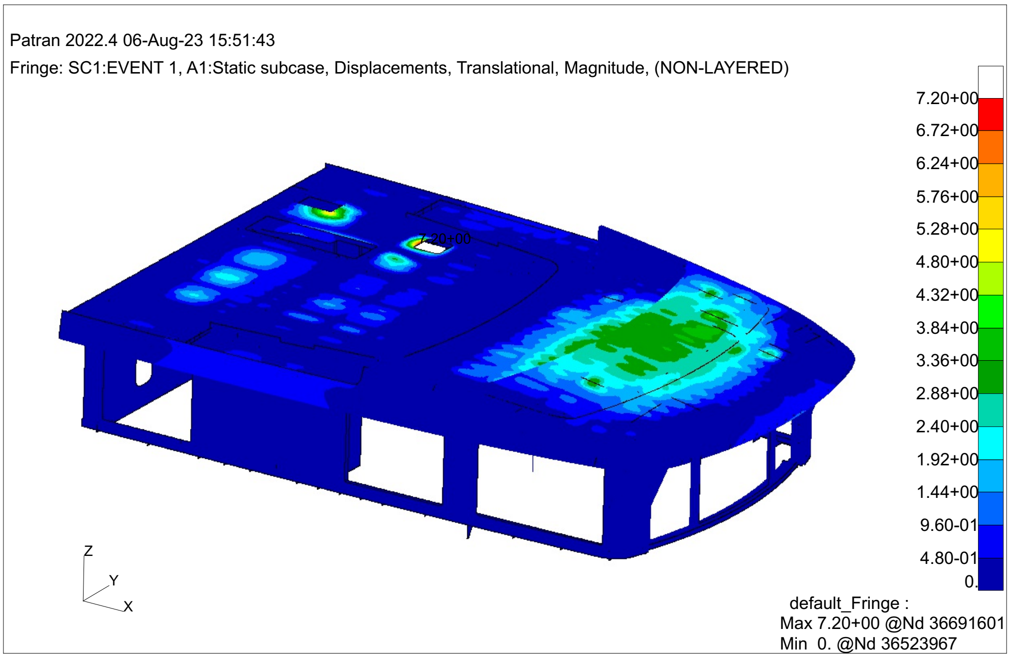


Figure 37: Displacement plot for block SB02.

From the plot, the maximum displacement occurs along one of the deck openings. This results is also consistent, since deck openings are expected to have greater displacements in the free edges, as discussed previously. Therefore, it is explained the location of the maximum deflection. This maximum occurs directly in the plate with a value of 7.20 mm. For a girder, the maximum displacement observed is 3.36 mm, in the front area. This area has a step to adapt the deck for aesthetics reasons, which creates local increase in the stress. For a secondary stiffener the maximum is 4.80 mm close to the deck opening. For frames, the maximum displacement observed is the same as for the girder.

Regarding stresses, Figure 38 below displays the plot for this block. It is possible to observe that the the maximum stress occurs for the stiffener positioned between the two deck openings with a value of 87.9 MPA. Figure 39 shows a closer shot, since it was hard to observe the location globally. Once again, openings are expected to create points of increased in stresses due to the discontinuities created by them. This could be an indication of necessity for local reinforcement at this stiffener.

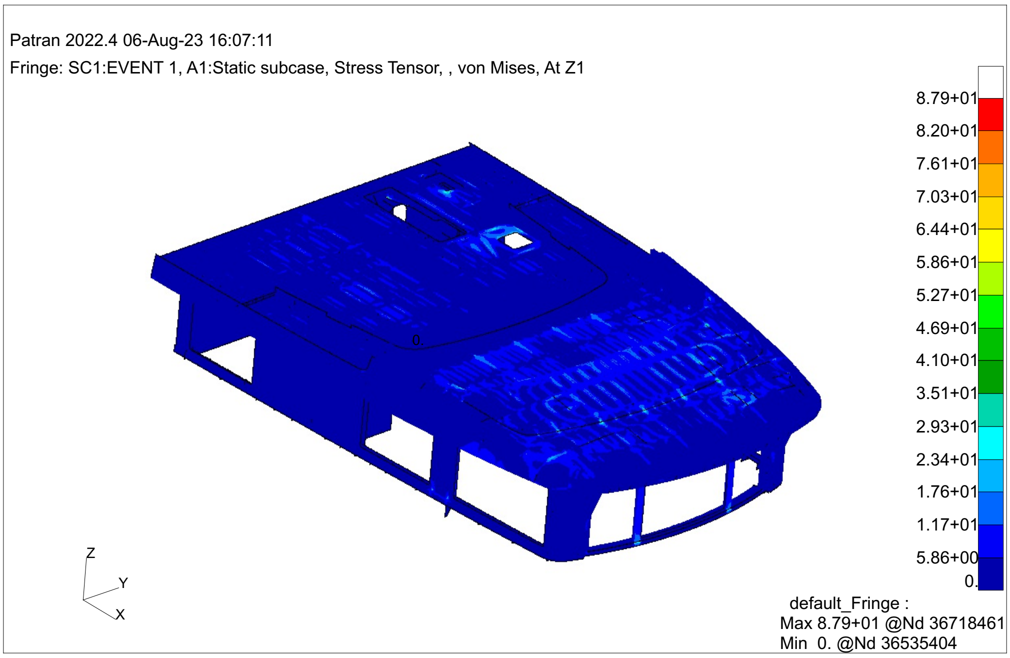


Figure 38: Von Mises stress plot for block SA01.

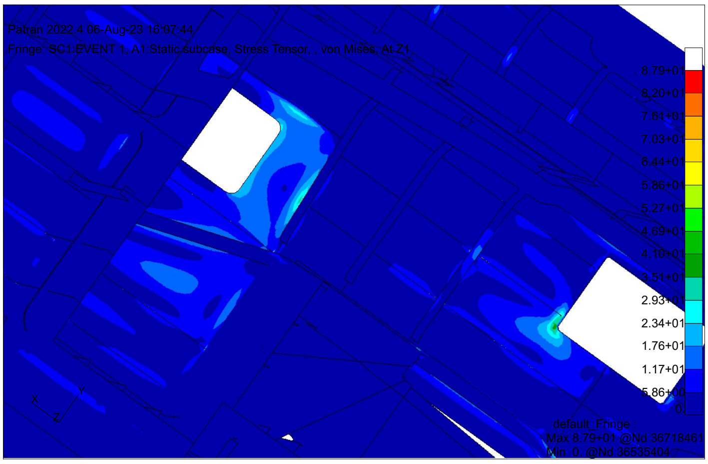


Figure 39: Approximation of region of maximum stress.

From the results, the maximum stress for primary members is 52.7 MPA, occurring at the girder flange close to the edge. For plating, the maximum value is 41 MPA, close to corner of the deck opening.

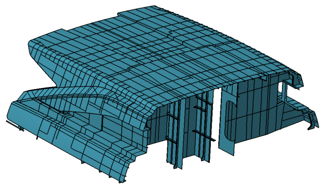
Table 37 summarizes the results for Block SB02. These values are gonna be compared to the defined criteria from LR in the next section.

Table 37: Summary from results obtained at block SB02.

Maximum Displacements		
Girder	3.36	$[mm]$
Frame	3.36	$[mm]$
Stiffener	4.80	$[mm]$
Global	7.20	$[mm]$
Maximum Von Mises Stress		
Primary stiffener	52.7	$[MPA]$
Plating	41.0	$[MPA]$
Global	87.9	$[MPA]$

5.4.6. Block SC01

Table 38: Details of block SC01.

Block SC01	Number of Elements
	293022
	Number of Nodes
	292052
	Analysis Time
	3 min

This block positioned in the aft part of third tier is subjected to only external deck pressure at the hard top. Figure 40 shows the displacement plot along the block for the load case studied. The legend values are in millimeters.

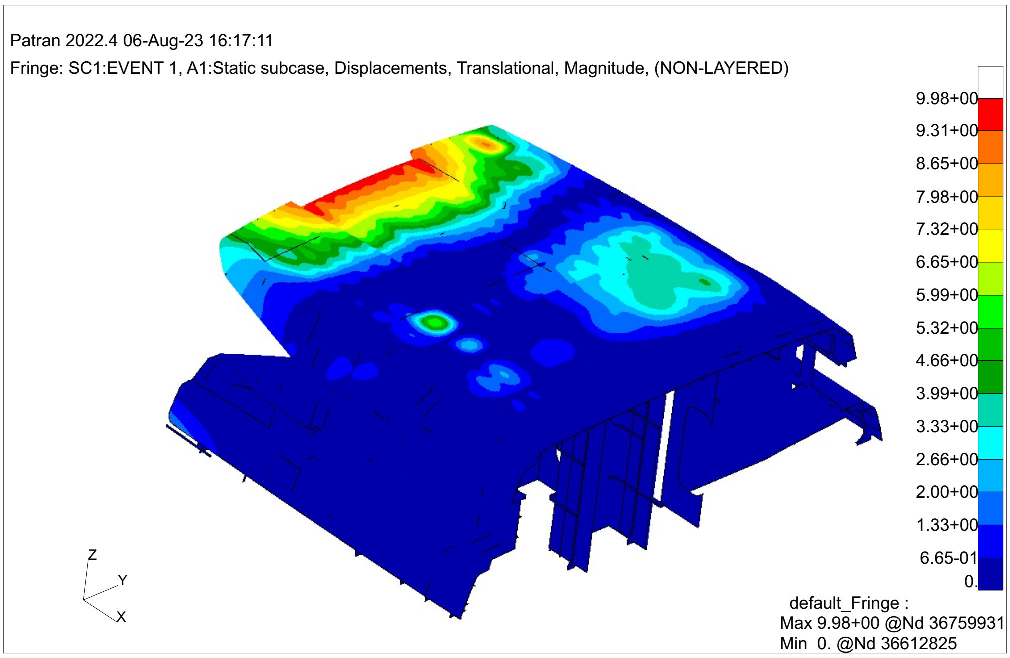


Figure 40: Displacement plot for block SC01.

Once again, it presents the same behavior as the other aft blocks because of the cantilevered structures. The maximum displacement value is 9.98 *mm* at the central aft part. Both girder and secondary stiffeners have the maximum displacement as the maximum global one. For frames, the maximum displacement is 6.65 *mm*. It is also interesting to notice an area of higher displacements between the bulkheads, because of the length of the unsupported span. The deflections at this part are up to 7.98 mm in one of the girder flanges.

Considering the stresses, the same is true. Figure 41 below displays the plot for this block. The maximum stress has a value of 108 MPA, happening at the girder flange close to the connection to the bulkhead. The maximum is also motivated by the cantilevered condition, close to the side clamped. And, it is also important to notice that the value was increased by the curvature in the geometry of this specifically girder. The others does not have this detail and present smaller values with maximum of 72 MPA.

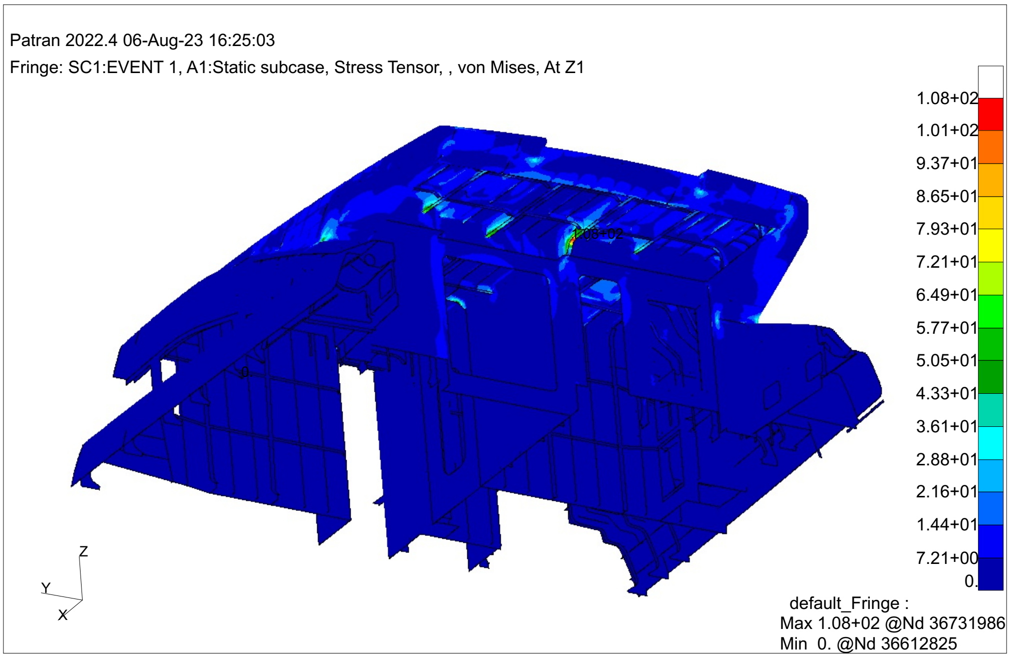


Figure 41: Von Mises stress plot for block SC01.

From the results, the maximum stress for primary members is the actual maximum stress discussed before. For plating, the maximum value found is 43 MPA, close to one sharp edge due to the geometry.

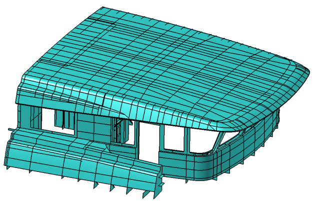
Table 39 summarizes the results for Block SC01. These values are gonna be compared to the defined criteria from LR in the next section.

Table 39: Summary from results obtained at block SC01.

Maximum Displacements		
Girder	9.98	$[mm]$
Frame	6.65	$[mm]$
Stiffener	9.98	$[mm]$
Global	9.98	$[mm]$
Maximum Von Mises Stress		
Primary stiffener	108.0	$[MPA]$
Plating	43.0	$[MPA]$
Global	108.0	$[MPA]$

5.4.7. Block SC02

Table 40: Details of block SC02.

Block SC02	**Number of Elements**
	278679
	Number of Nodes
	276663
	Analysis Time
	2 min

This block positioned in the front part of third tier is subjected to only external deck pressure at the hard top. Figure 42 shows the displacement plot along the block for the load case studied. The legend values are in millimeters.

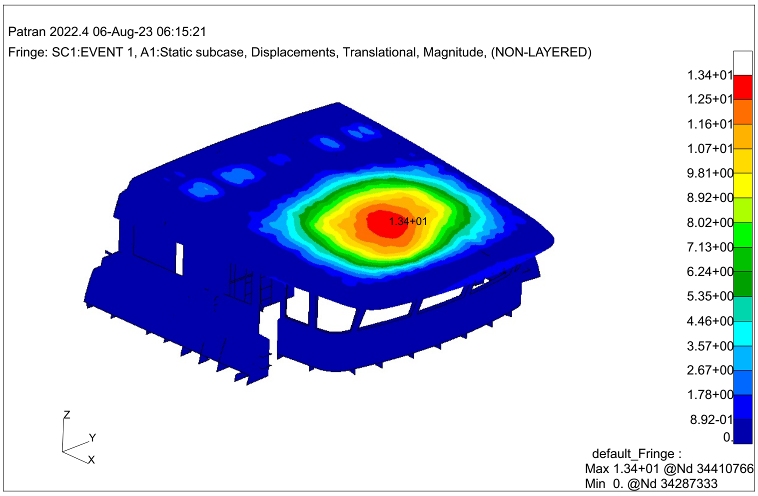


Figure 42: Displacement plot for block SC02.

It is possible to observe the maximum displacement of 13.4 *mm* happening in the middle of the unsupported area. Considering the configuration of this area, it can be approximated by a simple supported beam. Therefore, from theory, the largest deflection occurs in its middle, as it's happening in the situation. The maximum displacement value can be related to the frame and secondary stiffeners in the region. For the girders, the maximum displacement is of 11.6 *mm*.

Concerning the stresses, Figure 43 below displays the plot for this block. The maximum value of 102 MPA occurs in the web of the girder, edge attaching to a bulkhead. Since this edge can be considered clamped, it is consistent a maximum stress at this location. Also, from the modelling, the flange could have been extended until the end, which would probably decrease the maximum value.

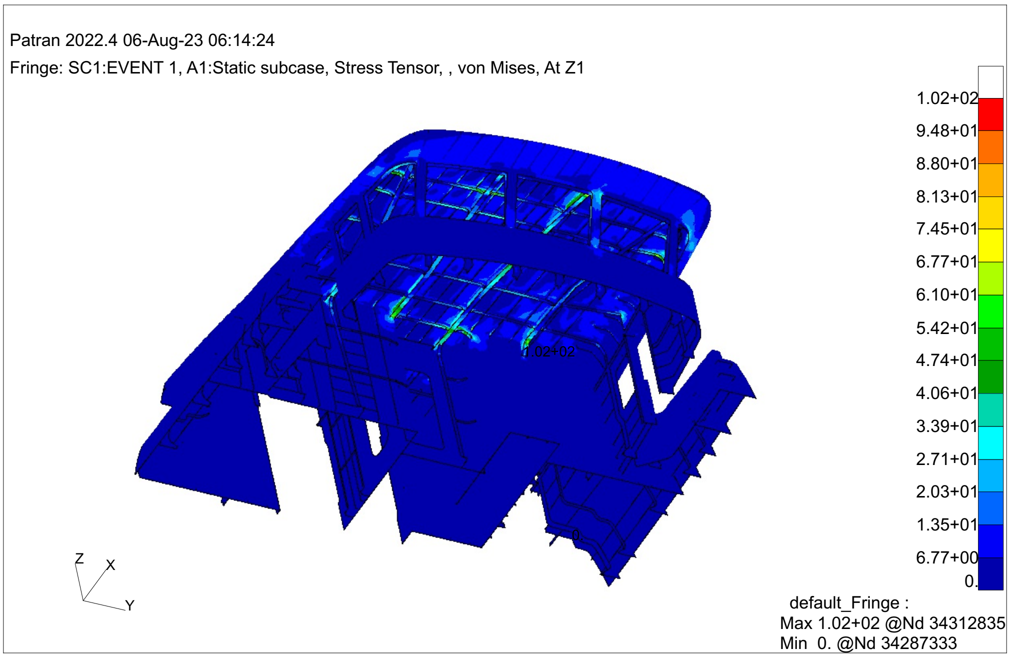


Figure 43: Von Mises stress plot for block SC02.

From the results, the maximum stress for primary members is the actual maximum stress discussed before. For plating, the maximum value found is 30 MPA approximately.

Table 41 summarizes the results for Block SC02. These values are gonna be compared to the defined criteria from LR in the next section.

Table 41: Summary from results obtained at block SC02.

Maximum Displacements		
Girder	11.6	$[mm]$
Frame	13.4	$[mm]$
Stiffener	13.4	$[mm]$
Global	13.4	$[mm]$
Maximum Von Mises Stress		
Primary stiffener	102.0	$[MPA]$
Plating	30.0	$[MPA]$
Global	102.0	$[MPA]$

6. Comparison FEA

This section will make the final comparison between the FEA results and the criteria from the classification society chosen, which is LR. Before reviewing the criteria, the results from previous sections are displayed again for the sake of better comprehension.

From Section 4, the optimization procedure achieved the results shown at Table 42 below. The table is replied here in order to remind the dimensions applied in the proposed design and to verify for the calculated section modulus against the required ones. For this type of analysis, the section modulus obtained is in compliance with the requirements from the rules for all members changed.

Table 42: Optimized dimensions with obtained section modulus against required ones.

Member Location		Member Type	Dimensions $[mm]$	Z_{req} $[cm^3]$	Z_o $[cm^3]$
Decks	Upper Deck	Transverse	$110 \times 4 + 60 \times 4$	41.74	42.08
		Frame 24 (CB)	$160 \times 4 + 98 \times 7$	122.70	137.25
		Frame 24 (O)	$200 \times 4 + 84 \times 6$	133.67	146.55
		Frame 12+550	$300 \times 6 + 158 \times 10$	506.97	517.31
		Frame 20	$168 \times 4 + 64 \times 4$	77.94	78.66
		Girder (0.6CL)	$205 \times 5 + 137 \times 15$	448.79	473.40
		Girder (1.8CL)	$300 \times 6 + 120 \times 8$	313.69	336.67
		Girder(0.6CL-CB)	$300 \times 6 + 200x17$	1018.92	1030.65
		Girder(1.8CL-CB)	$294 \times 6 + 196 \times 15$	954.89	959.84
		Girder (Box B.)	$200 \times 4 + 200 \times 22$	868.46	892.67
	Bridge Deck	Frame 29	$140 \times 4 + 94 \times 16$	227.77	229.89
		Girder (0.6CL)	$205 \times 5 + 137 \times 15$	447.79	473.40
		Girder(1.8CL)	$300 \times 6 + 100 \times 7$	235.81	259.66
		Girder(0.6CL-CB)	$300 \times 6 + 186 \times 12$	677.12	697.36
	Hard Top	Girder(0.6CL)	$200 \times 4 + 66 \times 5$	102.50	115.60
		Girder(1.8CL)	$150 \times 4 + 100 \times 11$	180.56	191.18
Superstr.	LT - Sides (DH)	Frame 13 (O)	$145 \times 4 + 48 \times 4$	53.12	54.34
		Side Stringer	$200 \times 4 + 113 \times 8$	207.81	229.45
	LT- Sides (SP)	Transverse	$130 \times 4 + 60 \times 4$	53.65	54.28
	2T - Sides	Frame 15 (O)	$200 \times 4 + 100 \times 7$	167.60	185.35
		Transverse (Box B.)	$120 \times 4 + 120 \times 10$	162.77	172.82
		Side Stringer	$200 \times 4 + 113 \times 8$	208.14	229.45
Bulkhead	Transv.	Vertical Web	$100 \times 4 + 67 \times 13$	96.48	98.56
		Horizontal Stringer	$100 \times 4 + 40 \times 4$	28.80	29.08
	Long.	Vertical Web	$78 \times 4 + 32 \times 4$	17.07	17.93
		Horizontal Stringer	$100 \times 4 + 40 \times 4$	28.80	29.08
		Stiffener (O)	102×7	21.32	22.45

From LR's rules applied in this work, Part7 Chapter 7 defines the failures controls modes for aluminium constructions. From this chapter, some criteria are determined for both deflections and stresses under bending situation. Concerning deflection, the criteria is given in terms of a limiting deflection coefficient. The criteria will be, thus, the span of the member splitted by the coefficient. Table 43 shows the coefficients applicable to superstructure stiffening.

Table 43: LR's deflection coefficients to apply in the criteria.

Reinforcement		**Deflection ratio f_δ**
Generally	Secondary	400
	Primary	475
House top	Secondary	400
	Primary	400

For the stresses, the chapter defines a safety coefficient to be applied at the yield stress and compared against the von mises stress. The safety factors, called limiting stress coefficient, are presented at Table 44 for the superstructure region.

Table 44: Stress coefficients for criteria application.

Element		**Limit stress coefficient f_σ**
Inner decks	Stiffening	0.60
	Plating	0.75
House top	Stiffening	0.75
	Plating	0.75
Superstructure sides	Stiffening	0.75
	Plating	0.75

In order to be able to compared this criteria to results obtained by FEA, it is necessary to take the spans of the elements with maximum displacement. From that and by applying the limiting stress coefficient in the aluminium yield stress, the limiting criteria are presented at Tables 45 and 46 against the achieved values.

Table 45: Deflections against LR's criteria.

Block	Element	Deflection [mm]	Limit [mm]	Situation
SA01	Girder	41.60	24.43	NOT OK
	Frame	27.70	10.86	NOT OK
	Stiffener	41.60	29.01	NOT OK
SA02	Girder	7.72	13.47	OK
	Frame	6.86	7.56	OK
	Stiffener	8.57	16.00	OK
SA03	Girder	2.71	10.41	OK
	Frame	3.80	6.78	OK
	Stiffener	3.80	12.37	OK
SB01	Girder	19.80	10.55	NOT OK
	Frame	16.00	13.32	NOT OK
	Stiffener	19.80	12.52	NOT OK
SB02	Girder	3.36	7.51	OK
	Frame	3.36	7.56	OK
	Stiffener	4.80	7.41	OK
SC01	Girder	9.98	7.03	NOT OK
	Frame	6.65	8.98	OK
	Stiffener	9.98	7.03	NOT OK
SC02	Girder	11.60	13.53	OK
	Frame	13.40	15.58	OK
	Stiffener	13.40	13.53	OK

It is possible to observe that some reinforcements do not comply with the deflection criteria from LR's rules. This situation happens for the aft blocks, which have cantilevered structures. Even though the loading situation was taken care of during the optimization, some considerations can be made about these results. First, the span used for the required section modulus calculation. At the time, the spans values were measured from 2D drawings and for this area specifically only the length with flange was considered. The tip of the reinforcements was left out, which for sure decreased the required section modulus. Even more when reminding that the span has a influence with the square in the formulation. Therefore, it is interest to note the sensitivity of the results regarding the span length.

The other consideration is the support. The rules treat these areas as a cantilever beam, which denotes that one edge is suppose to be clamped. However, the frames that hold for these longitudinal structures were also optimized. This means that they could also suffer deflections, not keeping the support fixed as they were suppose to. This situation is specifically true for the first block, where the discrepancies between the results are the largest. Figure 44 below shows the plot in another angle, and it is possible to observe that the frame is suffering deflections of 5.80 mm approximately. Taking this into consideration, the real deflection for the girder and longitudinal stiffener is 35 mm. Even though the value is still greater than the criteria, it is more in accordance with the other aft blocks discrepancies. Also, by checking the plot for the rotational displacement, it was discovered that the maximum occurs at the supporting frame. Therefore, it is not possible to say that the structure is clamped there.

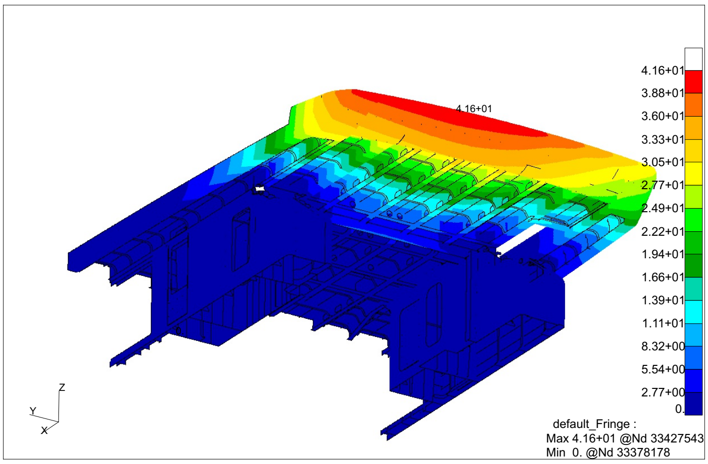


Figure 44: Different angle from displacement plot for block SA01.

Apart from the not complying cantilevered beams, the overall behavior is taken as positive. For the blocks SA02, SA03 and SB02 there is even more space for further improvements, considering the distance of the maximum value from the criteria. Of course, other load cases have to be evaluated before going to a further optimization. But, it is a good indication of the possibility.

Table 46: Von Mises Stress criteria against maximum values obtained from FEA.

Block	Element	Stress [MPA]	Limit [MPA]	Situation
SA01	Stiffening	116.00	75.00	NOT OK
	Plating	70.00	93.75	OK
SA02	Stiffening	98.90	75.00	NOT OK
	Plating	39.50	93.75	OK
SA03	Stiffening	79.10	75.00	NOT OK
	Plating	26.40	93.75	OK
SB01	Stiffening	83.60	75.00	NOT OK
	Plating	66.00	93.75	OK
SB02	Stiffening	57.70	75.00	OK
	Plating	41.00	93.75	OK
SC01	Stiffening	108.00	93.75	NOT OK
	Plating	43.00	93.75	OK
SC02	Stiffening	102.00	93.75	NOT OK
	Plating	30.00	93.75	OK

From the Table 46, it can be observed that for almost all the blocks the stiffening are not passing in the criteria. The first point to notice, however, is that the stress values are still below the yield strength from the aluminium. They are not passing within the safety coefficient, but the structure is not suffering yielding. The other consideration is the specific location that these stresses are happening. By looking at the stresses plots shown in Subsection 5.4, it is possible to understand that these maximum values occur in majority in localized points. Some are due to geometry modelling, which is easily changed by smoothing more the surfaces and connections. For example, at block SA02, the extension of the vertical web flange until the girder would decrease the stress peak at this location. The same is true for the flange of the girder at block SC02. Or for the block SA03, the increase in the radius for the frames curvature would help to decrease the stress concentration at these areas.

For the other cases in which the maximum stress is truly due to the loading scenario, it is necessary to locally increase these reinforcements. But, as explained, these are very localized points as a stiffener close to a deck opening or the edge near a clamped side of a beam. In overall, however, the stresses results for the proposed structure are positive. It is easier to verify these affirmation by analyzing the stresses plots at Figures 27, 30, 32, 35, 38, 41 and 43. The regions mostly in blue tones are in compliance with the stress criteria. To illustrate that, it is plotted the stress results filtered by the range above the stress criteria for the blocks SA01 and SA02 at Figures 45 and 46. In white is the area that is in accordance with the LR's criteria, while in colours are the areas that need some work (by geometry smoothing or reinforcement). The regions plotted are so localized that it is not even possible to visualize in the plots.

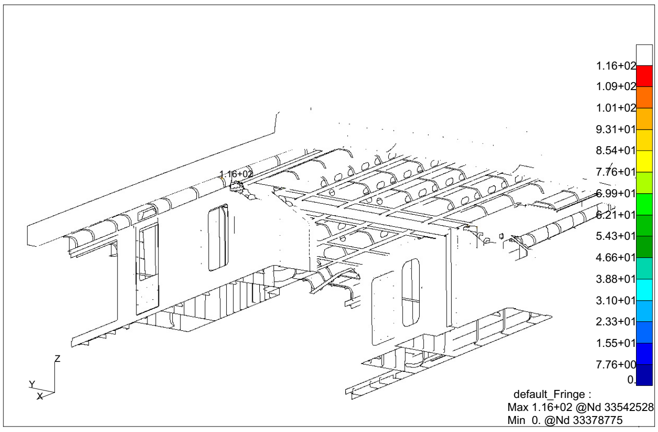


Figure 45: Stress plot filtered by range above 75 MPA for block SA01.

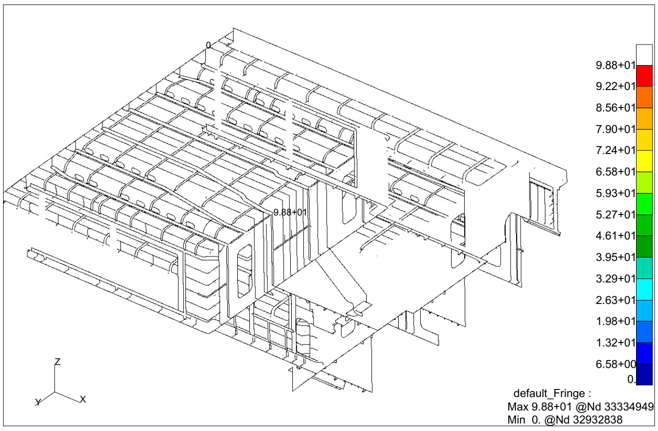


Figure 46: Stress plot filtered by range above 75 MPA for block SA02.

From the previous results, it is possible to consider that most of the design proposed is in compliance with LR's criteria. A local study would have to be made for certain spots in order to avoid the stress concentration. Besides that, the cantilevered structures need a new evaluation to be in accordance with the deflections criteria. But, in overall, the design is satisfactory for this load condition. Other load cases need to be studied to have a larger comprehension about the structure behavior.

7. CONCLUSION

This thesis fulfill its purpose to perform a comparison among different classification societies and also with a finite element analysis. From both parts, some relevant conclusions can be highlighted.

The first part of the work consisted in the calculation of the requirements for a study case. From the results, it was possible to compare both numerically and analytically the requirements from ABS and LR. The analytical comparison consisted in reviewing the register's formulations in terms of design loads and required section modulus for some locations of interest. Regarding the design loads, it was observed a higher severity from LR with respect to deck pressures. The opposite is true when the loads are applied in the superstructure sides, fronts and aft parts. From the required section modulus comparison, it was discovered that LR's safety coefficient tend to be more conservative than ABS' ones. However, this conclusion was taken considering a constant term that involves the design load. Since this last one is not constant between the registers, the real difference will depend also on the design load discrepancies between the classification societies.

In addition to that, it was observed that LR's requirements are broader than ABS. This is due to the fact that LR's formulation include options to consider different loading support conditions. Also, LR's have extra requirements for inertia and web area of reinforcements.

From the calculations results, it was also possible to compare the rules numerically. The results shown, as expected, that LR's are in general more conservative for deck locations. Meanwhile, even though LR presented a higher safety coefficient in the section modulus calculation, ABS's results are more severe concerning the superstructure sides, front and aft. This observation happens because of the difference between the design loads required at these locations. This variation was enough to surpass the higher safety coefficient from LR. From the results, it was also observed that for some locations the structure did not comply with ABS requirement. However, the structure is from a real yacht that did not suffer any failure problems. For that reason, it was conclude that ABS requirement are more conservative in several locations of the superstructure because of the design loads imposed. But, these loads appear to be overestimated by the classification society, since even a real structure had criteria problems in some locations.

From this initial study, LR requirements was used to performed an optimization procedure in the superstructure's dimensions. The initial calculations shown a favorable allowance for reducing the dimensions. The process applying SLSQP method obtained interesting results, with decreases up to 30% in the structural weight. Several reinforcements were analyzed at this stage and selected to be optimized. The next step is, thus, perform a structural analysis in the proposed design.

The second part of this report consisted into performing an Finite Element Analysis in the proposed design in order to evaluate its reliability. The modelling and meshing were very time consuming and took most part of this stage. Because of that, it was possible to perform the analysis for one load case. The load case chosen was the deck pressure indicated by LR. After obtaining a satisfactory mesh, the analysis was performed separately by each block from the superstructure because of limitations in the model.

The results from the FEA were compared with regards to deflections and stresses criteria. The maximum values for deflections happened in the free edge of the cantilevered structures. These locations did not comply with LR criteria. The conclusion for that result was that the support, considered as clamped, also suffer deflections. In addition to that, it was observed by the author a difference in the spans considered for the initial calculation from the 3D model. This motivated also an enlargement in the discrepancies within the criteria. However, it was interest to observe the sensitivity of the results with regard to the span considered. Other areas did not have problems with the deflection criteria. Moreover, they shown the existence of clearance for further improvements.

With regard to the stresses, the maximum values for the stiffening had compliance problems in most of the blocks. Even though the values were still lower than the material yield strength, the design at these locations seem to be unsafe. However, from a closer look to the maximum locations points it was comprehend that easy solutions could be taken. For some locations the simple smoothing of the geometry would be enough, while for other a local reinforcement is necessary. The most important, though, is that in overall the design comply with the stress criteria. For this load case, most of the block area had very low stress values and indicates that further optimization could be performed. However, this conclusion can only be final after performing more load cases analysis.

From an analysis of both studies performed in this work, it is possible to state that the requirements from both classification societies are very conservative when considering the FEA results. Therefore, an optimization would be better applied cooperatively with a finite element analysis. Nowadays, it is facilitated to connect a code with a FEA simulation. So, it would be a more effective approach to perform this study directly with a finite element analysis. This conclusion is because with FEA it is easier to observe the effect of the structure interaction with each other and optimize dimensions considering the actual final structural behavior. For the shipyard, however, there is more to be taken into account. The time invested to model and obtain such a fine mesh was huge. For that reason, this approach could not work for the daily tasks in the shipyard. It would be possible to evaluate more coarse meshes and simplified models in order to obtain an effective procedure. A trade-off study would have to be performed in order to understand the best compromise between the time consuming and analysis accuracy needed for the initial design phase.

This thesis opens the possibilities for different types of future works. At the level of the registers calculations, it would be interesting to refine even more the code. Additions as buckling effect, other ship's areas, hull girder section modulus could be also implemented. In the end a full code for the requirements of a classification society could be achieved and with more accurate results by the inclusion of other failure modes in the process.

In the FEA field, as explained, it would be necessary to evaluate the proposed design for other load cases in order to ensure the possibility for further improvements. It would also be interesting to correct the problematic areas shown in this report to obtain a final design proposition. Finally, the idea of joining the code with an optimization connected to a simplified FEA model would probably provide better and more accurate results concerning structural reliability. An extension of this thesis for this direction could provide interesting insights with respect to the discrepancies between a rule-based and a FEA approach.

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References

Andric, Jerolim, Pero Prebeg, Marin Palaversa, and Vedran Zanic (2021). "Influence of different topological variants on optimized structural scantlings of passenger ship". In: *Marine Structures* 78, p. 102981. ISSN: 0951-8339. DOI: `https://doi.org/10.1016/j.marstruc.2021.102981`. URL: `https://www.sciencedirect.com/science/article/pii/S0951833921000423`.

Ayyub, Bilal M. and Ibrahim A. Assakkaf (2003). "Chapter 19: Reliability-based Structural Design". In: *Ship design and construction*. Ed. by Thomas Lamb. Vol. 1. Society of Naval Architects and Marine Engineers, pp. 19-1-19–33.

Boote, Dario, Gianmarco Vergassola, and Vincenzo Di Matteo (2017). "Strength Analysis of Superyacht Superstructures with Large Openings". In: *International Review of Mechanical Engineering (IREME)* 11.1. doi:10.15866/ireme.v11i1.9289. ISSN: 2532-5655. URL: `https://www.praiseworthyprize.org/jsm/index.php?journal=ireme&page=article&op=view&path%5B%5D=19022`.

Boote, Dario, Gianmarco Vergassola, Tatiana Pais, and Michael Kramer (2017). "Finite Element Structural Analysis of Big Yacht Superstructures". In: *International Review of Mechanical Engineering (IREME)* 11.4. doi:10.15866/ireme.v11i4.9231. ISSN: 2532-5655. URL: `https://www.praiseworthyprize.org/jsm/index.php?journal=ireme&page=article&op=view&path%5B%5D=18973`.

Cui, Jin-ju and De-yu Wang (2013). "Application of knowledge-based engineering in ship structural design and optimization". In: *Ocean Engineering* 72, pp. 124–139. ISSN: 0029-8018. DOI: `https://doi.org/10.1016/j.oceaneng.2013.06.013`. URL: `https://www.sciencedirect.com/science/article/pii/S002980181300259X`.

Doan, Van Tuyen, Bin Liu, Y. Garbatov, Weiguo Wu, and C. Guedes Soares (2020). "Strength assessment of aluminium and steel stiffened panels with openings on longitudinal girders". In: *Ocean Engineering* 200, p. 107047. ISSN: 0029-8018. DOI: `https://doi.org/10.1016/j.oceaneng.2020.107047`. URL: `https://www.sciencedirect.com/science/article/pii/S0029801820301219`.

Guide for Building and Classing Yachts (Jan. 2022). American Bureau of Shipping.

Hoque, Kazi Naimul and Shahidul Islam (Dec. 2022). "FINITE ELEMENT APPROACH TO ANALYZE STRUCTURAL DISCONTINUITIES ASSOCIATED WITH SHIP HULL". In.

Kraft, D. (1988). *A Software Package for Sequential Quadratic Programming*. Deutsche Forschungs- und Versuchsanstalt für Luft- und Raumfahrt Köln: Forschungsbericht. Wiss. Berichtswesen d. DFVLR. URL: `https://books.google.it/books?id=4rKaGwAACAAJ`.

Mancuso, Antonio, Antonio Saporito, and Davide Tumino (2022). "Designing the internal reinforcements of a sailing boat using a topology optimization approach". In: *Applied Ocean Research* 129, p. 103384. ISSN: 0141-1187. DOI: `https://doi.org/10.1016/j.`

apor.2022.103384. URL: https://www.sciencedirect.com/science/article/pii/S0141118722003157.

Motta, Dario, Jean Caprace, Philippe Rigo, and Dario Boote (Sept. 2011). "Optimization of Hull Structures for a 60 meters Mega Yacht". In: *11th International Conference on Fast Sea Transportation, FAST 2011 - Proceedings*.

Pei, Zhiyong, Shuilin Zhang, Wei Cai, Weiguo Wu, Keqiang Chen, and Xiaoming Hu (Oct. 2015). "Structural Response of Mega Yacht in Waves". In.

Raikunen, Joni, Eero Avi, Heikki Remes, Jani Romanoff, Ingrit Lillemäe-Avi, and Ari Niemelä (2019). "Optimisation of passenger ship structures in concept design stage". In: *Ships and Offshore Structures* 14.sup1, pp. 320–334. DOI: 10.1080/17445302.2019.1590947. eprint: https://doi.org/10.1080/17445302.2019.1590947. URL: https://doi.org/10.1080/17445302.2019.1590947.

Red Ensign Group Yacht Code - Part A (Jan. 2019). Red Ensign Group. URL: https://www.redensigngroup.org/media/1094/reg-yacht-code-january-2019-edition-part-a.pdf (visited on 04/11/2023).

Rigo, Philippe and Enrico Rizzuto (2003). "Chapter 18: Analysis and Design of Ship Structure". In: *Ship design and construction*. Ed. by Thomas Lamb. Vol. 1. Society of Naval Architects and Marine Engineers, pp. 18-1-18–77.

Rules and Regulations for the Classification of Special Service Craft (July 2022). Lloyd's Register Group Limited.

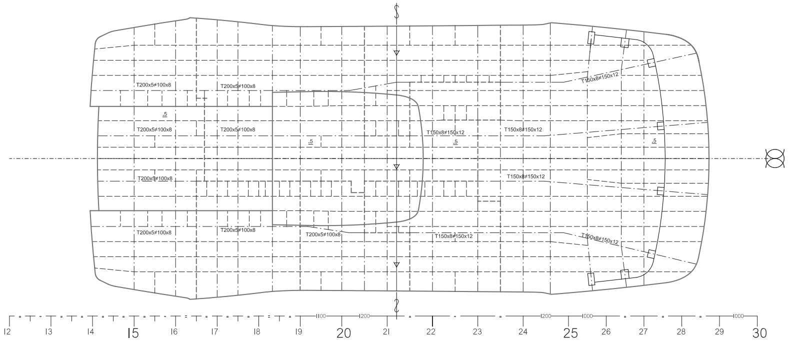
APPENDICES

A. Superstructure Structural Plan

Figure 47: Superstructure Structural Plan. [Reprinted with permission from *Superstructure Scantling Plan*,pages 1-4, provided by Sanlorenzo S.p.A.]

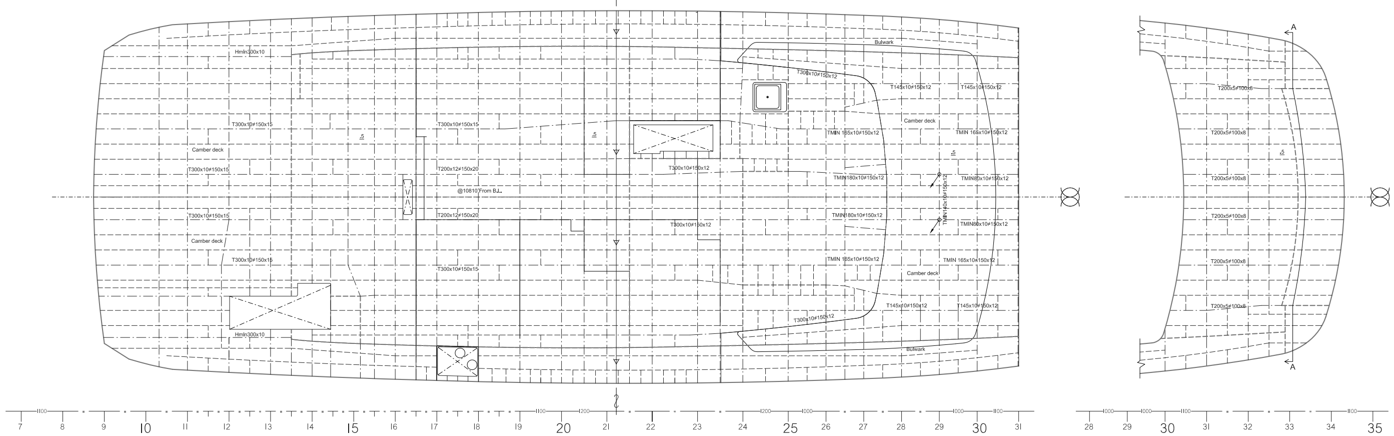
- HARD TOP -

Trans. Beams T 110x4≠60x5
Long. Stiffeners ≠50x6
UNLESS INDICATED OTHERWISE

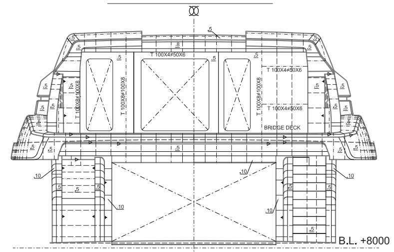


- BRIDGE DECK -

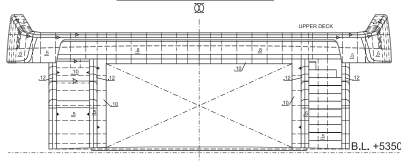
Trans. Beams T 110x4≠60x5
Long. Stiffeners ≠50x6
UNLESS INDICATED OTHERWISE



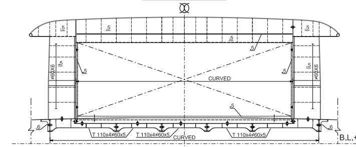
- STERN VIEW -
- BRIDGE DECK-



- STERN VIEW -
- UPPER DECK-

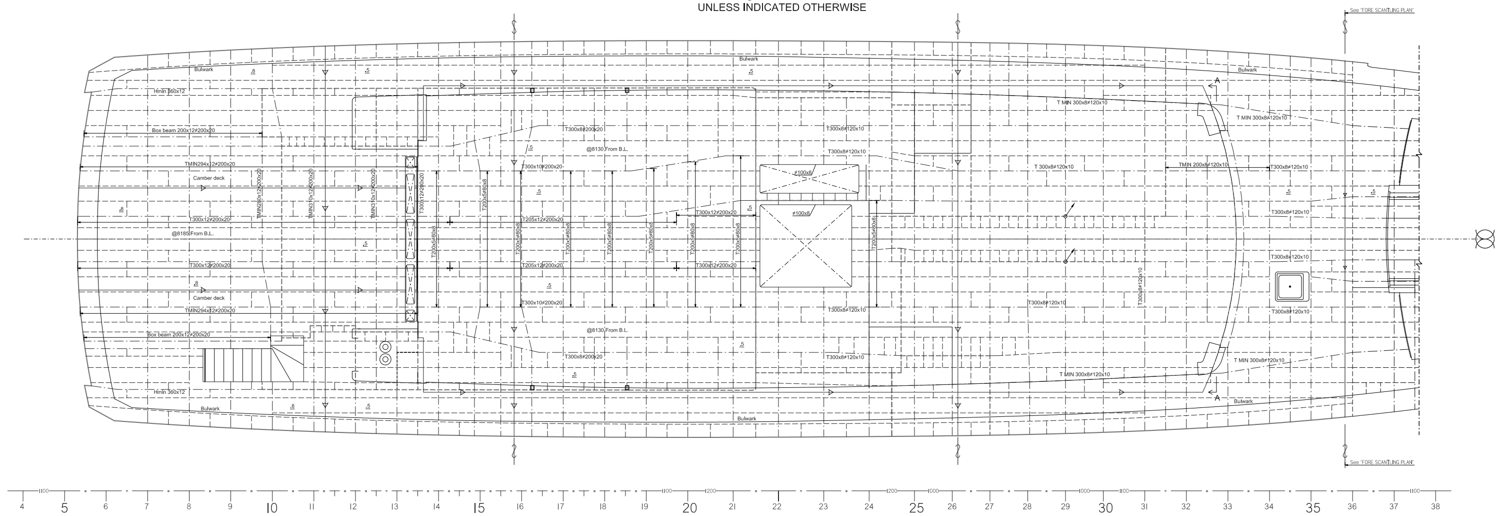


- SECTION A-A -



- UPPER DECK -

Trans. Beams T 110x4≠60x5
Long. Stiffeners ≠50x6
UNLESS INDICATED OTHERWISE



[redacted]

SANLORENZO

SANLORENZO S.p.A. – Viale San Bartolomeo, 362 – La Spezia (SP) – ITALIA

Building n° [redacted]

PIANO DEI FERRI SOVRASTRUTTURA

Drawing n° [redacted]

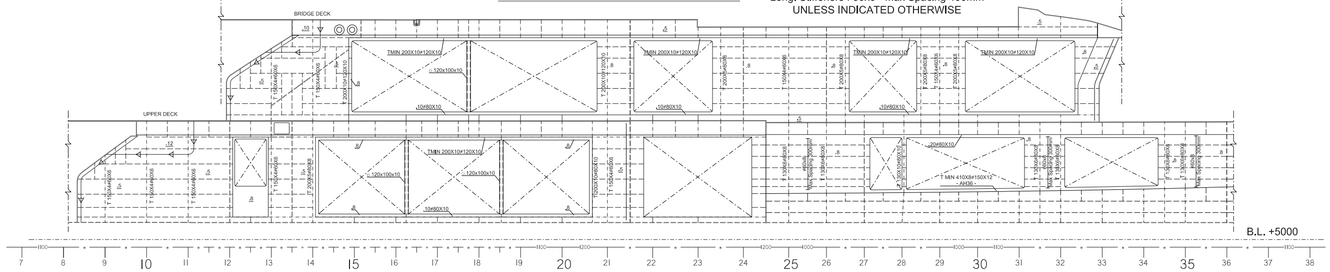
SUPERSTRUCTURE SCANTLING PLAN

[redacted]

UNI A0

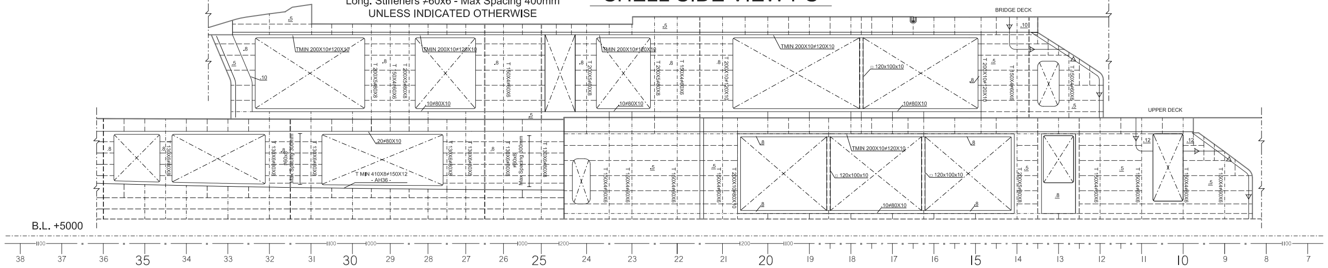
- SHELL SIDE VIEW SB -

Long. Stiffeners #60x6 - Max Spacing 400mm
UNLESS INDICATED OTHERWISE



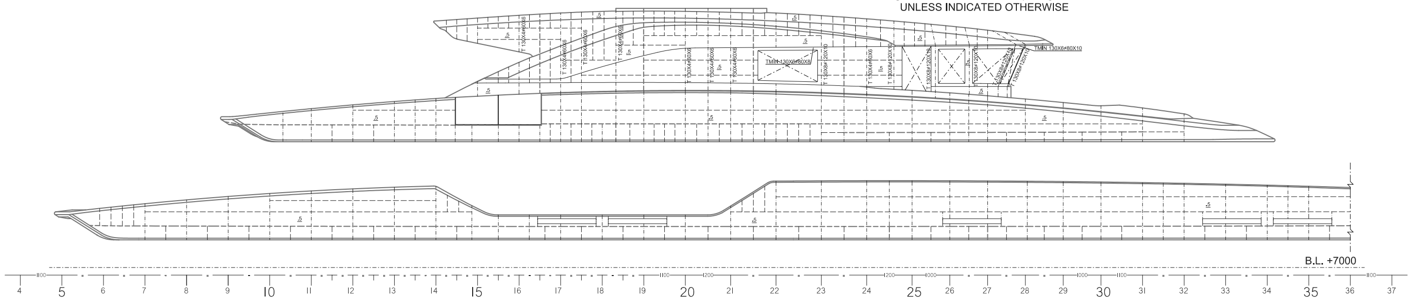
- SHELL SIDE VIEW PS -

Long. Stiffeners #60x6 - Max Spacing 400mm
UNLESS INDICATED OTHERWISE



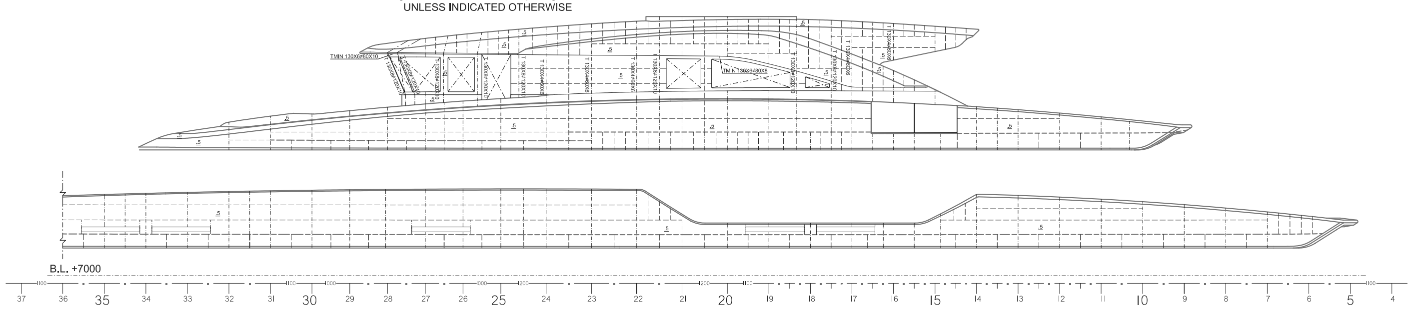
- SHELL SIDE VIEW SB -

Long. Stiffeners #60x6 - Max Spacing 400mm
UNLESS INDICATED OTHERWISE



- SHELL SIDE VIEW PS -

Long. Stiffeners #60x6 - Max Spacing 400mm
UNLESS INDICATED OTHERWISE

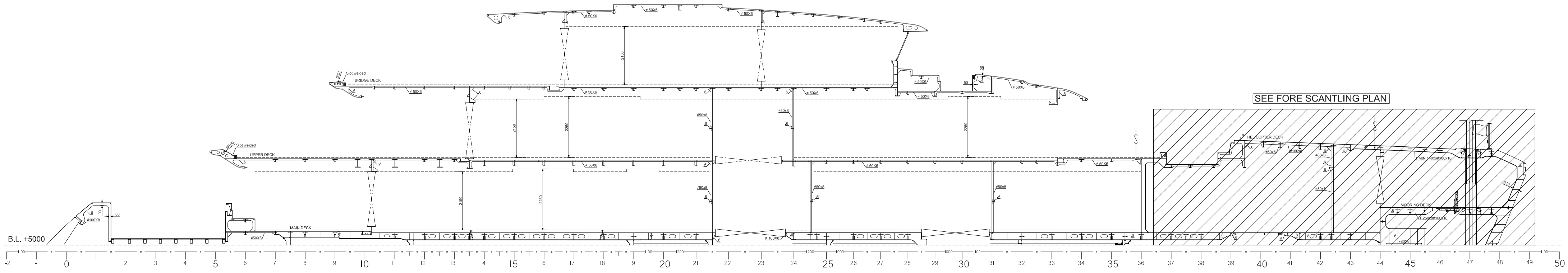


[redacted]

SANLORENZO S.p.A. - Viale San Bartolomeo, 362 - La Spezia (SP) - ITALIA	Dimensione foglio	Scala	Firmato da	Data
	A-0	1:50	[redacted]	

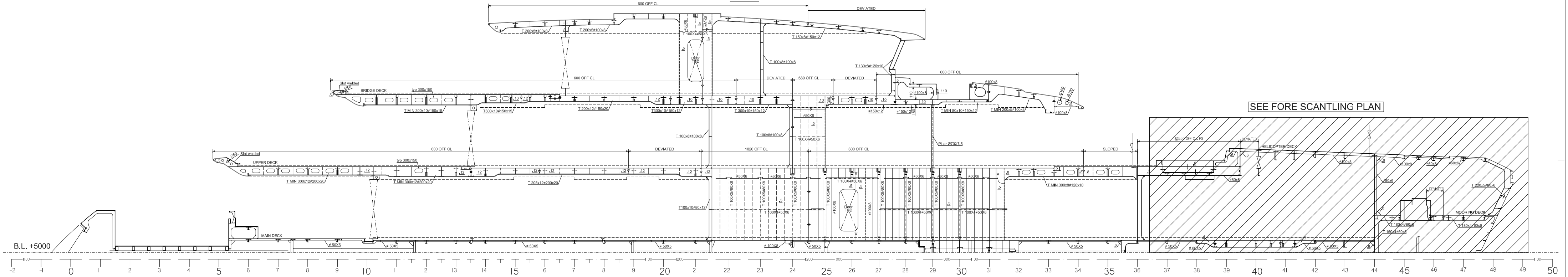
UNI AO

- C.L. -



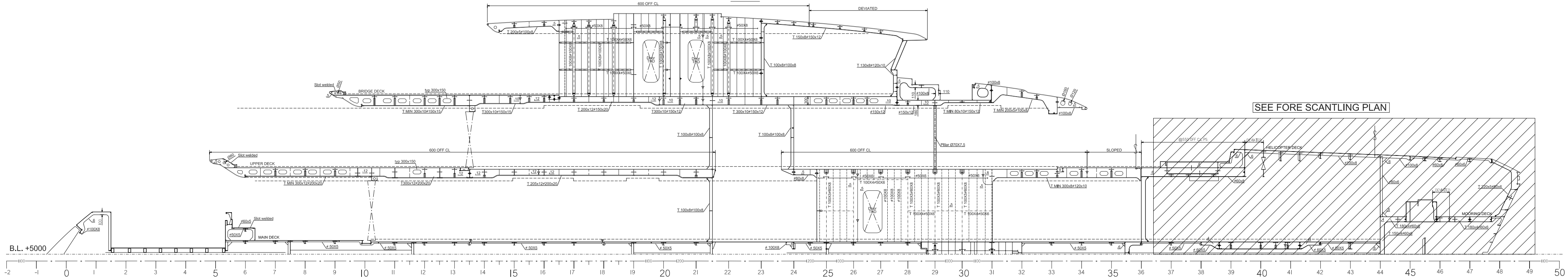
- 600 FROM C.L. -

- PS -



- 600 FROM C.L. -

- SB -



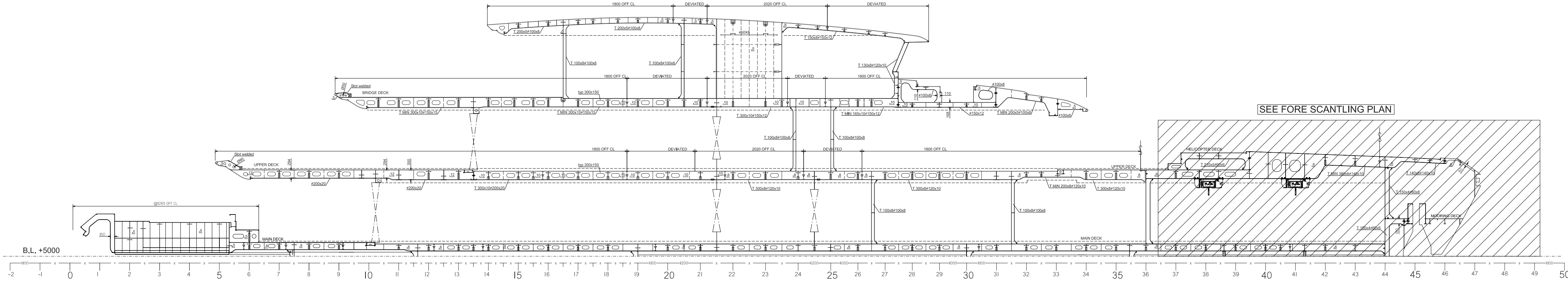
[redacted]

SANLORENZO S.p.A. - Viale San Bartolomeo, 362 - La Spezia (SP) - ITALIA	Dimensione foglio	Scala	Firmato da	Data
	A-0	1:50	[redacted]	

UNI AO

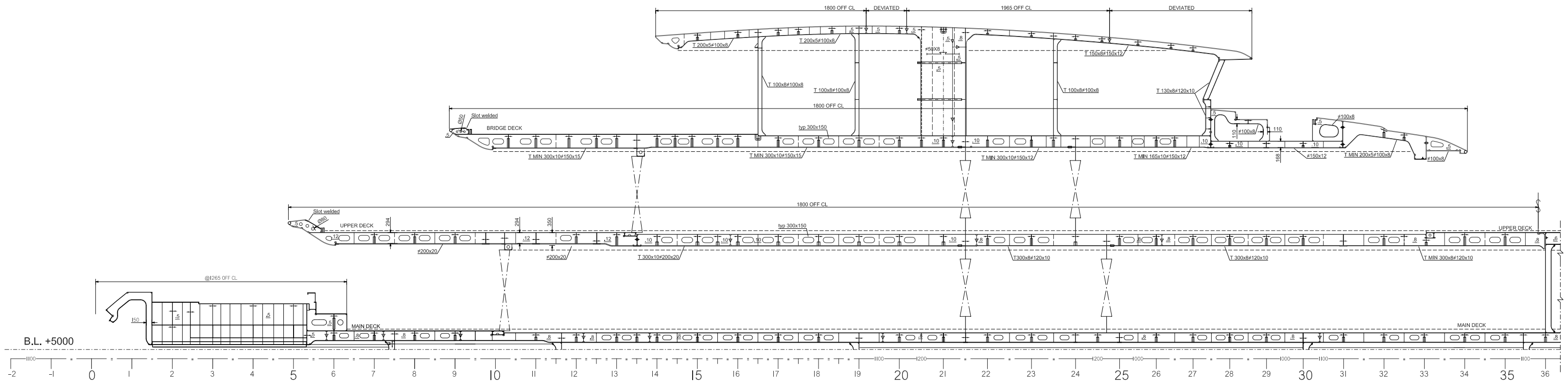
- 1800 FROM C.L. -

- PS -



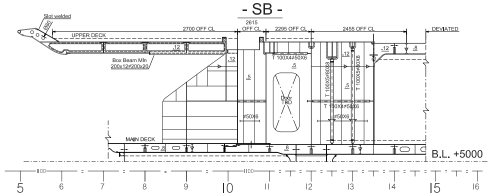
- 1800 FROM C.L. -

- SB -



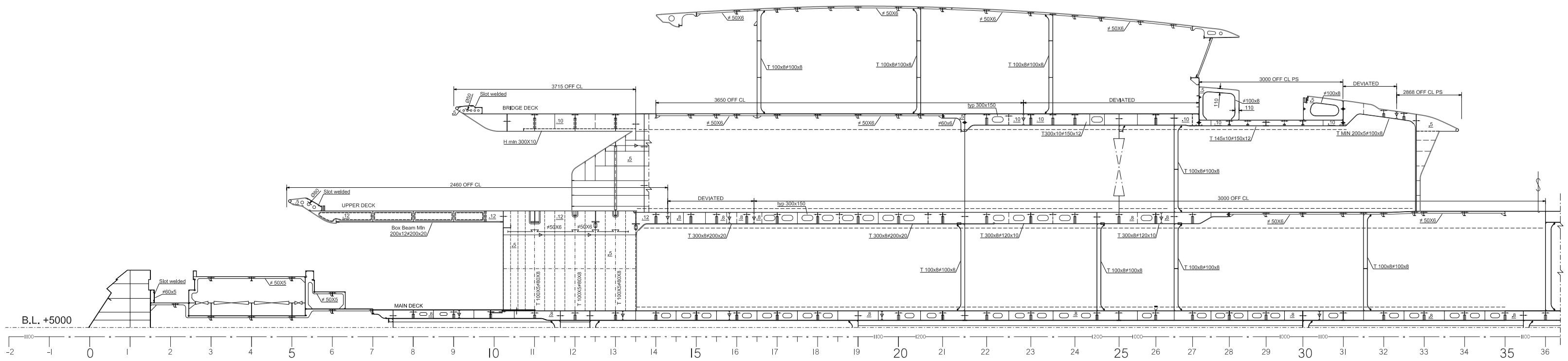
- 2700 FROM C.L. -

- SB -



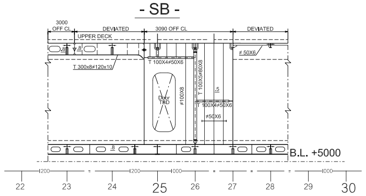
- 3000 FROM C.L. -

- PS - SB (SIMILAR) -



- 3000 FROM C.L. -

- SB -



[redacted]

Dimensione foglio A-0

Scala 1:50

UNI A0

B. LR's Python Code

B.1. Main File

```

##################################################################

#### Code Developed by Marianna Sipauba from LLoyds Register Rules for Special Service Craft ###
########## In the framework of master thesis for conclusion of EMSHIP Master Program ###########
#### Developed in: april/2023

from DataAccess import DataAccess_Plate, DataAccess_Stiff, Output
from Plating_Register import Plating_Register, Filter_plate
from Stiffener_Register import Stiffener_Register
#from Hull_Girder import Hull_Girder
import Config_file as cf

def __main__():
    ## Constants
    rho_sea = cf.rho_sea
    rho_alu = cf.rho_alu
    path_plate = cf.path_plate
    path_stiff = cf.path_stiff

    ## Main Dimensions ##
    L = cf.L_R
    L_pp = cf.L_pp
    Lwl = cf.Lwl
    B = cf.B
    D = cf.D
    T = cf.T
    Disp = cf.Disp
    C_b = Disp/(rho_sea*L*B*T)  #Block coefficient
    FB = D - T  #Freeboard in m
    Tay_quo = cf.Tay_quo

    dimensions = [L, B, D, T, Disp, L_pp, Lwl, C_b]
    #Plating
        ## Objects Creation

    list_plates = DataAccess_Plate(path_plate)

        ## Calculate Dimensions

    for plate in list_plates:
```

```
        Plating_Register(plate,L)

    #list_plates = Filter_plate(list_plates) #Filter for maximum thickness for plates at same location

    #Stiffeners
        ## Objects Creation
    list_stiff = DataAccess_Stiff(path_stiff, list_plates)

        ## Calculate Dimensions
    i=0

    for stiff in list_stiff:
        j=0
        add_sm = 0
        if stiff.position == 2:
            req = Stiffener_Register(stiff)
            stiff.sm_req = stiff.N_open*req.sm_req
            stiff.inertia_req = req.inertia_req
            stiff.a_web_req = req.aw_req
            #stiff = req.Optimize_Dimensions(stiff, rho_alu)
            stiff = req.Calculate_SM(stiff,rho_alu)
        else:
            for stiff_d in list_stiff:

                if stiff_d.position == 2 and stiff_d.type == stiff.type and stiff_d.ref == stiff.ref:
                    if "LT" in stiff.loc and stiff_d.loc == "Upper Deck I":
                        stiff.add_sm = stiff_d.P_d
                    elif "2T" in stiff.loc and stiff_d.loc == "Bridge Deck I":
                        stiff.add_sm = stiff_d.P_d
                    elif "3T" in stiff.loc and stiff_d.loc == "Hard Top":
                        stiff.add_sm = stiff_d.P_d
                j+=1

            #req = Stiffener_Register(stiff, stiff.add_sm)
            req = Stiffener_Register(stiff)
            stiff.sm_req = stiff.N_open*req.sm_req
            stiff.inertia_req = req.inertia_req
            stiff.a_web_req = req.aw_req
            #stiff = req.Optimize_Dimensions(stiff, rho_alu)
            stiff = req.Calculate_SM(stiff,rho_alu)


```

```
    Output(dimensions, list_plates, list_stiff, cf.path_out)

if __name__ == '__main__':
    __main__()
```

B.2. Configuration file

```
    from math import sqrt
## Global variables

op = 1
path_plate = 'C:/Users/Mari/OneDrive/Documentos/EMSHIP/MasterThesis/
    LLOYD/BD/lr_plate_db_op{:02d}.xlsx'.format(op)
path_stiff = 'C:/Users/Mari/OneDrive/Documentos/EMSHIP/MasterThesis/
    LLOYD/BD/lr_stiff_db_op{:02d}.xlsx'.format(op)
path_out = 'OUT/lr_output_op{:02d}.xlsx'.format(op)

#Constants
rho_sea = 1.025 #sea density in tons/m3
g = 9.81  #gravity in m/s2
t_min = 4 #mm
Gh_max = 310 #mm

## Material Properties -> aluminium
rho_alu = 2.7 #g/cm3
E = 69*10**3 #N/mm2
sig_a= 125 #N/mm2 (0,2 per cent proof stress (minimum))
sig_u = 275 #N/mm2 -> minimum ultimate strength
tau_a = sig_a/sqrt(3) #N/mm2
ka = 125/sig_a
km = 385/(sig_a+sig_u)

## Main Dimensions ##
L_pp = 52.03   # Length between perpendiculars in m
L_R = 52.282  # Rule length in m
Lwl = 54.464 # Waterline length in m
B = 10.5  # Maximum Breadth in m
D = 5.45  # Depth in m
T = 2.95  # Draft in m
Disp = 970 # Displacement in tons
V = 16.5 #Speed in knots
Tay_quo = V/sqrt(Lwl)
G_f = 1.25 # Service area restriction notation factor -> G6 yachts in
     unrestricted service
S_f = 1.1 # Service type notation factor -> Yacht
H_f = 1.05 # Hull notation -> displacement
```

```
w = 1.0 #  service type correction factor -> Yacht

#Superstructure
UD_b = 10.487 #upper deck breadth at Midship Section in m
BD_b = 9.702 #bridge deck breadth at Miship Section in m
SH = 2.68 #standard height between decks in superstructure in m

Ship_SM_b = 0.624*10**4  #Section modulus at bottom in cm2-m
Ship_SM_d = 0.44*10**4 #Section modulus at deck in cm2-m
M_sh = 20664 # Maximum still water bending moment in hogging in kN-m
y_n = D - 2.2535 # neutral axis from deck in m (approx)
Ship_inertia = Ship_SM_b*y_n  # Midship inertia in cm2-m2
Ship_area = 350000*10**-6 #m2
```

B.3. Read me file

```
    ########### READ ME FILE ###############

#### Instructions to Fill Database files

### Plate File

# Fields: id_position, length, width, location, loc_dp, E_index, loc_C1, loc_t, y_dist

# id_position: define if plate is a deckhouse, bulkhead  or deck plate
    # options: 0 - deckhouse and superstructure / 1 - bulkheads / 2 - internal decks

# length: length of plate in METERS
# width: width of plate in METERS

# location: describe location of plates -> string

# loc_dp: first location index for design pressure calculation
    # options:
        # For Decks and Deckhouses:
                        # Location 0: from aft end to 0,88L_R at weather decks
                        # Location 1: from 0,88L_R to 0,925L_R at weather decks
                        # Location 2: from 0,925L_R to forward end at weather decks
                        # Location 3: for interior decks
        # For Bulkheads: 0
```

```
    # In the case of deckhouses and superstructures, consider the location deck on which is supported by.


# E_index: index necessary for the parameter E in the pressure on weather and interior deck calculation
    # options:
        # For Decks and Deckhouses:
            # Key 0: for interior decks and superstructure decks aft of the forward quarter
            # Key 1: for exposed decks
        # For Bulkheads: 0

# loc_C1: location index for deisng pressura calculation of deckhouses and superstructure
    # options:
        # For deckhouses and superstructures and bulkheads:
            # Key 0: for deckhouse and superstructure fronts on upper deck within the forward third of L_R
            # Key 1: for deckhouse and superstructure fronts on upper deck outside the forward third of L_R and exposed machinery casings on the upper deck
            # Key 2: for deckhouse and superstructure fronts above the lowest tie
            # Key 3: for superstructure sides.
            # Key 4: for deckhouses sides (stepped more than 1 m inside)
            # Key 5: elsewhere
        # Decks: 0

# loc_t: location index necessary for minimum thickness and Bending Factor in Plating_Register
    #options:
        # Location 0 = Superstructure side plating
        # Location 1 =  Deckhouse front 1st tier
        # Location 2 =  Deckhouse front upper tiers
        # Location 3 = Deckhouse aft
        # Location 4 = Deck Inside deckhouse -> DECK
        # Location 5 = Watertight bulkhead plating -> BULKHEAD

# y_dist: vertical distance from maindeck to one-third of the height of the panel -> y in METERS

#######################################################
#######################################################

## Stiffeners File
```

```

# Fields: id_position, type_prof, type, type_id,location, spacing, span, y_dist, loc_register, support,
# web heigth, web thickness, width flange, thickness flange, holes, hole_height, opening

# id_position: define if stiffener is on a deck or bulkhead panel
    # options: 0 - Deckhouse and Superstructure / 1 - Bulkheads / 2 - Decks

# type_prof: define type of stiffener profile
    # options: T-bar, L-bar, Box, Flat bar

# type: define type of stiffener
    # options: Long Stiffener, Girder, Transverse and Stringer
    # Notice that Girder refer to primary stiffeners in longitudinal direction over decks,
    # Transverse refers to primary stiffeners in transversal direction
    # Stringer refers to primary sitffeners in longitudinal direction over side plates
    # Stiffener can be use for secondary stiffeners in any direction.

# type_id: index to identify primary and secondary stifferners
    # options:
        # Key 0: Primary stiffeners
        # Key 1 : Secondary stiffeners

# location: describe location of plates -> string (NEED TO WRITTEN THE SAME AS IN PLATE FILE)

# spacing: spacing between each side of member in METERS

# span: unsupported span of stiffener considered in METERS

# y_dist: vertical distance between midspan stiffener and maindeck in METERS

# loc_register: location index used in required section modulus calculation, from LLoyds register.
    # options:
        # Location 0 = Deckhouse aft and sides:
        # Location 1 =  Deckhouse front 1st tier
        # Location 2 =  Deckhouse front upper tiers
        # Location 3 = House top
        # Location 4 = Lower/inner decks and house top subject to personnel loading -> DECK
```

```
        # Location 5 = Minor bulkhead (both primary and secondary are
            the same) -> BULKHEAD

# support: index to identify type of support in the stiffener edges
    # options:
        # Location 0 = Primary and other members where the end fixity
            is considered clamped (at edges)
        # Location 1 = Local, secondary and other members where the
           end fixity is considered to be partial
        # Location 2 = clamped at one side and simple supported in
           the other side (clamped edge)
        # Location 3 = cantilver beam (at clamped edge)
        # Location 4 = simple supported beam (at middle span)

# web height, web thickness, width flange, thickness flange: initial
   dimensions of stiffener in MILIMETERS
    # For Flat Bar, flange dimensions should be 0.
    # For Box type, add the thickness of flanges to consider a
       equivalent T-bar in calculations.

# holes: indicate if there are cut-out at the member to consider the
   weaker section modulus.
    # options: True or False

# hole_height: in case there is holes at the member, indicate the
   height of the cut-out in MILIMETERS.
# in the case of no holes, put 0.

# openings: indicate if the member is along an opening.
    # options: True or False
```

B.4. Plate Class

```
    from Design_Pressure import Design_Pressure

class Plate:
    def __init__(self, id_position, length, width, location, loc_dp,
       E_index, loc_C1, loc_t, y_dist,t):
        self.position = id_position
        self.l = length*1000 #measure in mm
        self.w = width*1000  #measure in mm
        self.loc = location

        self.loct = loc_t
        self.y = y_dist

```

```
        self.locDP = loc_dp
        self.E_id = E_index
        self.locC1  = loc_C1


        D_P = Design_Pressure(self.position,loc_dp,E_index,loc_C1,
            self.y, 7.2)
        self.P_d = D_P.Calculate_Plate(E_index)

        self.t = t
```

B.5. Stiffener Class

```
    from Design_Pressure import Design_Pressure

class Stiffener:
    def __init__(self, id_position, type_prof, type, type_id,
        location, spacing, span, y_dist,ref,loc_reg, support,h,t1,w,
        t2, holes,hole_h,opening,N_open,list_plates):
        self.position = id_position
        self.loc = location
        self.type_prof = type_prof
        self.type = type
        self.type_id = type_id
        self.s = (spacing/2)*1000 #spacing in mm
        self.l = span
        self.locR = loc_reg
        self.support = support
        self.ref = ref

        self.h = h
        self.t1 = t1
        self.w = w
        self.t2 = t2
        self.holes = holes
        self.hole_h = hole_h
        self.open = opening
        self.N_open = N_open

        for plate in list_plates:
            if plate.position == self.position and plate.loc == self.
                loc:
                self.t = plate.t
                loc_DP = plate.locDP
                E_id = plate.E_id
                loc_C1 = plate.locC1
```

```
        DP = Design_Pressure(self.position,loc_DP,E_id,loc_C1, y_dist)
        self.P_d = DP.Calculate_Stiff(type_id,E_id)

        ##OUTPUT PARAMETERS
        self.w_0 = 0
        self.w_f = 0
        self.sm_0 = 0
        self.sm_f = 0
        self.inertia_f=0
        self.a_webf=0
        self.sm_req = 0
        self.inertia_req = 0
        self.a_web_req = 0
        self.nit = 0
        self.e_plate = 0
        self.optimal = ""
        self.add_sm = 0
```

B.6. Design Pressure Class

```
    rom Config_file import Lwl, D, T, Tay_quo, H_f, S_f, G_f

class Design_Pressure:
    def __init__(self, id_position, loc_factor, E_index, loc_C1, h_b, coef=1):
        self.position = id_position
        dic_f = {0: 1, 1:1.25, 2:1.5, 3:1}
        dic_E = {0:0, 1:min((0.7+0.08*Lwl)/(D-T),3)}
        f_l = dic_f[loc_factor]
        E = dic_E[E_index]

        self.P_wh = f_l*(6+0.01*Lwl)*(1+0.05*Tay_quo) + E # Pressure on weather and interior decks in kN/m2

        if self.position == 0 or self.position == 1:
            dic_c1 = {0: 1.25, 1: 1.15, 2:1.0, 3:0.8, 4:0.64,5:0.5}
            C1 = dic_c1[loc_C1]

            self.P_h = C1*self.P_wh  #Design Pressure for Deckhouses and Superstrucutures
        #elif self.position == 1:
        #    self.P_h = 11.2*coef*h_b  # Design Pressure for watertights bulkhead and supporting doors.

```

```
        else:
            self.P_h = self.P_wh



    def Calculate_Plate(self, E_index):
        if self.position == 0:
            self.P_dp = H_f*S_f*G_f*self.P_h

        elif self.position == 1:
            self.P_dp = self.P_h

        else:
            self.P_dp = H_f*S_f*self.P_h

        return self.P_dp

    def Calculate_Stiff(self, type_id,E_index):
        dic_deltaf = {0: 0.5, 1: 0.8}
        deltaf = dic_deltaf[type_id]

        if self.position == 0:
            self.P_ds = deltaf*H_f*S_f*G_f*self.P_h

        elif self.position == 1:
            self.P_ds = self.P_h

        else:
            self.P_ds = deltaf*H_f*S_f*self.P_h


        return self.P_ds
```

B.7. Plating Register Class

```
    rom math import sqrt, ceil
from operator import attrgetter
from Config_file import km, sig_a,w

def Plating_Register(plate,L_r):
    s = plate.w
    A_r = plate.l/plate.w # aspect ratio
    beta = A_r*(1-0.25*A_r) if A_r <= 2 else 1 # aspect ratio correction
    gamma = 1 # considering only straight panels

```

```
    min_t = {0:max(3*w,w*sqrt(km)*(0.4*sqrt(L_r)+1.1)), 1:max(3.5*w,w*sqrt(km)*(0.62*sqrt(L_r)+1.8)),
             2:max(3*w,w*sqrt(km)*(0.55*sqrt(L_r)+1.5)), 3:max(2.5*w,w*sqrt(km)*(0.25*sqrt(L_r)+0.7)),
             4: max(3*w,w*sqrt(km)*(0.3*sqrt(L_r)+1.3)), 5:max(3*w,w*sqrt(km)*(0.43*sqrt(L_r)+1.2))}

    dic_fsig = {0: 0.75, 1:0.65, 2: 0.75, 3: 0.75, 4: 0.75, 5: 0.65}
    fsig = dic_fsig[plate.loct]

    t = max(22.4*s*beta*gamma*sqrt(plate.P_d/(fsig*sig_a))*10**(-3), min_t[plate.loct]) ##thickness in mm

    if t> plate.t:
        plate.t = ceil(t)



def Filter_plate (list_plates):
    final_plates =[]

    for plate1 in list_plates:
        l_p =[]
        flag = False
        for plate2 in list_plates:
            if plate2.position == plate1.position and plate2.loc == plate1.loc:
                l_p.append(plate2)
                flag = True
            elif flag == True:
                break
        l_p.append(plate1)
        f_p = max(l_p, key=attrgetter('t'))
        final_plates.append(f_p) if any(obj == f_p for obj in final_plates) == False else 0


    return final_plates
```

B.8. Stiffener Register Class

```
import random as r
from math import ceil,sqrt,pi
from scipy import optimize
import numpy as np
from Config_file import t_min,sig_a,tau_a,E,Gh_max
```

```python



class Stiffener_Register:
    def __init__(self, stiff, add=0):
        dic_fsig = {0: 0.75, 1:0.60, 2:0.65, 3:0.75, 4:0.6, 5:0.65}
        if stiff.type_id == 0:
            dic_fdelta = {0:475, 1:475,2:475,3:400,4:625,5:475}
        else:
            dic_fdelta = {0:400, 1:400,2:400,3:400,4:475,5:400}

        dic_Phiz = {0: 1/12, 1: 1/10, 2:1/8, 3:1/2, 4:1/8}
        dic_Phii = {0: 1/384, 1: 1/288, 2:1/185, 3:1/8, 4:5/384}
        dic_Phia = {0: 1/2, 1: 1/2, 2:5/8, 3:1, 4:1/2}


        fsig = dic_fsig[stiff.locR]
        ftau = fsig
        fdelta = stiff.l*1000/dic_fdelta[stiff.locR]
        Phiz = dic_Phiz[stiff.support]
        Phii = dic_Phii[stiff.support]
        Phia = dic_Phia[stiff.support]



        self.sm_req = Phiz*((stiff.P_d+add)*stiff.s*stiff.l**2)/(fsig
            *sig_a) ##section modulus required in cm3
        self.inertia_req = Phii*fdelta*(stiff.P_d*stiff.s*stiff.l**3)
            /(E)*100 ## inertia required in cm4
        self.aw_req = Phia*(stiff.P_d*stiff.s*stiff.l)/(100*ftau*
            tau_a) ## web area required in cm2

    def Dimensions_Properties(self,d, holes,hole_h):
        # dimensions are in mm
        a_p = d[4]*d[5]
        a_flange= d[2]*d[3]
        if holes == False:
            a_web = d[0]*d[1]
            y_w = d[5]+d[0]/2
            i_web = d[1]*d[0]**3/12
        else:
            hw_s = (d[0]-hole_h)/2
            a_web = d[0]*d[1] - hole_h*d[1]
            y_w = d[5] + ((hw_s*d[1]*(hw_s/2)+hw_s*d[1]*(hw_s/2+
                hole_h))/a_web)
            i_web = 2*(d[1]*hw_s**3/12)

```

```python
        area = a_p + a_web + a_flange
        y_p = d[5]/2
        y_f = d[5]+d[0]+d[3]/2

        y_n = (y_p*a_p +y_w*a_web+y_f*a_flange)/area

        i_p = d[4]*d[5]**3/12
        i_flange = d[2]*d[3]**3/12
        Adist_w = (a_web/2)*(d[5]+hw_s/2-y_n)**2 +(a_web/2)*(d[5]+hw_s/2+hole_h-y_n)**2 if holes == True else (a_web)*(y_w-y_n)**2


        inertia = i_p + (a_p)*(y_p - y_n)**2 + i_web + Adist_w + i_flange + (a_flange)*(y_f-y_n)**2

        return inertia, y_n, a_web

    def Section_Modulus(self,d, holes,hole_h):
        inertia, y_n, a_web = self.Dimensions_Properties(d, holes, hole_h)
        sm = (inertia/max(y_n,d[5]+d[0]+d[3]-y_n))*(10**(-3))
        return   sm, inertia*10**(-4), a_web*10**(-2) # profile section modulus in cm3, inertia in cm4 and web area in cm2

    def Weight(self,d,l, rho_material):
        # dimensions in mm, density in g/cm3
        return (d[0]*d[1]+d[2]*d[3]+d[4]*d[5])*l*rho_material/1000 # weight in g

    def Optimize_Dimensions(self,stiff,rho_mat):
        d = np.array([stiff.h,stiff.t1,stiff.w,stiff.t2,0,stiff.t])

        N = stiff.N_open if stiff.open == True else 1


        constraint = [{'type':'ineq', 'fun': lambda x:self.Section_Modulus(x,stiff.holes,stiff.hole_h)[0]-(N*self.sm_req)},
                      {'type':'ineq', 'fun': lambda x:self.Section_Modulus(x,stiff.holes,stiff.hole_h)[1]-self.inertia_req},
                      {'type':'ineq', 'fun': lambda x:self.Section_Modulus(x,stiff.holes,stiff.hole_h)[2]-self.aw_req}]

```

```

        if stiff.type_id == 0:
            d[4] = stiff.s*min(1,0.3*(stiff.l/(stiff.s/1000))**(2/3))
            h_max = d[0]

        else:
            d[4] = min(stiff.s,2*stiff.t*sqrt(E/sig_a))
            h_max = Gh_max

        if stiff.type_prof == "Flat bar":
            coef = 15
            dl_t1  = t_min
            dl_t2 = 0
            ul_w, ul_t2 = 0,0
            dl_w = 0

        else:
            coef = 50
            dl_t2 =t_min
            dl_t1  = 2*t_min if stiff.type_prof == "Box" else t_min
            dl_w = 1
            ul_w, ul_t2 = np.inf, np.inf
            constraint.append({'type':'ineq', 'fun': lambda x: x[0]/x[2] - 1.5 if stiff.type_prof == "T-bar" else x[0]/x[2] - 1})
            constraint.append({'type':'ineq', 'fun': lambda x: x[3] - x[1] if stiff.type_prof == "T-bar" else x[3] - x[1]/2})
            constraint.append({'type':'ineq', 'fun': lambda x: 16*x[3] - x[2]})
            constraint.append({'type':'ineq', 'fun': lambda x: x[2] - 2*x[3]})
            constraint.append({'type':'ineq', 'fun': lambda x: x[0] - 2*stiff.hole_h if stiff.holes == True else 0})

        constraint.append({'type':'ineq', 'fun': lambda x: x[1] - x[0]/coef})
        #d[4] = d[4]/2 if stiff.open == True else d[4]



        stiff.w_0 = self.Weight(d,stiff.l*1000, rho_mat)
        stiff.sm_0, stiff.inertia_0, stiff.a_web0 = self.Section_Modulus(d,stiff.holes, stiff.hole_h)
        stiff.e_plate = d[4]

        bounds = optimize.Bounds([1,dl_t1,dl_w,dl_t2,d[4],d[5]],[
```

```
            h_max,np.inf,ul_w,ul_t2,d[4],d[5]])
        res = optimize.minimize(self.Weight,d,args =(stiff.l*1000,rho_mat) ,method='SLSQP',constraints=constraint, bounds = bounds, options={'ftol': 1, 'eps':1,'disp': False})
        self.res = res
        res.x = np.around(res.x,2)
        stiff.h,stiff.t1,stiff.w,stiff.t2,stiff.t = ceil(res.x[0]),ceil(res.x[1]),ceil(res.x[2]),ceil(res.x[3]),ceil(res.x[5])

        if stiff.type_prof == "Box":
            stiff.t1 = 2*ceil(stiff.t1/2)


        #stiff.hole_h = stiff.h/2
        df = np.array([stiff.h,stiff.t1,stiff.w,stiff.t2,d[4],stiff.t])

        stiff.w_f = self.Weight(df,stiff.l*1000,rho_mat)
        stiff.sm_f, stiff.inertia_f, stiff.a_webf = self.Section_Modulus(df,stiff.holes,stiff.hole_h)
        stiff.nit  = res.nit

        print(df, stiff.l, rho_mat,stiff.w_f)
        if stiff.w_f>stiff.w_0 and stiff.sm_0>=N*self.sm_req:

            stiff.h,stiff.t1,stiff.w,stiff.t2 = d[0],d[1],d[2],d[3]
            df = np.array([stiff.h,stiff.t1,stiff.w,stiff.t2,d[4],stiff.t])
            stiff.w_f = self.Weight(df,stiff.l*1000,rho_mat)
            stiff.sm_f, stiff.inertia_f, stiff.a_webf = self.Section_Modulus(df,stiff.holes,stiff.hole_h)
        #    stiff.optimal = "FAIL"
        #else:
        #    stiff.optimal = "SUCCESS"
        stiff.optimal = res.success

        return stiff

    def Calculate_SM(self,stiff, rho_mat):
        d = np.array([stiff.h,stiff.t1,stiff.w,stiff.t2,0,stiff.t])

        if stiff.type_id == 0:
            d[4] = stiff.s*min(1,0.3*(stiff.l/(stiff.s/1000))**(2/3))

        else:
            d[4] = min(stiff.s,2*stiff.t*sqrt(E/sig_a))
```

```

        stiff.w_0 = self.Weight(d,stiff.l*1000, rho_mat)
        stiff.sm_0, stiff.inertia_0, stiff.a_web0 = self.
            Section_Modulus(d,stiff.holes, stiff.hole_h)
        stiff.e_plate = d[4]
```

B.9. Data Access file

```
    import pandas as pd
#import openpyxl
from Plate import Plate
from Stiffener import Stiffener

def Read_Data(path_name: str):
    data = pd.read_excel(path_name)
    return data

def Write_Data(data, file_name, sheet_name):
    with pd.ExcelWriter(file_name, mode="a") as writer:
        data.to_excel(writer, sheet_name, index_label = "Object_ID")

def DataAccess_Plate(path_name):
    data = Read_Data(path_name)
    list_plates=[]
    for index,row in data.iterrows():
        list_plates.append(Plate(row['id_position'], row['length'],
            row['width'], row['location'],
        row['loc_dp'], row['E_index'],row['loc_C1'],row['loc_t'], row
            ['y_dist'], row['t']))

    return list_plates

def DataAccess_Stiff(path_name,list_plates):
    data = Read_Data(path_name)
    list_stiff=[]
    for index,row in data.iterrows():
        list_stiff.append(Stiffener(row['id_position'], row['
            type_profile'],row['type'],row['type_id'],row['location
            '], row['spacing'], row['span'], row['y_dist'],row['
            ref_id'],row['loc_register'],row['support'],
        row['web height'], row['thickness web'], row['width flange'],
             row['thickness flange'], row['holes'],row['hole_height
            '],row['opening'],row['N_open'],list_plates))
    return list_stiff

def Output(dimensions, list_plates, list_stiff,name_file):
```

```
    df1 = pd.DataFrame({'Main Dimensions':["Length [m]", "Breadth [m]", "Depth [m]", "Draft [m]", "Displacement [ton]", "LPP [m]", "Waterline Length [m]", "Block Coefficient"], "":[dimensions[0], dimensions[1], dimensions[2], dimensions[3], dimensions[4], dimensions[5], dimensions[6], dimensions[7]]})
    df1.to_excel(name_file,"Main Dimensions", index=False)

    struc, pos, loc, y, l, w, t =[],[],[],[],[],[],[]
    p = []
    for plate in list_plates:
        if plate.position == 0:
            pos.append("Deckhouse/Superstructure")
        elif plate.position == 1:
            pos.append("Bulkhead")
        else:
            pos.append("Deck")
        struc.append("Plate")
        loc.append(plate.loc), y.append(plate.y), l.append(plate.l/1000), w.append(plate.w/1000), t.append(plate.t)
        p.append(plate.P_d)

    df2 = pd.DataFrame({"Structure":struc,"Position":pos, "Location":loc, "Vertical Distance to Waterline [m]":y,
                        "Length [m]":l, "Width [m]":w, "Thickness [mm]":t, "Pressure[kN/m2]":p})
    Write_Data(df2,name_file,"Plating")

    struc, pos, type_prof, type,loc,l, s =[],[],[],[],[],[],[]
    h,t1,w,t2 = [],[],[],[]
    t, e_plate =[], []
    w_0, w_f, sm_0, sm_f, sm_req = [],[],[],[],[]
    inertia_0, inertia_f, inertia_req = [],[],[]
    a_web0, a_webf, a_web_req = [],[],[]
    nit, op = [], []
    add_sm = []
    p=[]
    for stiff in list_stiff:
        if stiff.position == 0:
            pos.append("Deckhouse/Superstructure")
        elif stiff.position == 1:
            pos.append("Bulkhead")
        else:
            pos.append("Deck")
        struc.append("Stiffener"), type_prof.append(stiff.type_prof), type.append(stiff.type)
        loc.append(stiff.loc), l.append(stiff.l), s.append(stiff.s)
        h.append(stiff.h), t1.append(stiff.t1), w.append(stiff.w), t2
```

```
            .append(stiff.t2), t.append(stiff.t)
        w_0.append(stiff.w_0), w_f.append(stiff.w_f), sm_0.append(stiff.sm_0), sm_f.append(stiff.sm_f), sm_req.append(stiff.sm_req)
        nit.append(stiff.nit), e_plate.append(stiff.e_plate), inertia_0.append(stiff.inertia_0), inertia_f.append(stiff.inertia_f),
        inertia_req.append(stiff.inertia_req), a_web0.append(stiff.a_web0), a_webf.append(stiff.a_webf), a_web_req.append(stiff.a_web_req),
        op.append(stiff.optimal), add_sm.append(stiff.add_sm), p.append(stiff.P_d)

    df3 = pd.DataFrame({"Structure":struc,"Position":pos, "Type":type,"Profile Type":type_prof,"Location":loc,
    "Spacing [m]":s, "Span [m]":l, "Web Height [mm]":h,
    "Web Thickness [mm]":t1, "Flange Width [mm]":w, "Flange Thickness [mm]":t2, "Plate Thickness [mm]":t, "Effective Plate [mm]":e_plate,"Pressure[kN/m2]":p,
    "Initial Weight [g]":w_0, "Final Weight [g]":w_f,"Initial SM": sm_0, "Final SM": sm_f,"Added SM":add_sm, "Required SM": sm_req,
    "Initial Inertia": inertia_0, "Final Inertia": inertia_f, "Required Inertia": inertia_req,
    "Initial Aw": a_web0, "Final Aw": a_webf, "Required Aw": a_web_req,"Iterations": nit, "Optimization":op })
    Write_Data(df3,name_file,"Stiffeners")
```

C. ABS's Python Code

C.1. Main file

```
    ###########################################################
#### Code Developed by Marianna Sipauba from LLoyds Register Rules for Special Service Craft ###
########## In the framework of master thesis for conclusion of EMSHIP Master Program ###########
#### Developed in: april/2023


from DataAccess import DataAccess_Plate, DataAccess_Stiff, Output
from Plating_Register import Plating_Register, Filter_plate
from Stiffener_Register import Stiffener_Register
#from Hull_Girder import Hull_Girder
import Config_file as cf

```

```
def __main__():
    ## Constants
    rho_sea = cf.rho_sea
    rho_alu = cf.rho_alu
    g = cf.g
    sig_y = cf.sig_y
    E = cf.E
    path_plate = cf.path_plate
    path_stiff = cf.path_stiff

    ## Main Dimensions ##
    L = cf.L
    L_f = cf.L_f
    B = cf.B
    D = cf.D
    T = cf.T
    Disp = cf.Disp
    C_b = Disp/(rho_sea*L*B*T)  #Block coefficient
    FB = D - T  #Freeboard in m
    #Ship = Hull_Girder(L,B,V,C_b)
    print(L)
    dimensions = [L, B, D, T, Disp]
    #Plating
        ## Objects Creation

    list_plates = DataAccess_Plate(path_plate,L,FB)

        ## Calculate Dimensions

    for plate in list_plates:
        Plating_Register(plate,sig_y)

    list_plates = Filter_plate(list_plates) #Filter for maximum thickness for plates at same location

    #Stiffeners
        ## Objects Creation
    list_stiff = DataAccess_Stiff(path_stiff, list_plates)

        ## Calculate Dimensions
    i=0
    for stiff in list_stiff:
        #print(i, stiff.head)
        add_sm = 0
        if stiff.position == 0:
            req = Stiffener_Register(stiff.position,stiff.head,stiff.s,stiff.l,stiff.locR)
```

```
            stiff.sm_req = stiff.N_open*req.sm_req
            #stiff = req.Optimize_Dimensions(stiff, rho_alu)
            stiff = req.Calculate_SM(stiff,rho_alu)
        else:
            for stiff_d in list_stiff:

                if stiff_d.position == 0 and stiff_d.type == stiff.type and stiff_d.ref == stiff.ref:
                    if "LT" in stiff.loc and stiff_d.loc == "Upper Deck":
                        stiff.add_sm = stiff_d.sm_req
                    elif "2T" in stiff.loc and stiff_d.loc == "Bridge Deck":
                        stiff.add_sm = stiff_d.sm_req
                    elif "3T" in stiff.loc and stiff_d.loc == "Hard Top":
                        stiff.add_sm = stiff_d.sm_req
            req = Stiffener_Register(stiff.position,stiff.head,stiff.s,stiff.l,stiff.locR)
            stiff.sm_req = stiff.N_open*req.sm_req
            #stiff = req.Optimize_Dimensions(stiff, rho_alu,stiff.add_sm)
            stiff = req.Calculate_SM(stiff,rho_alu)


    Output(dimensions, list_plates, list_stiff, cf.path_out)

if __name__ == '__main__':
    __main__()
```

C.2. Configuration file

```
    # Global variables

op = 1
path_plate = 'C:/Users/Mari/OneDrive/Documentos/EMSHIP/MasterThesis/ABS/BD/abs_plate_db_op{:02d}.xlsx'.format(op)
path_stiff = 'C:/Users/Mari/OneDrive/Documentos/EMSHIP/MasterThesis/ABS/BD/abs_stiff_db_op{:02d}.xlsx'.format(op)
path_out = 'OUT/abs_output_op{:02d}.xlsx'.format(op)

#Constants
rho_sea = 1.025 #sea density in tons/m3
rho_alu = 2.7 #g/cm3
E = 6.9*10**4 #N/mm2 (aluminium)
g = 9.81  #gravity in m/s2
```

```
sig_y = 125 #N/mm2
sig_u = 275 #N/mm2 -> minimum ultimate strength
t_min = 4 #mm
G_h_max = 300

## Main Dimensions ##
Lwl = 54.464 # Waterline length in m
Lpp = 52.03 # Lpp in m
L = 52.282  # Scantling length in m
L_f = 52.56  # Rule length in m
B = 10.5  # Maximum Breadth in m
D = 5.45  # Depth in m
T = 2.95  # Draft in m
FB = D - T
Disp = 970 # Displacement in tons
V = 16.5 #Speed in knots
```

C.3. Read me file

```
    ########### READ ME FILE ###############

#### Instructions to Fill Database files

### Plate File

# Fields: id_position, length, width, location, loc_dp, loc_minh, loc_t, y_dist, x_dist, k, c, support

# id_position: define if plate is a deck or bulkhead plate
    # options: 0 - decks and internal bulkheads / 1 - external bulkheads

# length: length of plate in METERS
# width: width of plate in METERS

# location: describe location of plates -> string

# loc_dp: first location index for design pressure calculation
    # options:
        # For Deck: # Location 1 = Superstructure and Deckhouse Decks Forward of 0.25L(exposed)
                    # Location 2 = Superstructure and Deckhouse Decks elsewhere (exposed), Deckhouse top, First tier
                    # Location 3 = Deckhouse tops above 2nd tier (used as weather coverings only)
```

```
                        # Location 4 = Internal accommodation decks(included in hull-girder section modulus)
                        # Location 5 = Internal accommodation only decks(not included in hull-girder section modulus)
        # For Bulkheads:
                        # Location 1 = Lowest tier - Unprotected front and Sides of Superstructures, inset from side not more than 0.04B
                        # Location 2 = Second tier - Unprotected front and Sides of Superstructures
                        # Location 3 = Third tiers - Unprotected front and Sides of Superstructures / Protected front All tiers and Sides of Deckhouses, All tiers, inset from side greater than 0.04B
                        # Location 4 = Aft ends, aft of amidships, All tiers
                        # Location 5 = Aft ends, forward of amidships, All tiers

# loc_minh: location index necessary for design pressure calculation of bulkheads.
    # options:
        # For Decks: 0
        # For Bulkheads:
                        # Location 1 = Unprotected Fronts on the Lowest Tier
                        # Location 2 = All Other Locations on Lowest Tier and Second Tier
                        # Location 3 = All Other Locations, Third Tier and Above

# loc_t: location index necessary for minimum thickness in Plating_Register
    #options:
        # Location 0 = exposed strength decks
        # Location 1 =  for enclosed strength and internal decks
        # Location 2 =  exposed deckhouse/superstructure bulkheads
        # Location 3 = for all other locations

# y_dist: vertical distance from maindeck to midpoint of stiffener or panel -> y in METERS

# x_dist: horizontal distance between the after perpendicular and the bulkhead being considered -> x in METERS
  # for decks consider midpoint of deck
  # for side bulkheads need to plit into N pieces of 0.1L maximum length and take to the midpoint of the piece
```

```

# k: service factor from ABS register, used in design pressure calculations
    # options:
        # Key 0 = for Yachting Service, Commercial Yachting Service
        # Key 1 = for restricted yachting service notation R

# c: index from ABS register, used in design pressure calculations
    # options:
        # Key 0  = for superstructures
        # Key 1 = for deckhouses


##############################################
##############################################

## Stiffeners File

# Fields: id_position, type_prof, type, location, loc_dp, loc_minh, spacing, span, loc_register,
# web heigth, web thickness, width flange, thickness flange, holes, hole_height, opening

# id_position: define if stiffener is on a deck or bulkhead panel
    # options: 0 - decks and internal bulkheads / 1 - external bulkheads

# type_prof: define type of stiffener profile
    # options: T-bar, L-bar, Box, Flat bar

# type: define type of stiffener
    # options: Long Stiffener, Girder, Transverse and Stringer
    # Notice that Girder refer to primary stiffeners in longitudinal direction over decks,
    # Transverse refers to primary stiffeners in transversal direction
    # Stringer refers to primary sitffeners in longitudinal direction over side plates
    # Stiffener can be use for secondary stiffeners in any direction.

# location: describe location of plates -> string (NEED TO WRITTEN THE SAME AS IN PLATE FILE)

# spacing: spacing between each side of member in METERS

# span: unsupported span of stiffener considered in METERS

```

```
# loc_register: location index used in required section modulus
    calculation, from ABS register.
    # options:
        # For Deck position:
            # Location 0 = strength deck longitudinals amidships,
                0.48 outside amidships
            # Location 1 = for all other strength and internal deck
                members, and for girders and webs on watertight
                bulkheads
            # Location 2 = for attached-end, watertight bulkhead
                stiffeners
            # Location 3 = for unattached-end, watertight bulkhead
                stiffeners
        # For Bulkhead position: 0

# web height, web thickness, width flange, thickness flange: initial
    dimensions of stiffener in MILIMETERS
    # For Flat Bar, flange dimensions should be 0.
    # For Box type, add the thickness of flanges to consider a
        equivalent T-bar in calculations.

# holes: indicate if there are cut-out at the member to consider the
    weaker section modulus.
    # options: True or False

# hole_height: in case there is holes at the member, indicate the
    height of the cut-out in MILIMETERS.
# in the case of no holes, put 0.

# openings: indicate if the member is along an opening.
    # options: True or False
```

C.4. Plate Class

```
    from Design_Pressure import Design_Pressure

class Plate:
    def __init__(self, id_position, length, width, location, loc_dp,
        loc_minh, loc_t, y_dist, x_dist, k, c, t,L, FB):
        self.position = id_position
        self.l = length*1000 #measure in mm
        self.w = width*1000  #measure in mm
        self.loc = location

        self.loct = loc_t
        self.y = y_dist
```

```
        self.x = x_dist


        D_P = Design_Pressure(L,self.position,loc_dp)
        self.head = D_P.Calculate(k, c, self.x, self.y+FB,loc_minh)

        self.t = t
```

C.5. Stiffener Class

```
    from Design_Pressure import Design_Pressure

class Stiffener:
    def __init__(self, id_position, type_prof, type, type_id,
        location, spacing, span, loc_reg, ref_id,h,t1,w,t2, holes,
        hole_h,opening,N_open,list_plates):
        self.position = id_position
        self.loc = location
        self.type_prof = type_prof
        self.type = type
        self.type_id = type_id
        self.s = spacing/2
        self.l = span
        self.locR = loc_reg
        self.ref = ref_id

        self.h = h
        self.t1 = t1
        self.w = w
        self.t2 = t2
        self.holes = holes
        self.hole_h = hole_h
        self.open = opening
        self.N_open = N_open

        for plate in list_plates:
            if plate.position == self.position and plate.loc == self.
                loc:
                self.t = plate.t
                self.head = plate.head

        ##OUTPUT PARAMETERS
        self.w_0 = 0
        self.w_f = 0
        self.sm_0 = 0
        self.sm_f = 0
```

```
        self.sm_req = 0
        self.nit = 0
        self.e_plate = 0
        self.optimal = ""
        self.add_sm = 0
```

C.6. Design Pressure Class

```
    from Config_file import FB

class Design_Pressure:
    def __init__(self, L, id_position, location):

        self.position = id_position
        self.location = location
        self.L = L

    def Calculate(self,k=1,c=1,x=1, y=1, loc_minh=1):
        if self.position == 0:
            dic_dh = {1: 0.02*self.L+0.46,2:0.01*self.L+0.46,3: 0.01*self.L+0.15,4:0.01*self.L+0.3,5:0.35}
            self.head = dic_dh[self.location]
        else:
            dic_a = {1:2+self.L/120, 2:1+self.L/120, 3:0.5+self.L/150, 4:0.7+self.L/1000-0.8*x/self.L, 5:0.5+self.L/1000-0.4*x/self.L}
            dic_b = {0.1*self.L:1.19,0.2*self.L:1.1,0.3*self.L:1.04,0.4*self.L:1,0.45*self.L:1,0.5*self.L:1,0.6*self.L:1.05,0.7*self.L:1.15,0.8*self.L:1.29,0.9*self.L:1.49}
            dic_f = {24: 1.24, 40:2.57, 60:4.07, 80:5.41,90:6}
            dic_k = {0:1,1:0.85}
            dic_c = {0:1,1:0.85}
            min_h = {1:0.01*self.L+2.5, 2:0.005*self.L+1.25,3:1.5}


            b = dic_b[min(dic_b, key=lambda i:abs(i-x))]
            k = dic_k[k]
            c = dic_c[c]

            try:
                f = dic_f[self.L]
                a = dic_a[self.location]
            except:
                x_0 = min(dic_f, key=lambda i:abs(i-self.L))
                y_0 = dic_f[x_0]
```

```
                x_1 = list(dic_f.keys())[list(dic_f.keys()).index(x_0)+1]
                y_1 = dic_f[x_1]

                f = y_0 + (self.L-x_0)*(y_1-y_0)/(x_1 - x_0)
                a = 0

            self.head = max(a*k*((b*f)-y)*c,min_h[loc_minh])
            print(self.location, a,b,y, self.head)

        return self.head
```

C.7. Plating Register Class

```
    import math as m
from operator import attrgetter

def Plating_Register(plate,sig_y):
    s = min(plate.l,plate.w)
    min_t = {0:5, 1:4,2:4,3:4}
    q = 235/sig_y

    if plate.position == 0:
        t = max((q*plate.head)**(1/s)/272 + 2, min_t[plate.loct]) ## thickness in mm

    else:
        t = max(0.003*s*m.sqrt(q*plate.head),min_t[plate.loct]) ## thickness in mm

    if plate.t<t:
        plate.t = m.ceil(t)


def Filter_plate (list_plates):
    final_plates =[]

    for plate1 in list_plates:
        l_p =[]
        flag = False
        for plate2 in list_plates:
            if plate2.position == plate1.position and plate2.loc == plate1.loc:
                l_p.append(plate2)
                flag = True
            elif flag == True:
```

```
                break
        l_p.append(plate1)
        f_p = max(l_p, key=attrgetter('t'))
        final_plates.append(f_p) if any(obj == f_p for obj in final_plates) == False else 0


    return final_plates
```

C.8. Stiffener Register

```
import random as r
from math import ceil,sqrt
from scipy import optimize
import numpy as np
from Config_file import t_min, G_h_max, E, sig_y

class Stiffener_Register:
    def __init__(self, id_position, head, s,l, location=0):
        self.position = id_position
        q = 235/sig_y
        dic_c = {0: 0.64, 1:0.51, 2:0.37, 3:0.46}

        if self.position == 0:
            c = dic_c[location]
            self.sm_req = 7.8*c*head*s*q*l**2 ##section modulus required in cm3

        else:
            self.sm_req = 3.43*head*s*q*l**2 ##section modulus required in cm3



    def Dimensions_Properties(self,d, holes,hole_h):
        # dimensions are in mm
        a_p = d[4]*d[5]
        a_flange= d[2]*d[3]
        if holes == False:
            a_web = d[0]*d[1]
            y_w = d[5]+d[0]/2
            i_web = d[1]*d[0]**3/12
        else:
            hw_s = (d[0]-hole_h)/2
            a_web = d[0]*d[1] - hole_h*d[1]
            y_w = d[5] + ((hw_s*d[1]*(hw_s/2)+hw_s*d[1]*(hw_s/2+
```

```
                hole_h))/a_web)
            i_web = 2*(d[1]*hw_s**3/12)

        area = a_p + a_web + a_flange
        y_p = d[5]/2
        y_f = d[5]+d[0]+d[3]/2

        y_n = (y_p*a_p +y_w*a_web+y_f*a_flange)/area

        i_p = d[4]*d[5]**3/12
        i_flange = d[2]*d[3]**3/12
        Adist_w = (a_web/2)*(d[5]+hw_s/2-y_n)**2 +(a_web/2)*(d[5]+hw_s/2+hole_h-y_n)**2 if holes == True else (a_web)*(y_w-y_n)**2


        inertia = i_p + (a_p)*(y_p - y_n)**2 + i_web + Adist_w + i_flange + (a_flange)*(y_f-y_n)**2

        return inertia, y_n, area

    def Section_Modulus(self,d, holes,hole_h):
        inertia, y_n, area = self.Dimensions_Properties(d, holes, hole_h)
        #print(d,inertia)
        return  (inertia/max(y_n,d[5]+d[0]+d[3]-y_n))*(10**(-3)) # profile section modulus in cm3

    def Weight(self,d,l, rho_material):
        # dimensions in mm, density in g/cm3
        return (d[0]*d[1]+d[2]*d[3]+d[4]*d[5])*l*rho_material/1000 # weight in g

    def Calculate_SM(self,stiff, rho_mat):
        d = np.array([stiff.h,stiff.t1,stiff.w,stiff.t2,0,stiff.t])

        if stiff.type_id == 0:
            d[4] = min(stiff.s/2,0.33*stiff.l,0.75)*1000

        else:
            d[4] = min(stiff.s*1000/2,60*stiff.t)

        stiff.w_0 = self.Weight(d,stiff.l*1000, rho_mat)
        stiff.sm_0 = self.Section_Modulus(d,stiff.holes, stiff.hole_h)
        stiff.e_plate = d[4]
```

D. LR Input Tables

Table 47: Input database plate for LR calculations.

id_position	length	width	location	loc_dp	E _index	loc _C1	loc _t	y _dist	t
2	1.2	0.4	Upper Deck I	3	0	0	4	2.68	5
2	1.2	0.4	Upper Deck E	3	1	0	4	2.68	5
2	1.2	0.4	Bridge Deck I	3	0	0	4	5.36	5
2	1.2	0.4	Bridge Deck E	3	1	0	4	5.36	5
2	1.2	0.4	Hard Top	3	1	0	4	8.36	5
0	1.1	0.4	LT - Side DH	0	0	4	0	0.89	5
0	1.49	1.1	LT - Side SP	0	0	3	0	1.33	8
0	0.82	1.2	LT - Aft Ends	0	0	5	3	2.53	8
0	1.1	0.4	2T - Side	0	0	4	0	3.57	5
0	0.77	1.2	2T - Aft Ends	0	0	5	3	5.06	5
0	0.72	0.4	2T - Front	0	0	2	2	3.59	5
0	1.2	0.4	2T - Shell	0	0	3	0	2.80	5
0	1.2	0.4	3T - Shell	0	0	3	0	5.40	5
0	1.22	1.0	3T - Aft Ends	0	0	5	3	6.64	5
0	2.3	0.4	3T - Front	0	0	2	2	6.13	5
1	0.4	2.68	TBulk FR21+600	3	0	5	5	0.89	5
1	0.3	2.68	LBulk 600CLPS	3	0	5	5	0.89	5

Table 48: Input database stiffeners for LR calculations.

id__ position	type__ profile	type	type__ id	location	spacing	span	y__ dist	ref__ id	loc__ register	support	h__w	t__w	w__f	t__f	holes	hole__ height	open	N__ open
2	T-bar	Transverse	0	Upper Deck I	2.0	2.99	2.68	t1	4	0	110	4	60	5	False	0	False	1
2	T-bar	Transverse	0	Upper Deck E	2.4	1.69	2.68	t2	4	3	160	5	80	8	False	0	False	1
2	T-bar	Transverse	0	Upper Deck E	2.4	1.22	2.68	t2	4	3	130	5	80	8	False	0	False	1
2	T-bar	Transverse	0	Upper Deck I	2.4	2.82	2.68	t3	4	0	200	5	80	8	False	0	True	3
2	T-bar	Transverse	0	Upper Deck E	2.74	6.43	2.68	t4	4	4	310	12	200	20	True	150	False	1
2	T-bar	Transverse	0	Upper Deck I	2.3	3.81	2.68	t5	4	0	200	5	80	8	False	0	False	1
2	T-bar	Girder	0	Upper Deck E	2.4	4.87	2.68	g1	4	3	300	12	200	20	True	150	False	1
2	T-bar	Girder	0	Upper Deck E	2.1	5.04	2.68	g2	4	3	294	12	200	20	False	0	False	1
2	Box	Girder	0	Upper Deck E	1.98	4.95	2.68	g3	4	3	200	24	200	20	False	0	True	1
2	Box	Girder	0	Upper Deck E	1.98	4.74	2.68	g4	4	3	200	24	200	20	False	0	False	1
2	T-bar	Girder	0	Upper Deck I	2.4	8.95	2.68	g5	4	0	205	12	200	20	False	0	False	1
2	T-bar	Girder	0	Upper Deck I	3.24	6.44	2.68	g6	4	0	300	8	120	10	True	150	False	1
2	Flat bar	Stiffener	1	Upper Deck I	0.8	1.2	2.68	s2	4	1	50	6	0	0	False	0	False	1

Table 48: Input database stiffeners for LR calculations.

id__ position	type__ profile	type	type__ id	location	spacing	span	y__ dist	ref__ id	loc__ register	support	h__w	t__w	w__f	t__f	holes	hole__ height	open	N__ open
2	T-bar	Transverse	0	Bridge Deck I	2.2	2.99	5.36	t1	4	0	110	4	60	5	False	0	False	1
2	T-bar	Transverse	0	Bridge Deck E	3.6	3.76	5.36	t2	4	4	140	10	150	12	False	0	False	1
2	T-bar	Girder	0	Bridge Deck E	2.4	3.97	5.36	g1	4	3	300	10	150	15	True	150	False	1
2	T-bar	Girder	0	Bridge Deck I	2.4	8.94	5.36	g3	4	0	205	12	200	20	False	0	False	1
2	T-bar	Girder	0	Bridge Deck I	3.12	5.69	5.36	g4	4	0	300	10	150	12	True	150	False	1
2	T-bar	Girder	0	Bridge Deck I	2.4	2.07	5.36	g5	4	3	80	10	150	12	False	0	False	1
2	T-bar	Transverse	0	Hard Top	2.29	2.89	8.04	t1	3	0	110	4	60	5	False	0	False	1
2	T-bar	Transverse	0	Hard Top	7.23	1.64	8.04	t2	3	0	200	5	100	8	False	0	False	1
2	T-bar	Girder	0	Hard Top	2.4	4.23	8.04	g1	3	0	200	5	100	8	False	0	False	1
2	T-bar	Girder	0	Hard Top	3.1	4.94	8.04	g2	3	0	150	8	150	12	False	0	False	1
0	T-bar	Transverse	0	LT - Side DH	2.2	2.68	1.34	t1	0	0	150	4	60	6	False	0	False	1
0	T-bar	Transverse	0	LT - Side SP	2.0	2.68	1.7	t1	0	0	130	6	80	8	False	0	False	1
0	T-bar	Transverse	0	LT - Side DH	1.65	2.11	1.06	t1	0	0	150	4	60	6	False	0	True	2

Table 48: Input database stiffeners for LR calculations.

id__ position	type__ profile	type	type__ id	location	spacing	span	y__ dist	ref__ id	loc__ register	support	h__w	t__w	w__f	t__f	holes	hole__ height	open	N__ open
0	T-bar	Transverse	0	LT - Side DH	3.02	2.11	1.06	t1	0	0	200	5	80	8	False	0	True	2.5
0	T-bar	Transverse	0	LT - Side DH	3.41	2.11	1.06	t1	0	0	200	10	80	10	False	0	True	2.5
0	Box	Transverse	0	LT - Side DH	4.93	2.11	1.06	t1	0	0	120	20	100	10	False	0	True	1.5
0	T-bar	Transverse	0	LT - Side SP	1.1	2.68	1.7	t1	0	0	130	6	80	8	False	0	True	2
0	T-bar	Stringer	0	LT - Side DH	2.54	7.4	0.89		0	0	200	10	120	10	False	0	True	1
0	T-bar	Transverse	0	2T - Side	2.2	2.04	4.02	t1	0	0	150	4	60	6	False	0	False	1
0	T-bar	Transverse	0	2T - Side	4.12	2.2	4.02	t1	0	0	200	10	20	10	False	0	True	2.5
0	Box	Transverse	0	2T - Side	6.85	1.88	4.02	t1	0	0	120	20	100	10	False	0	True	2
0	T-bar	Transverse	0	2T - Side	2.99	2.04	4.02	t1	0	0	200	5	80	8	False	0	True	3
0	T-bar	Stringer	0	2T - Side	2.51	7.45	3.57		0	0	200	10	120	10	False	0	True	1
0	T-bar	Transverse	0	2T - Shell	2.4	1.56	4.02	t1	0	0	150	4	60	6	False	0	False	1
0	Flat bar	Stiffener	1	2T - Shell	0.8	1.2	3.57		0	1	60	6	0	0	False	0	False	1
0	T-bar	Transverse	0	3T - Shell	1.7	1.57	6.70	t1	0	0	130	4	60	6	False	0	False	1
0	T-bar	Transverse	0	3T - Shell	2.2	0.97	6.70	t1	0	0	150	4	60	6	False	0	False	1
0	T-bar	Transverse	0	3T - Shell	3.01	1.57	6.70	t1	0	0	130	8	120	10	False	0	True	2
0	T-bar	Stringer	0	3T - Shell	1.6	5.52	6.25		0	0	130	6	80	8	False	0	True	1
1	T-bar	Girder	0	TBulk FR21+600	3.6	2.68	1.75		5	0	100	10	80	12	False	0	True	2
1	Flat bar	Stiffener	1	TBulk FR21+600	0.8	2.37	1.75		5	1	100	8	0	0	False	0	True	2
1	T-bar	Stringer	0	TBulk FR21+600	2.68	2.4	2.37		5	0	100	4	50	6	False	0	True	1

Table 48: Input database stiffeners for LR calculations.

id__ position	type__ profile	type	type__ id	location	spacing	span	y__ dist	ref__ id	loc__ register	support	h__w	t__w	w__f	t__f	holes	hole__ height	open	N__ open
1	T-bar	Stringer	0	LBulk 600CLPS	2.68	2.4	2.17		5	0	100	4	50	6	False	0	True	1
1	T-bar	Transverse	0	LBulk 600CLPS	2.4	1.33	1.81	t1	5	0	100	5	80	8	False	0	False	1
1	T-bar	Transverse	0	LBulk 600CLPS	2.09	1.15	1.73	t1	5	0	100	5	80	8	False	0	True	2
1	Flat bar	Stiffener	1	LBulk 600CLPS	0.6	2.3	1.08		5	1	100	8	0	0	False	0	True	3

E. LR Output Table

Table 49: Output of plate objects for LR calculations.

Object_ID	Position	Location	Vertical Distance to Waterline [m]	Length [m]	Width [m]	Thickness [mm]	Pressure [kN/m2]
0	Deck	Upper Deck I	2.68	1.2	0.4	5	8.40
1	Deck	Upper Deck E	2.68	1.2	0.4	5	10.74
2	Deck	Bridge Deck I	5.36	1.2	0.4	5	8.40
3	Deck	Bridge Deck E	5.36	1.2	0.4	5	10.74
4	Deck	Hard Top	8.36	1.2	0.4	5	10.74
5	Deckhouse/ Superstructure	LT - Side DH	0.89	1.1	0.4	5	6.72
6	Deckhouse/ Superstructure	LT - Side SP	1.33	1.49	1.1	8	8.40
7	Deckhouse/ Superstructure	LT - Aft Ends	2.53	0.82	1.2	8	5.25
8	Deckhouse/ Superstructure	2T - Side	3.57	1.1	0.4	5	6.72
9	Deckhouse/ Superstructure	2T - Aft Ends	5.06	0.77	1.2	5	5.25
10	Deckhouse/ Superstructure	2T - Front	3.59	0.72	0.4	6	10.51
11	Deckhouse/ Superstructure	2T - Shell	2.8	1.2	0.4	5	8.40

Table 49: Output of plate objects for LR calculations.

Object_ID	Position	Location	Vertical Distance to Waterline [m]	Length [m]	Width [m]	Thickness [mm]	Pressure [kN/m2]
12	Deckhouse/ Superstructure	3T - Shell	5.4	1.2	0.4	5	8.40
13	Deckhouse/ Superstructure	3T - Aft Ends	6.64	1.22	1	5	5.25
14	Deckhouse/ Superstructure	3T - Front	6.13	2.3	0.4	6	10.51
15	Bulkhead	TBulk FR21+600	0.89	0.4	2.68	5	3.64
16	Bulkhead	LBulk 600CLPS	0.89	0.3	2.68	5	3.64

Table 50: Output of stiffeners objects for LR calculations.

Object_ ID	Type	Profile Type	Location	Spacing [m]	Span [m]	H_w [mm]	t_w [mm]	W_f [mm]	t_f [mm]	t_p [mm]	b_p [mm]	Pressure [kN/m2]	Weight [g]	Initial Z [cm3]	Required Z [cm3]	Initial I [cm4]	Required I [cm4]	Initial Aw [cm2]	Required Aw [cm2]
0	Transverse	T-bar	Upper Deck I	1000	2.99	110	4	60	5	5	622	4.20	31081.05	48.49	41.74	494.42	2.03	4.40	1.45
1	Transverse	T-bar	Upper Deck E	1200	1.69	160	5	80	8	5	452	5.37	16883.10	136.07	122.70	1685.42	15.24	8.00	2.52
2	Transverse	T-bar	Upper Deck E	1200	1.22	130	5	80	8	5	363	5.37	10227.87	104.47	63.94	1026.21	4.14	6.50	1.82
3	Transverse	T-bar	Upper Deck I	1200	2.82	200	5	80	8	5	636	4.20	36699.48	183.64	133.67	2971.63	1.93	10.00	1.64
4	Transverse	T-bar	Upper Deck E	1370	6.43	310	12	200	20	5	1152	5.37	234026.28	1271.77	506.97	25783.77	379.72	19.20	5.46
5	Transverse	T-bar	Upper Deck I	1150	3.81	200	5	80	8	5	766	4.20	56269.89	185.41	77.94	3107.52	6.15	10.00	2.13
6	Girder	T-bar	Upper Deck E	1200	4.87	300	12	200	20	5	915	5.37	160089.08	1213.46	1018.92	22092.97	1050.68	18.00	7.25

Table 50: Output of stiffeners objects for LR calculations.

Object__ ID	Type	Profile Type	Location	Spacing [m]	Span [m]	H__w [mm]	t__w [mm]	W__f [mm]	t__f [mm]	t__p [mm]	b__p [mm]	Pressure [kN/m2]	Weight [g]	Initial Z [cm3]	Required Z [cm3]	Initial I [cm4]	Required I [cm4]	Initial Aw [cm2]	Required Aw [cm2]
7	Girder	T-bar	Upper Deck E	1050	5.04	294	12	200	20	5	896	5.37	163404.86	1314.75	954.89	22413.47	1054.59	35.28	6.56
8	Girder	Box	Upper Deck E	990	4.95	200	24	200	20	5	868	5.37	175616.10	915.00	868.46	11013.77	925.19	48.00	6.08
9	Girder	Box	Upper Deck E	990	4.74	200	24	200	20	5	843	5.37	166565.97	911.49	796.33	10882.11	777.90	48.00	5.82
10	Girder	T-bar	Upper Deck I	1200	8.95	205	12	200	20	5	1200	4.20	301095.90	897.69	448.79	12293.56	195.38	24.60	5.21
11	Girder	T-bar	Upper Deck I	1620	6.44	300	8	120	10	5	1219	4.20	168576.66	420.91	313.69	10641.38	70.71	12.00	5.06
13	Stiffener	Flat bar	Upper Deck I	400	1.2	50	6	0	0	5	234	6.72	4762.80	5.24	5.16	24.55	0.06	3.00	0.37
14	Transverse	T-bar	Bridge Deck I	1100	2.99	110	4	60	5	5	642	4.20	31888.35	48.53	45.91	496.79	2.23	4.40	1.60
15	Transverse	T-bar	Bridge Deck E	1800	3.76	140	10	150	12	5	882	5.37	77256.72	297.04	227.77	3149.73	58.33	14.00	4.20
16	Girder	T-bar	Bridge Deck E	1200	3.97	300	10	150	15	5	799	5.37	99097.16	719.04	677.12	14752.61	464.00	15.00	5.91
17	Girder	T-bar	Bridge Deck I	1200	8.94	205	12	200	20	5	1200	4.20	300759.48	897.69	447.79	12293.56	194.51	24.60	5.21
18	Girder	T-bar	Bridge Deck I	1560	5.69	300	10	150	12	5	1108	4.20	158853.42	604.74	235.81	14040.13	41.49	15.00	4.31
19	Girder	T-bar	Bridge Deck I	1200	2.07	80	10	150	12	5	517	4.20	28978.97	153.63	144.04	879.04	26.84	8.00	2.41
22	Transverse	T-bar	Hard Top	1145	2.89	110	4	60	5	5	636	5.37	30587.76	48.52	45.65	496.09	4.05	4.40	1.64
23	Transverse	T-bar	Hard Top	3615	1.64	200	5	100	8	5	640	5.37	22140.00	214.27	46.41	3363.17	1.33	10.00	2.94
24	Girder	T-bar	Hard Top	1200	4.23	200	5	100	8	5	833	5.37	68126.27	217.08	102.50	3595.24	19.47	10.00	2.52
25	Girder	T-bar	Hard Top	1550	4.94	150	8	150	12	5	1007	5.37	107170.83	314.25	180.56	3689.87	46.77	12.00	3.80
27	Transverse	T-bar	LT - Side DH	1100	2.68	150	4	60	6	5	597	3.36	28546.02	81.34	23.61	1077.88	1.52	6.00	0.92
28	Transverse	T-bar	LT - Side SP	1000	2.68	130	6	80	8	8	578	4.20	43734.38	115.51	26.83	1368.55	1.72	7.80	1.04
29	Transverse	T-bar	LT - Side DH	825	2.11	150	4	60	6	5	462	3.36	18629.19	80.43	21.95	1022.79	0.44	6.00	0.54

Table 50: Output of stiffeners objects for LR calculations.

Object_ ID	Type	Profile Type	Location	Spacing [m]	Span [m]	H_w [mm]	t_w [mm]	W_f [mm]	t_f [mm]	t_p [mm]	b_p [mm]	Pressure [kN/m2]	Weight [g]	Initial Z [cm3]	Required Z [cm3]	Initial I [cm4]	Required I [cm4]	Initial Aw [cm2]	Required Aw [cm2]
30	Transverse	T-bar	LT - Side DH	1510	2.11	200	5	80	8	5	566	3.36	25465.59	182.41	50.22	2882.11	0.80	10.00	0.99
31	Transverse	T-bar	LT - Side DH	1705	2.11	200	10	80	10	5	589	3.36	32729.27	258.10	56.71	3817.86	0.90	20.00	1.12
32	Transverse	Box	LT - Side DH	2465	2.11	120	20	100	10	5	666	3.36	38340.81	187.19	49.19	1708.43	1.31	24.00	1.62
33	Transverse	T-bar	LT - Side SP	550	2.68	130	6	80	8	8	474	4.20	37714.03	114.60	29.51	1314.75	0.95	7.80	0.57
34	Stringer	T-bar	LT - Side DH	1270	7.4	200	10	120	10	5	1233	3.36	187112.70	349.71	207.81	5736.03	101.72	20.00	2.92
37	Transverse	T-bar	2T - Side	1100	2.04	150	4	60	6	5	498	3.36	19002.60	80.72	13.68	1039.58	0.51	6.00	0.70
38	Transverse	T-bar	2T - Side	2060	2.2	200	10	20	10	5	645	3.36	32224.50	150.23	74.48	2509.84	1.29	20.00	1.41
39	Transverse	Box	2T - Side	3425	1.88	120	20	100	10	5	688	3.36	34719.84	187.84	72.34	1726.85	1.14	24.00	2.00
40	Transverse	T-bar	2T - Side	1495	2.04	200	5	80	8	5	551	3.36	24207.66	182.11	55.77	2861.07	0.69	10.00	0.95
41	Stringer	T-bar	2T - Side	1255	7.45	200	10	120	10	5	1234	3.36	188477.55	349.73	208.14	5737.21	103.26	20.00	2.90
43	Transverse	T-bar	2T - Shell	1200	1.56	150	4	60	6	5	428	4.20	13057.20	80.13	10.91	1005.14	0.24	6.00	0.73
45	Transverse	T-bar	3T - Shell	850	1.57	130	4	60	6	5	383	4.20	11848.01	66.36	7.83	719.90	0.17	5.20	0.52
46	Transverse	T-bar	3T - Shell	1100	0.97	150	4	60	6	5	303	4.20	6482.03	78.52	3.87	919.46	0.03	6.00	0.41
47	Transverse	T-bar	3T - Shell	1505	1.57	130	8	120	10	5	464	4.20	19329.84	184.49	27.71	1677.41	0.31	10.40	0.92
48	Stringer	T-bar	3T - Shell	800	5.52	130	6	80	8	5	800	4.20	80779.68	113.13	91.05	1297.20	24.80	7.80	1.71
50	Girder	T-bar	TBulk FR21+600	1800	2.68	100	10	80	12	5	704	3.64	39653.28	121.42	96.48	1043.13	2.68	10.00	1.87
52	Stiffener	Flat bar	TBulk FR21+600	400	2.37	100	8	0	0	5	234	3.64	12606.03	24.37	20.12	197.87	0.58	8.00	0.37
53	Stringer	T-bar	TBulk FR21+600	1340	2.4	100	4	50	6	5	592	3.64	23716.80	42.76	28.80	402.46	1.29	4.00	1.25
54	Stringer	T-bar	LBulk 600CLPS	1340	2.4	100	4	50	6	5	592	3.64	23716.80	42.76	28.80	402.46	1.29	4.00	1.25
55	Transverse	T-bar	LBulk 600CLPS	1200	1.33	100	5	80	8	5	385	3.64	11006.42	77.21	7.92	615.32	0.11	5.00	0.62
56	Transverse	T-bar	LBulk 600CLPS	1045	1.15	100	5	80	8	5	334	3.64	8725.05	76.57	10.31	588.87	0.05	5.00	0.47
58	Stiffener	Flat bar	LBulk 600CLPS	300	2.3	100	8	0	0	5	234	3.64	12233.70	24.37	21.32	197.87	0.38	8.00	0.27

F. ABS Input Tables

Table 51: Input database plates for ABS calculations.

id_position	length	width	location	loc_dp	loc_minh	loc_t	y_dist	x_dist	k	c	t
0	1.2	0.4	Upper Deck E	2	0	0	2.68	28.0	0	1	5
0	1.2	0.4	Upper Deck I	5	0	1	2.68	28.0	0	1	5
0	1.2	0.4	Bridge Deck E	2	0	0	5.36	22.0	0	1	5
0	1.2	0.4	Bridge Deck I	5	0	1	5.36	22.0	0	1	5
0	1.1	0.4	Hard Top	3	0	3	8.36	23.2	0	1	5
1	0.4	1.1	LT - Side DH	3	2	2	1.34	11.0	0	1	5
1	0.4	1.1	LT - Side DH	3	2	2	1.34	15.4	0	1	5
1	0.4	1.1	LT - Side DH	3	2	2	1.34	19.8	0	1	5
1	0.4	1.2	LT - Side DH	3	2	2	1.34	24.4	0	1	5
1	1.0	1.55	LT - Side SP	1	2	2	1.34	28.9	0	0	8
1	3.12	1.55	LT - Side SP	1	2	2	1.34	33.1	0	0	8
1	1.1	1.55	LT - Side SP	1	2	2	1.34	37.4	0	0	8
1	0.82	1.2	LT - Aft Ends	4	2	2	1.54	5.5	0	1	8
1	0.4	1.1	2T - Side	3	2	2	4.02	15.4	0	1	5
1	0.4	1.1	2T - Side	3	2	2	4.02	19.8	0	1	5
1	0.4	1.2	2T - Side	3	2	2	4.02	24.4	0	1	5
1	0.4	1.0	2T - Side	3	2	2	4.02	28.9	0	1	5
1	0.4	1.1	2T - Side	3	2	2	4.02	33.1	0	1	5
1	0.4	1.1	2T - Side	3	2	2	4.02	35.75	0	1	5
1	0.77	1.2	2T - Aft Ends	4	2	2	4.13	8.8	0	1	5

Table 51: Input database plates for ABS calculations.

id_position	length	width	location	loc_dp	loc_minh	loc_t	y_dist	x_dist	k	c	t
1	0.4	0.72	2T - Front	2	2	2	4.04	36.3	0	1	5
1	0.4	1.1	2T - Shell	2	2	2	2.86	7.7	0	1	5
1	0.4	1.1	2T - Shell	2	2	2	2.98	12.1	0	1	5
1	0.4	1.1	2T - Shell	2	2	2	2.99	16.5	0	1	5
1	0.4	1.1	2T - Shell	2	2	2	2.73	20.95	0	1	5
1	0.4	1.2	2T - Shell	2	2	2	3.06	25.6	0	1	5
1	0.4	1.0	2T - Shell	2	2	2	3.06	30.0	0	1	5
1	0.4	1.1	2T - Shell	2	2	2	3.05	34.15	0	1	5
1	0.4	1.1	2T - Shell	2	2	2	3.02	38.5	0	1	5
1	0.4	1.1	3T - Shell	3	3	2	5.42	12.1	0	1	5
1	0.4	1.1	3T - Shell	3	3	2	5.54	16.5	0	1	5
1	0.4	1.1	3T - Shell	3	3	2	5.67	20.95	0	1	5
1	0.4	1.2	3T - Shell	3	3	2	5.66	25.6	0	1	5
1	0.4	1.0	3T - Shell	3	3	2	5.56	30.0	0	1	5
1	0.4	1.1	3T - Shell	3	3	2	5.41	34.15	0	1	5
1	1.0	1.22	3T - Aft Ends	4	3	2	6.54	17.6	0	1	5
1	0.4	2.3	3T - Front	3	3	2	6.51	31.0	0	1	5
1	0.4	2.68	TBulk FR21+600	4	2	3	1.34	23.8	0	1	5
1	0.3	2.68	LBulk 600CLPS	4	2	3	1.34	26.4	0	1	5
1	0.25	2.68	LBulk 600CLPS	4	2	3	1.34	31.55	0	1	5

Table 52: Input database stiffeners for ABS calculations.

id__ position	type__ profile	type	type__ id	location	spacing	span	loc__ register	ref__ id	h__w	t__w	w__f	t__f	holes	hole__ height	open	N__ open
0	T-bar	Transverse	0	Upper Deck I	2.0	2.99	1	t1	110	4	60	5	False	0	False	1
0	T-bar	Transverse	0	Upper Deck E	2.4	1.69	1	t2	160	5	80	8	False	0	False	1
0	T-bar	Transverse	0	Upper Deck I	2.4	2.82	1	t3	200	5	80	8	False	0	True	3
0	T-bar	Transverse	0	Upper Deck E	2.74	5.09	1	t4	310	12	200	20	True	150	False	1
0	T-bar	Transverse	0	Upper Deck I	2.3	3.81	1	t5	200	5	80	8	False	0	False	1
0	T-bar	Girder	0	Upper Deck E	2.4	4.87	0	g1	300	12	200	20	True	150	False	1
0	T-bar	Girder	0	Upper Deck E	2.1	5.04	0	g2	294	12	200	20	False	0	False	1
0	Box	Girder	0	Upper Deck E	1.98	4.95	0	g3	200	24	200	20	False	0	True	1
0	Box	Girder	0	Upper Deck E	1.98	4.74	0	g4	200	24	200	20	False	0	False	1
0	T-bar	Girder	0	Upper Deck I	2.4	8.95	0	g5	205	12	200	20	False	0	False	1
0	T-bar	Girder	0	Upper Deck I	3.24	6.44	0	g6	300	8	120	10	True	150	False	1
0	Flat bar	Stiffener	1	Upper Deck E	0.8	1.2	1	s2	50	6	0	0	False	0	False	1
0	T-bar	Transverse	0	Bridge Deck I	2.2	2.99	1	t1	110	4	60	5	False	0	False	1

Table 52: Input database stiffeners for ABS calculations.

id__ position	type__ profile	type	type__ id	location	spacing	span	loc__ register	ref__ id	h__w	t__w	w__f	t__f	holes	hole__ height	open	N__ open
0	T-bar	Transverse	0	Bridge Deck E	3.6	3.76	1	t2	140	10	150	12	False	0	False	1
0	T-bar	Girder	0	Bridge Deck E	2.4	3.97	0	g1	300	10	150	15	True	150	False	1
0	T-bar	Girder	0	Bridge Deck E	3.32	8.97	0	g2	300	10	150	15	True	150	True	1
0	T-bar	Girder	0	Bridge Deck I	2.4	8.94	0	g3	205	12	200	20	False	0	False	1
0	T-bar	Girder	0	Bridge Deck I	3.12	5.69	0	g4	300	10	150	12	True	150	False	1
0	T-bar	Girder	0	Bridge Deck E	2.4	2.07	0	g5	80	10	150	12	False	0	False	1
0	T-bar	Transverse	0	Hard Top	2.29	2.89	1	t1	110	4	60	5	False	0	False	1
0	T-bar	Transverse	0	Hard Top	7.23	1.64	1	t2	200	5	100	8	False	0	False	1
0	T-bar	Girder	0	Hard Top	2.4	4.23	0	g1	200	5	100	8	False	0	False	1
0	T-bar	Girder	0	Hard Top	3.1	4.94	0	g2	150	8	150	12	False	0	False	1
1	T-bar	Transverse	0	LT - Side DH	2.2	2.68	0	t1	150	4	60	6	False	0	False	1
1	T-bar	Transverse	0	LT - Side DH	1.65	2.11	0	t1	150	4	60	6	False	0	True	2
1	T-bar	Transverse	0	LT - Side SP	2.0	2.68	0	t1	130	6	80	8	False	0	False	1

Table 52: Input database stiffeners for ABS calculations.

id__ position	type__ profile	type	type__ id	location	spacing	span	loc__ register	ref__ id	h__w	t__w	w__f	t__f	holes	hole__ height	open	N__ open
1	T-bar	Transverse	0	LT - Side DH	3.02	2.11	0	t1	200	5	80	8	False	0	True	2.5
1	T-bar	Transverse	0	LT - Side DH	3.41	2.11	0	t1	200	10	80	10	False	0	True	2.5
1	Box	Transverse	0	LT - Side DH	4.93	1.95	0	t1	120	20	100	10	False	0	True	1.5
1	T-bar	Transverse	0	LT - Side SP	1.1	2.68	0	t1	130	6	80	8	False	0	True	2
1	T-bar	Stringer	0	LT - Side DH	2.54	7.4	0		200	10	120	10	False	0	True	1
1	T-bar	Transverse	0	2T - Side	2.2	2.04	0	t1	150	4	60	6	False	0	False	1
1	T-bar	Transverse	0	2T - Side	4.12	2.2	0	t1	200	10	20	10	False	0	True	2.5
1	Box	Transverse	0	2T - Side	6.85	1.88	0	t1	120	20	100	10	False	0	True	2
1	T-bar	Transverse	0	2T - Side	2.99	2.04	0	t1	200	5	80	8	False	0	True	3
1	T-bar	Stringer	0	2T - Side	2.51	7.45	0		200	10	120	10	False	0	True	1
1	T-bar	Transverse	0	2T - Shell	2.4	1.56	0	t1	150	4	60	6	False	0	False	1
1	T-bar	Transverse	0	3T - Shell	1.7	1.57	0	t1	130	4	60	6	False	0	False	1
1	T-bar	Transverse	0	3T - Shell	2.2	0.97	0	t1	150	4	60	6	False	0	False	1
1	T-bar	Transverse	0	3T - Shell	3.01	1.57	0	t1	130	8	120	10	False	0	True	2
1	T-bar	Stringer	0	3T - Shell	1.6	5.52	0		130	6	80	8	False	0	True	1
1	T-bar	Stringer	0	TBulk FR21+600	2.68	2.4	0		100	4	50	6	False	0	False	1
1	T-bar	Girder	0	TBulk FR21+600	3.6	2.68	0		100	10	80	12	False	0	False	1
1	Flat bar	Stiffener	1	TBulk FR21+600	0.8	2.37	0		100	8	0	0	False	0	False	1

Table 52: Input database stiffeners for ABS calculations.

id__ position	type__ profile	type	type__ id	location	spacing	span	loc__ register	ref__ id	h__w	t__w	w__f	t__f	holes	hole__ height	open	N__ open
1	T-bar	Stringer	0	LBulk 600CLPS	2.68	2.4	0		100	4	50	6	False	0	False	1
1	T-bar	Transverse	0	LBulk 600CLPS	2.4	1.33	0	t1	100	5	80	8	False	0	False	1
1	T-bar	Transverse	0	LBulk 600CLPS	2.09	1.15	0	t1	100	5	80	8	False	0	True	2
1	Flat bar	Stiffener	1	LBulk 600CLPS	0.6	2.3	0		100	8	0	0	False	0	True	3

G. ABS Output Table

Table 53: Output of plate objects for ABS calculations.

Object_ID	Position	Location	Vertical Distance to Waterline [m]	Horizontal Distance to AP [m]	Length [m]	Width [m]	Thickness [mm]	Head [m]
0	Deck	Upper Deck E	2.68	28.00	1.20	0.40	5	0.98
1	Deck	Upper Deck I	2.68	28.00	1.20	0.40	5	0.35
2	Deck	Bridge Deck E	5.36	22.00	1.20	0.40	5	0.98
3	Deck	Bridge Deck I	5.36	22.00	1.20	0.40	5	0.35
4	Deck	Hard Top	8.36	23.20	1.10	0.40	5	0.67
5	Bulkhead	LT - Side DH	1.34	11.00	0.40	1.10	5	1.51
6	Bulkhead	LT - Side SP	1.34	28.90	1.00	1.55	8	1.51
7	Bulkhead	LT - Aft Ends	1.54	5.50	0.82	1.20	8	1.51
8	Bulkhead	2T - Side	4.02	15.40	0.40	1.10	5	1.51
9	Bulkhead	2T - Aft Ends	4.13	8.80	0.77	1.20	5	1.51
10	Bulkhead	2T - Front	4.04	36.30	0.40	0.72	5	1.51
11	Bulkhead	2T - Shell	2.86	7.70	0.40	1.10	5	1.51
12	Bulkhead	3T - Shell	5.42	12.10	0.40	1.10	5	1.50
13	Bulkhead	3T - Aft Ends	6.54	17.60	1.00	1.22	6	1.50
14	Bulkhead	3T - Front	6.51	31.00	0.40	2.30	5	1.50
15	Bulkhead	TBulk FR21+600	1.34	23.80	0.40	2.68	5	1.51
16	Bulkhead	LBulk 600CLPS	1.34	26.40	0.30	2.68	5	1.51

Table 54: Output of stiffeners objects for ABS calculations.

Object_ID	Position	Type	Profile Type	Location	Spacing [m]	Span [m]	H__w [mm]	t__w [mm]	W__f [mm]	t__f [mm]	t__p [mm]	b__p [mm]	Head [m]	Weight [g]	Initial Z [cm3]	Required Z [cm3]
0	Deck	Transverse	T-bar	Upper Deck I	1.00	2.99	110	4	60	5	5	500	0.35	26156.52	48.14	23.40
1	Deck	Transverse	T-bar	Upper Deck E	1.20	1.69	160	5	80	8	5	557	0.98	19278.68	137.71	25.19
2	Deck	Transverse	T-bar	Upper Deck I	1.20	2.82	200	5	80	8	5	600	0.35	35328.96	183.04	74.94
3	Deck	Transverse	T-bar	Upper Deck E	1.37	5.09	310	12	200	20	5	685	0.98	153165.74	1225.32	260.89
4	Deck	Transverse	T-bar	Upper Deck I	1.15	3.81	200	5	80	8	5	575	0.35	46445.81	182.58	43.70
5	Deck	Girder	T-bar	Upper Deck E	1.20	4.87	300	12	200	20	5	600	0.98	139379.40	1096.61	262.51
6	Deck	Girder	T-bar	Upper Deck E	1.05	5.04	294	12	200	20	5	525	0.98	138162.02	1012.27	246.01
7	Deck	Girder	Box	Upper Deck E	0.99	4.95	200	24	200	20	5	495	0.98	150690.38	719.71	223.74
8	Deck	Girder	Box	Upper Deck E	0.99	4.74	200	24	200	20	5	495	0.98	144297.45	719.71	205.16
9	Deck	Girder	T-bar	Upper Deck I	1.20	8.95	205	12	200	20	5	600	0.35	228600.90	743.43	315.74
10	Deck	Girder	T-bar	Upper Deck I	1.62	6.44	300	8	120	10	5	750	0.35	127801.80	412.37	220.69
12	Deck	Stiffener L	Flat bar	Upper Deck E	0.40	1.20	50	6	0	0	5	200	0.98	4212.00	5.18	4.23
13	Deck	Transverse	T-bar	Bridge Deck I	1.10	2.99	110	4	60	5	5	550	0.35	28174.77	48.30	25.74

Table 54: Output of stiffeners objects for ABS calculations.

Object_ID	**Position**	**Type**	**Profile Type**	**Location**	**Spacing [m]**	**Span [m]**	**H_w [mm]**	**t_w [mm]**	**W_f [mm]**	**t_f [mm]**	**t_p [mm]**	**b_p [mm]**	**Head [m]**	**Weight [g]**	**Initial Z [cm3]**	**Required Z [cm3]**
14	Deck	Transverse	T-bar	Bridge Deck E	1.80	3.76	140	10	150	12	5	750	0.98	70556.40	293.77	187.04
15	Deck	Girder	T-bar	Bridge Deck E	1.20	3.97	300	10	150	15	5	600	0.98	88431.75	705.78	174.45
16	Deck	Girder	T-bar	Bridge Deck E	1.66	8.97	300	10	150	15	5	750	0.98	217971.00	716.29	1231.97
17	Deck	Girder	T-bar	Bridge Deck I	1.20	8.94	205	12	200	20	5	600	0.35	228345.48	743.43	315.03
18	Deck	Girder	T-bar	Bridge Deck I	1.56	5.69	300	10	150	12	5	750	0.35	131353.65	592.54	165.90
19	Deck	Girder	T-bar	Bridge Deck E	1.20	2.07	80	10	150	12	5	600	0.98	31298.40	155.47	47.43
22	Deck	Transverse	T-bar	Hard Top	1.15	2.89	110	4	60	5	5	572	0.67	28090.80	48.36	48.12
23	Deck	Transverse	T-bar	Hard Top	3.62	1.64	200	5	100	8	5	541	0.67	19948.14	212.18	48.92
24	Deck	Girder	T-bar	Hard Top	1.20	4.23	200	5	100	8	5	600	0.67	54820.80	213.50	135.58
25	Deck	Girder	T-bar	Hard Top	1.55	4.94	150	8	150	12	5	750	0.67	90031.50	308.93	238.85
27	Bulkhead	Transverse	T-bar	LT - Side DH	1.10	2.68	150	4	60	6	5	550	1.51	26845.56	81.07	77.00
28	Bulkhead	Transverse	T-bar	LT - Side DH	0.83	2.11	150	4	60	6	5	412	1.51	17204.94	79.97	71.60
29	Bulkhead	Transverse	T-bar	LT - Side SP	1.00	2.68	130	6	80	8	8	500	1.51	39219.12	114.86	70.00

Table 54: Output of stiffeners objects for ABS calculations.

Object_ID	Position	Type	Profile Type	Location	Spacing [m]	Span [m]	H_w [mm]	t_w [mm]	W_f [mm]	t_f [mm]	t_p [mm]	b_p [mm]	Head [m]	Weight [g]	Initial Z [cm3]	Required Z [cm3]
30	Bulkhead	Transverse	T-bar	LT - Side DH	1.51	2.11	200	5	80	8	5	696	1.51	29168.64	184.53	163.80
31	Bulkhead	Transverse	T-bar	LT - Side DH	1.71	2.11	200	10	80	10	5	696	1.51	35777.16	262.15	184.95
32	Bulkhead	Transverse	Box	LT - Side DH	2.47	1.95	120	20	100	10	5	643	1.51	34827.98	186.47	137.03
33	Bulkhead	Transverse	T-bar	LT - Side SP	0.55	2.68	130	6	80	8	8	275	1.51	26194.32	111.30	77.00
34	Bulkhead	Stringer	T-bar	LT - Side DH	1.27	7.40	200	10	120	10	5	635	1.51	127372.50	332.88	677.80
37	Bulkhead	Transverse	T-bar	2T - Side	1.10	2.04	150	4	60	6	5	550	1.51	20434.68	81.07	44.62
38	Bulkhead	Transverse	T-bar	2T - Side	2.06	2.20	200	10	20	10	5	726	1.51	34630.20	152.02	242.93
39	Bulkhead	Transverse	Box	2T - Side	3.43	1.88	120	20	100	10	5	620	1.51	32994.00	185.72	235.96
40	Bulkhead	Transverse	T-bar	2T - Side	1.50	2.04	200	5	80	8	5	673	1.51	27567.54	184.21	181.91
41	Bulkhead	Stringer	T-bar	2T - Side	1.26	7.45	200	10	120	10	5	627	1.51	127428.53	332.50	678.88
43	Bulkhead	Transverse	T-bar	2T - Shell	1.20	1.56	150	4	60	6	5	514	1.51	14868.36	80.83	28.46
45	Bulkhead	Transverse	T-bar	3T - Shell	0.85	1.57	130	4	60	6	5	425	1.50	12738.20	66.69	20.27
46	Bulkhead	Transverse	T-bar	3T - Shell	1.10	0.97	150	4	60	6	5	320	1.50	6704.64	78.80	10.01
47	Bulkhead	Transverse	T-bar	3T - Shell	1.51	1.57	130	8	120	10	5	518	1.50	20474.37	186.06	71.76
48	Bulkhead	Stringer	T-bar	3T - Shell	0.80	5.52	130	6	80	8	5	400	1.50	50971.68	109.01	235.78
50	Bulkhead	Stringer	T-bar	TBulk FR21+600	1.34	2.40	100	4	50	6	5	670	1.51	26244.00	42.91	75.22
51	Bulkhead	Girder	T-bar	TBulk FR21+600	1.80	2.68	100	10	80	12	5	750	1.51	41317.56	121.89	126.00
53	Bulkhead	Stiffener L	Flat bar	TBulk FR21+600	0.40	2.37	100	8	0	0	5	200	1.51	11518.20	23.92	21.90

Table 54: Output of stiffeners objects for ABS calculations.

Object_ID	**Position**	**Type**	**Profile Type**	**Location**	**Spacing [m]**	**Span [m]**	**H__w [mm]**	**t__w [mm]**	**W__f [mm]**	**t__f [mm]**	**t__p [mm]**	**b__p [mm]**	**Head [m]**	**Weight [g]**	**Initial Z [cm3]**	**Required Z [cm3]**
54	Bulkhead	Stringer	T-bar	LBulk 600CLPS	1.34	2.40	100	4	50	6	5	670	1.51	26244.00	42.91	75.22
55	Bulkhead	Transverse	T-bar	LBulk 600CLPS	1.20	1.33	100	5	80	8	5	438	1.51	11958.03	77.73	20.69
56	Bulkhead	Transverse	T-bar	LBulk 600CLPS	1.05	1.15	100	5	80	8	5	379	1.51	9423.68	77.14	26.94
58	Bulkhead	Stiffener L	Flat bar	LBulk 600CLPS	0.30	2.30	100	8	0	0	5	150	1.51	9625.50	23.01	46.40

H. Optimization Output Table

Table 55: Output for optimized reinforcements using LR requirements.

Object_ ID	Type	Profile Type	Location	Spacing [mm]	Span [m]	H_w [mm]	t_w [mm]	W_f [mm]	t_f [mm]	t_p [mm]	b_p [mm]	Pressure [kN/m2]	Initial Weight [g]	Final Weight [g]	Initial Z [cm3]	Final Z [cm3]	Required Z [cm3]	Iterations
0	Transverse	T-bar	Upper Deck I	1000	2.99	110	4	60	4	5	622	4.20	31081.05	30596.67	48.49	42.08	41.74	2
1	Transverse	T-bar	Upper Deck E	1200	1.69	160	4	98	7	5	452	5.37	16883.10	16362.92	136.07	137.26	122.70	5
2	Transverse	T-bar	Upper Deck E	1200	1.22	130	4	74	5	5	363	5.37	10227.87	8910.27	104.47	67.65	63.94	2
3	Transverse	T-bar	Upper Deck I	1200	2.82	200	4	83	6	5	636	4.20	36699.48	34095.49	183.64	146.55	133.67	3
4	Transverse	T-bar	Upper Deck E	1370	6.43	300	6	158	10	5	1152	5.37	234026.28	158679.54	1271.77	517.31	506.97	3
5	Transverse	T-bar	Upper Deck I	1150	3.81	168	4	64	4	5	766	4.20	56269.89	48945.55	185.41	78.66	77.94	5
6	Girder	T-bar	Upper Deck E	1200	4.87	300	6	200	17	5	915	5.37	160089.08	128531.48	1213.46	1030.65	1018.92	2
7	Girder	T-bar	Upper Deck E	1050	5.04	294	6	196	15	5	896	5.37	163404.86	124975.87	1314.75	959.84	954.89	2
8	Girder	Box	Upper Deck E	990	4.95	200	8	200	22	5	868	5.37	175616.10	138194.10	915.00	892.67	868.46	2
9	Girder	Box	Upper Deck E	990	4.74	200	8	200	20	5	843	5.37	166565.97	125612.37	911.49	823.51	796.33	2
10	Girder	T-bar	Upper Deck I	1200	8.95	205	5	137	15	5	1200	4.20	301095.90	219418.20	897.69	473.40	448.79	4
11	Girder	T-bar	Upper Deck I	1620	6.44	300	6	119	8	5	1219	4.20	168576.66	153831.64	420.91	334.32	313.69	2
13	Stiffener	Flat bar	Upper Deck I	400	1.2	50	6	0	0	5	234	6.72	4762.80	4762.80	5.24	5.24	5.16	3
14	Transverse	T-bar	Bridge Deck I	1100	2.99	110	4	60	5	5	642	4.20	31888.35	31888.35	48.53	48.53	45.91	3
15	Transverse	T-bar	Bridge Deck E	1800	3.76	140	4	94	16	5	882	5.37	77256.72	65724.05	297.04	229.89	227.77	7

Table 55: Output for optimized reinforcements using LR requirements.

Object_ ID	Type	Profile Type	Location	Spacing [mm]	Span [m]	H_w [mm]	t_w [mm]	W_f [mm]	t_f [mm]	t_p [mm]	b_p [mm]	Pressure [kN/m2]	Initial Weight [g]	Final Weight [g]	Initial Z [cm3]	Final Z [cm3]	Required Z [cm3]	Iterations
16	Girder	T-bar	Bridge Deck E	1200	3.97	300	6	186	12	5	799	5.37	99097.16	86041.41	719.04	697.36	677.12	5
17	Girder	T-bar	Bridge Deck I	1200	8.94	205	5	137	15	5	1200	4.20	300759.48	219173.04	897.69	473.40	447.79	4
18	Girder	T-bar	Bridge Deck I	1560	5.69	300	6	100	7	5	1108	4.20	158853.42	123518.52	604.74	259.66	235.81	3
19	Girder	T-bar	Bridge Deck I	1200	2.07	80	4	54	27	5	517	4.20	28978.97	24384.81	153.63	119.44	144.04	24
22	Transverse	T-bar	Hard Top	1145	2.89	110	4	60	5	5	636	5.37	30587.76	30587.76	48.52	48.52	45.65	3
23	Transverse	T-bar	Hard Top	3615	1.64	130	4	49	4	5	640	5.37	22140.00	17340.05	214.27	47.10	46.41	8
24	Girder	T-bar	Hard Top	1200	4.23	199	4	66	5	5	833	5.37	68126.27	60428.51	217.08	114.79	102.50	3
25	Girder	T-bar	Hard Top	1550	4.94	150	4	101	11	5	1007	5.37	107170.83	89978.15	314.25	192.80	180.56	4
27	Transverse	T-bar	LT - Side DH	1100	2.68	145	4	47	4	5	597	3.36	28546.02	27156.71	81.34	53.77	53.12	3
28	Transverse	T-bar	LT - Side SP	1000	2.68	130	4	59	4	8	578	4.20	43734.38	38929.68	115.51	53.76	53.65	3
29	Transverse	T-bar	LT - Side DH	825	2.11	141	4	44	4	5	462	3.36	18629.19	17375.85	80.43	49.43	49.39	3
30	Transverse	T-bar	LT - Side DH	1510	2.11	200	4	73	5	5	566	3.36	25465.59	22759.52	182.41	120.43	113.00	3
31	Transverse	T-bar	LT - Side DH	1705	2.11	200	4	80	6	5	589	3.36	32729.27	24069.83	258.10	142.55	127.59	3
32	Transverse	Box	LT - Side DH	2465	2.11	120	8	102	7	5	666	3.36	38340.81	28507.79	187.19	118.08	110.68	4
33	Transverse	T-bar	LT - Side SP	550	2.68	130	4	67	5	8	474	4.20	37714.03	33625.69	114.60	66.19	59.02	3
34	Stringer	T-bar	LT - Side DH	1270	7.4	200	4	113	8	5	1233	3.36	187112.70	157222.62	349.71	229.45	207.81	2
37	Transverse	T-bar	2T - Side	1100	2.04	105	4	40	4	5	498	3.36	19002.60	16909.56	80.72	30.96	30.78	7
38	Transverse	T-bar	2T - Side	2060	2.2	200	4	99	7	5	645	3.36	32224.50	28024.92	150.23	184.00	167.58	19
39	Transverse	Box	2T - Side	3425	1.88	120	8	120	10	5	688	3.36	34719.84	28425.60	187.84	172.82	162.77	5
40	Transverse	T-bar	2T - Side	1495	2.04	200	4	80	5	5	551	3.36	24207.66	21784.14	182.11	127.01	125.49	2
41	Stringer	T-bar	2T - Side	1255	7.45	200	4	113	8	5	1234	3.36	188477.55	158385.51	349.73	229.45	208.14	2
43	Transverse	T-bar	2T - Shell	1200	1.56	90	4	33	4	5	428	4.20	13057.20	11085.98	80.13	22.36	21.82	11

Table 55: Output for optimized reinforcements using LR requirements.

Object_ ID	Type	Profile Type	Location	Spacing [mm]	Span [m]	H_w [mm]	t_w [mm]	W_f [mm]	t_f [mm]	t_p [mm]	b_p [mm]	Pressure [kN/m2]	Initial Weight [g]	Final Weight [g]	Initial Z [cm3]	Final Z [cm3]	Required Z [cm3]	Iterations
45	Transverse	T-bar	3T - Shell	850	1.57	80	4	30	4	5	383	4.20	11848.01	9982.85	66.36	17.93	17.83	8
46	Transverse	T-bar	3T - Shell	1100	0.97	55	4	22	4	5	303	4.20	6482.03	4774.44	78.52	8.93	8.81	7
47	Transverse	T-bar	3T - Shell	1505	1.57	130	4	73	5	5	464	4.20	19329.84	13586.00	184.49	67.80	63.13	3
48	Stringer	T-bar	3T - Shell	800	5.52	130	4	87	7	5	800	4.20	80779.68	76442.62	113.13	100.12	91.05	3
50	Girder	T-bar	TBulk FR21+600	1800	2.68	100	4	67	13	5	704	3.64	39653.28	34667.68	121.42	98.56	96.48	3
52	Stiffener	Flat bar	TBulk FR21+600	400	2.37	99	7	0	0	5	234	3.64	12606.03	11921.34	24.37	21.24	20.12	2
53	Stringer	T-bar	TBulk FR21+600	1340	2.4	100	4	40	4	5	592	3.64	23716.80	22809.60	42.76	29.08	28.80	3
54	Stringer	T-bar	LBulk 600CLPS	1340	2.4	100	4	40	4	5	592	3.64	23716.80	22809.60	42.76	29.08	28.80	3
55	Transverse	T-bar	LBulk 600CLPS	1200	1.33	78	4	31	4	5	385	3.64	11006.42	8478.35	77.21	17.62	17.07	4
56	Transverse	T-bar	LBulk 600CLPS	1045	1.15	86	4	38	4	5	334	3.64	8725.05	6725.43	76.57	22.47	22.23	4
58	Stiffener	Flat bar	LBulk 600CLPS	300	2.3	102	7	0	0	5	234	3.64	12233.70	11699.64	24.37	22.45	21.32	2