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Design of the Hull Structure of Double-Ended Ferries for the Adriatic

Abstract

The main topic of this paper is a hull structure design of an 80 m double-ended ferry, intended for navigation in the Adriatic Sea. The structural ship elements were dimensioned according to the rules of the Croatian Ship Register using the Mathcad software. The preliminary drawing of the main midship frame was made in AutoCAD. Then follows the verification of previously calculated primary structural elements using beam finite element method model (DNV 3D-Beam software). The obtained results of main deck model and the racking model meet the strength criteria. Docking stress of the bottom structure was also checked and meets the strength criteria. Furthermore, the distribution of global longitudinal stresses in midship section is verified using the finite element method in DNV GeniE software.

Keywords: passenger ferry, structural design, *FEA*

1. Introduction

In recent years, the development of road infrastructure and a constantly increasing number of vehicles has also had a positive influence on the development of maritime passenger transport. Passenger transport on ferries, therefore, led to an important expansion of ferries and Ro-Pax fleet, but also to an important development of port infrastructure [1]. In the last few years, the world fleet of ferry ships has grown in three directions: the construction of comfortable ferries relatively fast, intended for the night and fairly long routes; superfast ferries used exclusively for daytime travel, Ro-Pax ferries designed primarily for the transport of commercial and private vehicles and passengers and Ro-Ro ferries for short intesive sailling routes for veichles and passsangers with mutual loading and unloading ramps at both ends, so celled double-ended ferries. As a result, this opens up space for the shipbuilding, in terms of designing and building such ferries. Although all the mentioned types of ferries are interesting for the Adriatic Sea, due to the indented coast, numerous inhabited islands and the tourist orientation of Croatia, specific double-ended ferries are of special interest. The process of ship design combines wide range of disciplines, analysis methods and software used, and by no doubts it should be methodically approached. The ship design may be considered as being composed of four main phases: a concept design, a preliminary design, a contractual design, and detailed design [2]. The first two phases are also known as basic design. Therefore, the objectives of this paper are part of ship designing process called ship structural design. Within structure design process the aims are to determine the dimensions of the structural elements of the ferry in accordance with the rules of the classification society [3], [4], the calculation and verification of the primary structural elements of the ferry under local loads using appropriate finite element (FE) model, and the assessment of the distribution of global longitudinal stresses in the structure of the ferry using finite element method (FEM).

During preliminary design of the structure, which often takes place in a limited period of time, in which the design office does not have enough time to create a detailed computer model of the structure, use the number of different software tools is inevitable. Therefore, the paper uses *Mathcad* to code and speed up the calculation of the structure's dimensions according to the rules, *NAPA* [5] and *DNV 3D beam* to check the primary longitudinal structure, *DNV Nauticus Hull* [6] *and SESAM* [7] modules such as *GeniE, SESTRA* and *Xtract* as *FEA* tool and/or to check the possibility of including the primary longitudinal structural elements above the main deck in the calculation of the ship's longitudinal strength.

2. Project requirements

One of the usual steps when the preliminary ship design is elaborated is data gathering of built similar ships. Data to be gathered may include a ship type, size, deadweight, speed, main engine power, etc. These data are available in various publications or databases. Until present days, a lot of databases were made in which ship's basic parameters were gathered and analyzed. These studies were mostly made for cargo ships, i.e. containerships, bulk carriers, tankers, general cargo ships [8] [9], [10], and only few were focused on Ro-Pax and double-ended ferries [11], [12]. As a result of designers thinking based on shipowner request main particulars of ferries are defined, Table 1. Subject of this paper is a Ro-Ro passenger ship designed with double-ended loading and unloading ramps, featuring bow-stern symmetry. It serves the purpose of transporting passengers, cars, and heavy vehicles, with vehicle and passenger embarkation and disembarkation taking place via ramps positioned at both the bow and stern. The ship has a design speed of 12 knots, with a mean draft of 2.4 meters. It features six decks, with vehicles stowed at the double bottom (Deck 1) and the main deck (Deck 2). The third and fourth decks accommodate passenger lounges and crew quarters. The fifth deck houses an anti-roll tank designed to enhance navigation comfort, with the wheelhouse positioned above it.

Table 1: Main ship particulars

Length overall	L_{OA}	79,5	m
Width	B	18	m
Height to the main deck	D	4,6	m
Draft, mean	T_1	2,4	m
Draft, max.	T	2,6	m
Block Coefficient	C_B	0,68	

The frame spacing is set at 600 mm, with every fourth frame designated as a primary frame. In the determination of vehicle capacity on the main deck, conventional dimensions for heavy vehicles (16m x 2.50m) were applied to ascertain the maximum cargo load capacity. Within the enclosed garage located on the first deck, standard parking dimensions were employed, measuring 4.65 m in length and 2.20 m in width. This measurement comprehensively includes 0.40 m of spacing between vehicles. As for heavy vehicles on the main deck, the interspacing, both crosswise and longitudinally, extends to 0.60 m. Consequently, the main deck has the capacity to accommodate 12 heavy vehicles and 10 passenger cars, or alternatively, 96 passenger cars. In parallel, the top deck has the capability to house up to 41 passenger cars.

3. Scantlings determination according to the classification society rules

The structural dimensioning in this paper adhered to the guidelines of the Croatian Register of Shipping (CRS) for the Technical Supervision of Maritime Vessels. The ferry utilized a combination construction system, employing longitudinal construction for the double bottom and decks, while the sides and the external hull beyond the first deck were constructed transversely. The structural connection between the hull and superstructure was established with side frames and hull plating, necessitating special attention.

The initial step in dimensioning the structure was to determine the loads on the ship's construction. There are green sea loads, cargo and accommodation deck load, tank structure loads, and acceleration-induced loads. Following this, a calculation of the main frame longitudinal strength was conducted, following the Register's guidelines. The calculation was performed using the *Mathcad* software tool, and detailed calculation is outlined in [13]. Figure 1 illustrates midship section structural arrangement, and its detailed design can be found in [13].

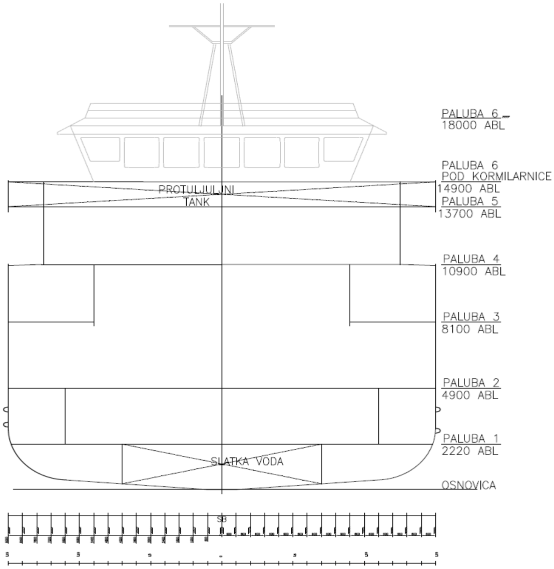


Figure 1: Midship section arrangement

3.1 Hull Material

Two types of shipbuilding steel are used as material for the construction of the ferry's hull: ordinary steel and high-strength steel. By using high-strength shipbuilding steel, we reduce the overall weight of the ship, since its mechanical properties allow the application of thinner plating and elements with a smaller cross-section. High-strength steel with a tensile strength of 355 N/mm^2, is used for the construction of the second and third decks. For other parts of the hull, shipbuilding steel of normal strength of tensile strength 235 N/mm^2, is used.

3.2. Longitudinal strength

Loads cause ship bending and the appearance of transverse forces and bending moments in individual ship's girder cross sections. In the longitudinal members of the ship structure, bending moments cause normal stresses, while transverse forces cause shear stresses.

Calm water bending moments are defined by the distribution of weight and buoyancy along the ship. Bending moment and shear stresses were obtained from diagram produced in the NAPA software, Figure 2. The bending moment curve is the second integral of the load curve. The highest bending moment is located at the midpoint of the ship, with the highest shear forces occurring at approximately 20% and 80% of the ship's length measured from the bow perpendicular. To be on safe side, in collaboration with the ship-owner, the design bending moment and the selected shear forces were substantially increased from the initial values to ensure alignment with the final specifications.

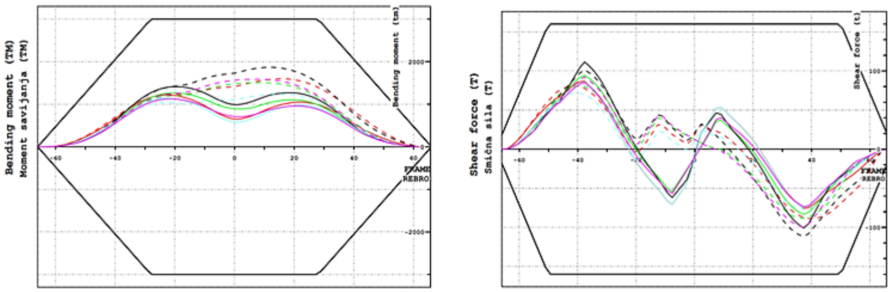


Figure 2: Bending moments (left) and shear forces (right)

Section modulus of the main frame was calculated using the Nauticus Hull software. For the purposes of calculation, only the longitudinal elements of the structure were modelled. Deck section modulus, comparing to bottom section modulus, due to its smaller value, was relevant for dimensioning.

4. Primary structure verification under local loads

DNV 3D Beam is an application for linear static analysis of 2D and 3D beam structures developed by *DNV*, distributed as part of the *Nauticus* program. It is a quicker tool for evaluating primary supports compared to the *FEM*. The primary ship structure is idealized in a beam model with nodes and beams. The program is based on the matrix displacement method. Elastic beams are analysed as so-called Timoshenko beams. In strength analysis, the actual ship structure is replaced by a mathematical model. The portion of the structure being analysed is isolated, and the influence of the remaining part of the structure is substituted by boundary conditions.

Three models were created using the 3D-Beam software: beam model of the main deck's primary structure, a model of the side frame of the garage space and superstructure, and a bulkhead model used to examine the stress in the bottom structure during docking. All 3D Beam models were created based on scantlings calculated according to the CRS. The allowable stresses in calculations with beam finite element models are defined by the rules of the Register.

4.1. Main deck

Deck 2 is the main deck. Midship was modelled from frame -16 to frame 16 (Figure 3). The grid-like primary structure of the main deck consists of T-profile beams with web plate dimensions of 550 x 15 mm and flanges of 250 x 22 mm.

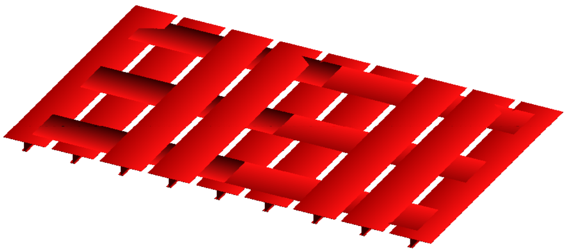


Figure 3: Main deck 3D Beam model

Due to height constraints within the lower garage area, high-strength shipbuilding steel was employed to minimize the height of the transverse girders. In this paper, structural vibration analysis hasn't been verified, allowing for potential refinement of structural solutions.

Local load (LC3) of the main deck's primary structure model is composed of a combination of the following fundamental loads: self-weight (LC1), maximum static axial loading (LC2), all increased by the dynamic coefficient due to the ship's motion on waves.

In the case of the maximum static axial loading (LC2), the deck structure is transversely loaded with a force of 44 N/mm, Figure 4) simulating the axial loading of the heaviest anticipated cargo type that the ferry will transport, trucks.

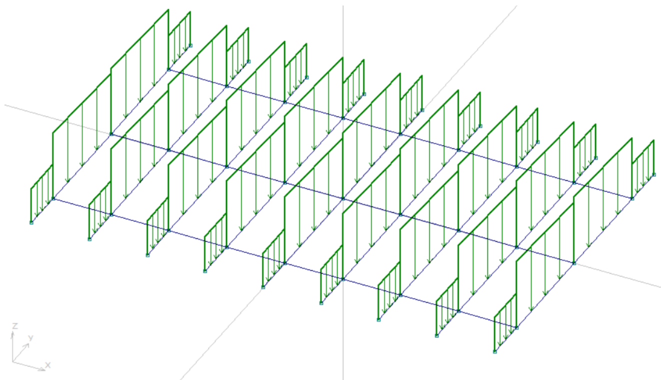
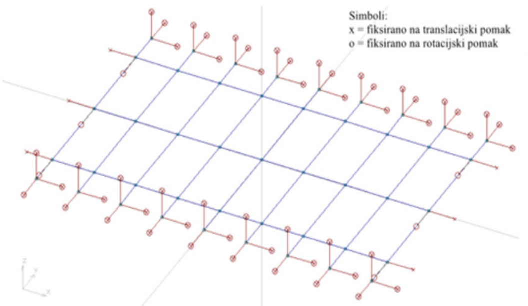


Figure 4: Main deck loads

Fixed boundary conditions are applied at the connection of the primary transverse deck and side girders. Boundary conditions which prevent longitudinal translation and transverse rotation are applied at longitudinal girders, due to their continuity beyond the boundaries of the computational model. Boundary conditions of the main deck model are shown in Figure 5.



		R0, R4, R8, R12, R16, R-4, R-8, R-12, R-16	L0, L-8, L8
Translation	X	Fixed	Fixed
	Y	Fixed	Free
	Z	Fixed	Free
Rotation	X	Fixed	Free
	Y	Fixed	Fixed
	Z	Fixed	Free

Figure 5: Boundary conditions

The results obtained from stress analysis in 3D-Beam must be below the maximum allowable stress values for high-strength shipbuilding steel, calculated in accordance with the rules of the Register (σ = 208 N/mm^2, σ_{ekv}=250 N/mm^2, τ =138 N/mm^2). Results as ‘Beam Stresses’ and ‘Effective Stress’ [13 Appendix C], show that all stress values are lower than the previously mentioned thresholds. Therefore, it is concluded that the strength requirements have been met, and the grillage structure of the main deck has been accurately dimensioned.

Figure 6 illustrates the displacement of the main deck structure when subjected to loading. As anticipated, the most significant displacement occurs at the centre, in the negative direction of the z-axis.

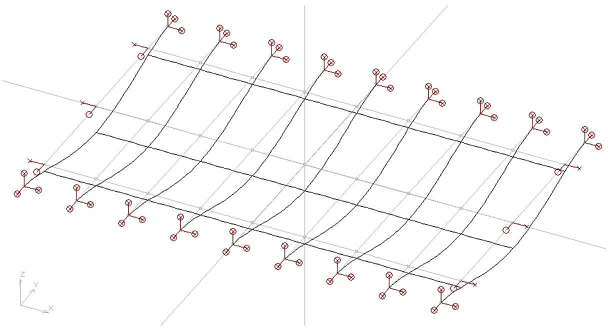


Figure 6: Main deck displacement

4.2. Racking stresses of the side structure

Parallel mid-body of the ferry was modelled for the purpose of this racking evaluation. The model is symmetrical with respect to the main frame, Figure 7.

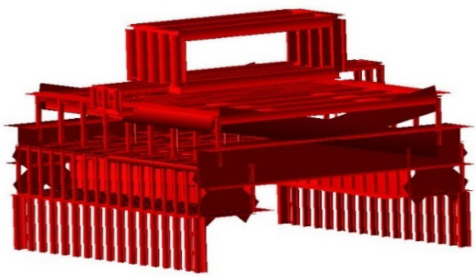
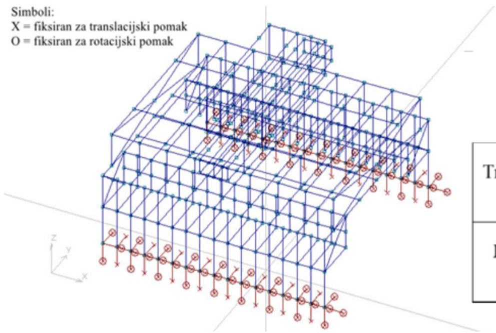


Figure 7: Garage space side frame model

The wheelhouse and anti-roll tank structure has been simplified. Boundary conditions, as shown in Figure 8, limit rigid body translational and rotational displacements. Supports are placed on the main deck's stiff structure to handle reaction forces. Three loading cases are applied to the garage frame model: transverse acceleration field (LC1), deck loads and self-weight (LC2), and wind loading (LC3). Transverse acceleration field, LC1, is determined in accordance with Chapter 3.5 of CRS [3]. The dimensionless component for transverse acceleration (perpendicular to the side) due to rolling, pitching, and heaving is a_y=0,645, multiplied by gravitational acceleration, 9,81 m/s^2. Final transverse acceleration field is equal to 6,327 m/s^2."



		R0, R4, R8, R12, R16, R-4, R-8, R-12, R-16	R2, R6, R10, R14 R-2, R-6, R-10, R-14
Translacijski pomak	X	Fixed	Fixed
	Y	Fixed	Fixed
	Z	Fixed	Fixed
Rotacijski pomak	X	Fixed	Fixed
	Y	Fixed	Free
	Z	Fixed	Free

Figure 8: Garage space side frame model boundary conditions

The load case LC2 consists of deck loads and structure's self-weight and equipment. All masses are represented by scaling material densities to correspond to actual masses on the ship. The mass factor is obtained as the ratio of the actual mass derived from the mass distribution book to the initial model mass in 3D Beam, followed by the material density correction. The adjusted density, in kg/m^3, is presented in detail in [13 Appendix D].

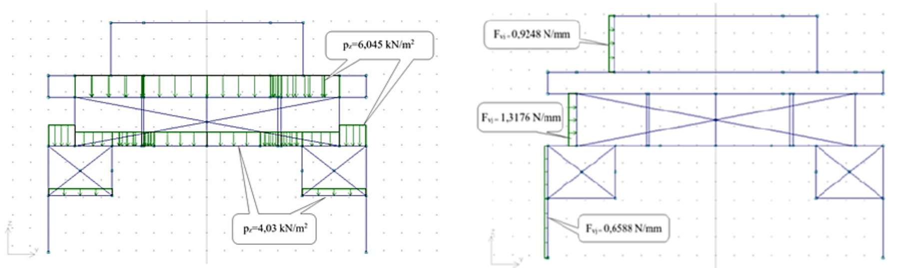


Figure 9: Deck loads (left) and wind loads (right)

Each transverse frame handles deck loads within one frame spacing, Figure 9 left. Grean sea effect, as well as the vessel's resilience to adverse weather conditions, especially strong lateral wind, must be taken into consideration. Wind impact depends on lateral surface, wind speed, and direction. The influence of the wind is determined for three different areas depending on the bearing surface under the influence of the wind. Wind loads are shown in Figure 9 right.

Normal-strength shipbuilding steel permits following values: σ= 150 N/mm^2, σ_{ekv}=180 N/mm^2, τ=100 N/mm^2, while high-strength shipbuilding steel allows σ= 208 N/mm^2, σ_{ekv}=250 N/mm^2, τ=138 N/mm^2.

All elements, except two beams which representing salon bulkheads on the fourth deck meet these criteria, since, in reality they are part of a robust transverse bulkhead. Consequently, resulting stresses are unrealistic and will undergo detail *FEA* in the subsequent project phase of a design spiral which is beyond the scope of the paper. Figure 10 showing structural displacement after applying the three loading cases.

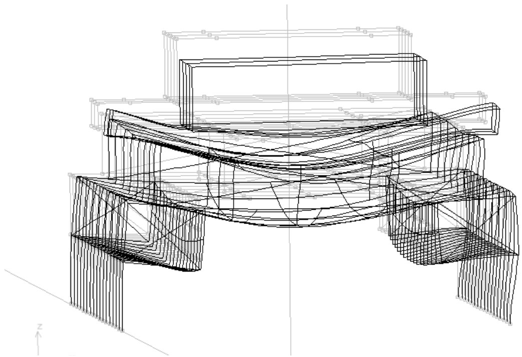


Figure 10: Garage space side frame model displacement

Racking is critical for ferries [14], [15], [17] since the connection between the superstructure and the hull is established solely through the structure of the side plating. This issue appears in cases of hull rolling combined with high lateral wind speeds. The solution lies in robust side frame supports.

4.3. Stress of the bottom structure due to docking

Considering the significant double bottom height, a structural assessment for docking was conducted on a single plate floor. Anticipated stress levels are low due to the uniform bottom structure, proving no need for a 3D model. For validation, an earlier docking plan was created, with a 25% margin on the initial displacement calculation to account for potential inaccuracies and support intensity variations. During docking, the vessel's weight is evenly distributed along the central line, encompassing 29 docking blocks. The force in the blocks (Pz_{dok}) during docking is determined by dividing displacement by the number of central line blocks. Blocks for lateral stability are strategically placed in the transverse and longitudinal bulkhead regions outside the central line area. Consequently, a force of 638 kN is applied along the central line to simulate the docking force, Figure 11. Conservatively, the contribution of the primary longitudinal bottom structure is ignored. The analysis focuses on the plate floor with manhole openings, which are more challenging than watertight solid ones due to reduced moment of inertia and strake thickness.

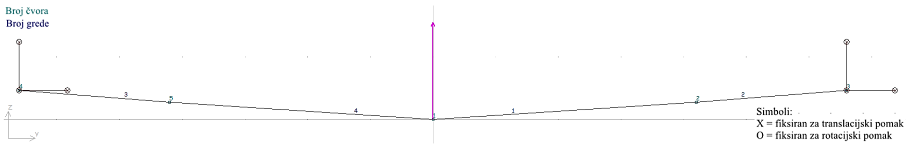


Figure 11: Plate floor with applied docking force and boundary conditions

Fixed boundary conditions have been imposed on all rotational and translational movements. Results [13 Appendix E] shows that the dominant stresses are shear stresses, with a maximum shear stress of 72 N/mm^2. This value, when compared to the maximum allowable stresses for normal-strength shipbuilding steel discussed earlier, validates the initial assumption of satisfactory stress levels, obviating the necessity for a 3D model. The most significant structural displacement takes place along the vessel's central axis, where the docking blocks are located.

5. FEM verification of the longitudinal stresses distribution

The Finite Element Method (FEM) serves as a tool to validate assumptions and the goal is to verify the distribution of global longitudinal stresses. Each part of the ship's longitudinal structure will be evaluated for its contribution to longitudinal strength and stress condition. Software package *GeniE* was utilized as the pre-processing tool, while *Sestra* was used as the processing tool, and *Xtract* as the post-processing tool.

5.1. Modelling

Ferry is positioned in the software workspace according to standard shipbuilding practices, Figure 12. The coordinate system originates at the baseline-central plane intersection. The x-axis runs longitudinally, bow toward as positive. The y-axis spans transversely, with portside as positive. The global z-axis extends vertically, with positive direction from the baseline to the ship's superstructure.

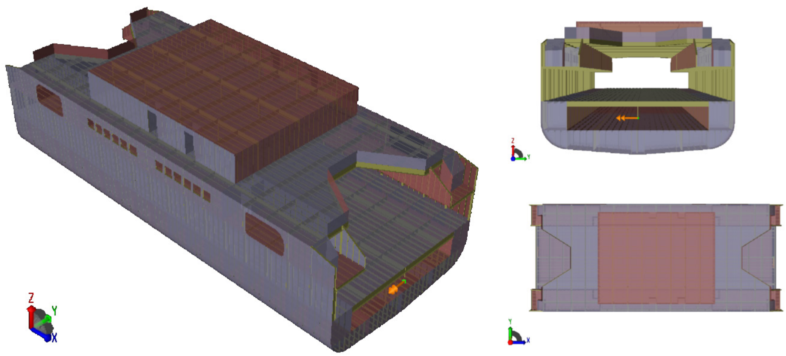


Figure 12: Ferry model made in GeniE

The structure incorporated into the model contains primary and secondary structural elements.

5.2. Boundary conditions and loads

The boundary conditions have been adopted in accordance with the ShipRight procedures from Lloyd's Register [4], [16]. To minimize the influence of these boundary conditions on the structural response, supports have been placed at the intersections of strong structural elements. Therefore, transverse constraints have been applied to the transverse bulkheads at frames +12 and -12, as well as at the very ends of the model.

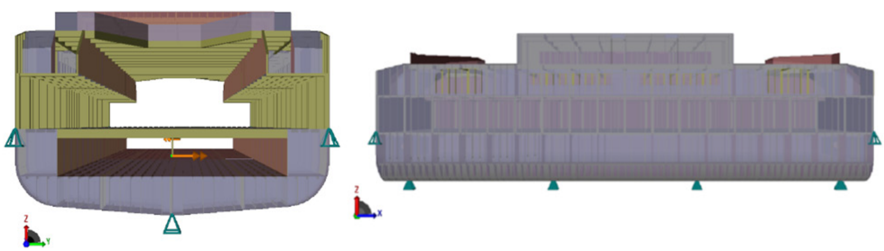


Figure 13: FEA Model boundary conditions

Two loading cases were applied to the ferry model: ship in hogging and ship in sagging conditions. To apply the loading cases for both hogging and sagging conditions, it is necessary to determine the total bending moment for each condition. The total bending moment in hogging is the sum of the bending moment in calm water ($M_{BH\ SW}$) and the bending moment in wavy water (M_{WH}). Similarly, the total bending moment in sagging is the sum of the bending moment in calm water ($M_{BS\ SW}$) and the bending moment in wavy water (M_{WS}). Therefore, the final loading cases of the *FEA* model for sagging and hogging conditions, Table 2, applied on the model boundaries. However, it is not possible to include all the masses in the model and therefore the structural mass is artificially increases over increased material density, in order to match weight distribution in accordance to Trim and Stability Book.

Table 2: FEA Model Loading Cases

		Coordinate, mm			M_y, N/mm
		x	y	z	
LC1	hogging	21600	0	3374	$9{,}899 \cdot 10^{10}$
		-21600	0	3374	$-9{,}899 \cdot 10^{10}$
LC2	sagging	21600	0	3374	$-1{,}1115 \cdot 10^{11}$
		-21600	0	3374	$1{,}1115 \cdot 10^{11}$

Ro-Pax ferries are often in hogging condition in calm water due to their weight distribution and shape, with excess buoyancy amidships and greater weight at the ends. This leads to significant calm water bending moments, especially when combined with wave-induced bending. The highest longitudinal stresses occur under this condition. Conversely, the scenario of the minimum bending moment in calm water and the maximum bending moment in waves leads to compressive stresses in the upper decks, which should be avoided. Specifically, as the superstructure of the fourth deck is made of thin 7 mm plates, it needs to be checked for buckling. The mesh was generated automatically, with square elements chosen as a preference. The selected mesh element length is 300 mm for mathematical convenience, considering the frame spacing of 600 mm, and it has proven to be a suitable choice.

5.3. FEM results

After modelling, applying two loading cases, and defining boundary conditions, a linear static analysis was conducted. *Xtract* is part of the *Sesam* software package, used for visual presentation of results, animation, and generating result reports. Although in the *GeniE* program, the ferry was modelled from frame -36 to frame 36, in the *Xtract* program, stress analysis will only be performed in the area of the parallel midship (the area from frame -18 to frame 18), to avoid regions near the influence of boundary conditions, where the results would be unrealistic. Parts of the structure can be grouped into sets, allowing for the analysis of specific groups of elements, such as the main deck, superstructure, hull plating, etc. Additionally, the stress scale range can be adjusted as desired. In this scenario, the visual representation is configured such that warm colours (red, orange, and yellow) signify positive stresses, while cool colours (an array of blue shades) denote negative stresses. The chosen attribute for displaying results is the so-called D-STRESS, which contains the dissected stresses. Specifically, SIGMX (σMx) stresses in the local x-axis direction were analysed.

5.3.1 Hogging

In the hogging condition of the vessel, tensile stresses occur on the deck, while compressive stresses manifest in the ship bottom, Figure 14.

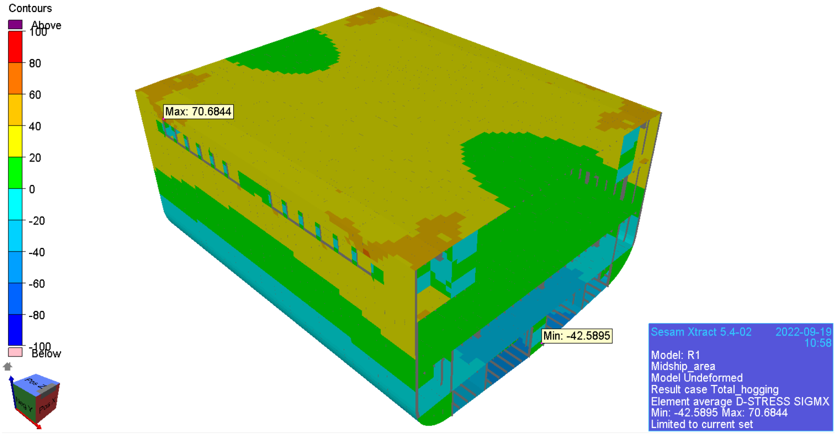


Figure 14: Hogging Stresses σ_x

5.3.2 Sagging

On the other hand, when the ship is in a sagging condition, compressive stresses appear on the deck, and tensile stresses appear in the bottom (Figure 15).

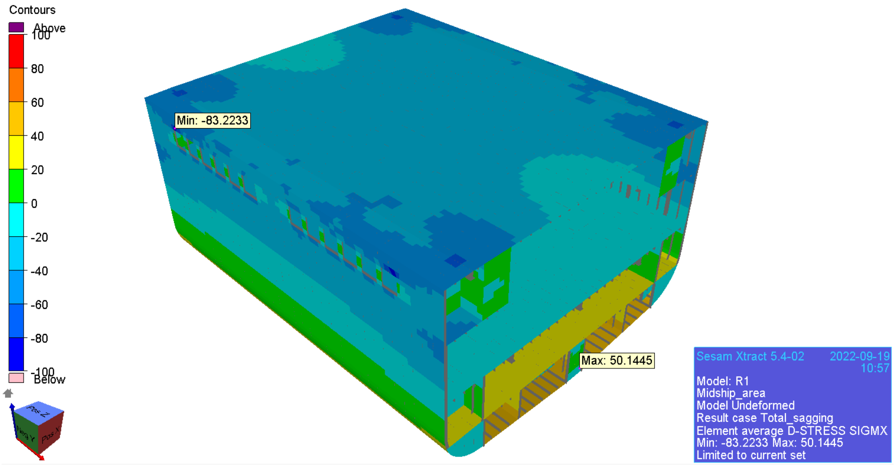


Figure 15: Sagging Stresses σ_x

5.3.3 Verification of the inclusion of the ship's structure in global strength response

Partial inclusion of the ship's structure above Deck 3, initially designated as a strength deck, is demonstrated by the FEA analysis of the ship's hull. To ensure the prevention of elastic plating deformation under maximum loads, an assessment of the structural stability of this region under maximum longitudinal bending moments is deemed essential. As a result of an iterative factorization method concerning the inclusion of the structure above the strength deck, it is determined that the longitudinal bulkhead of the salon and the external plating above Deck 3 are 55% incorporated into longitudinal strength. This, the same inclusion factor is applicable to Deck 4. Calibration of stresses derived from cross-sectional characteristics, calculated via *Nauticus Hull*, with resultant stresses obtained from *FEA* determines the inclusion factor. Given that Deck 4 contributes partially to longitudinal strength, measures need to be implemented to secure it against buckling in accordance with Chapter 4.6 CRS.

5.3.4 Discussion

The structural fitness analysis identifies elements that may not withstand loads based on stress and deformation responses. As all stresses are within allowable limits, the elements are adequately sized, and the stress distribution along the longitudinal axis is acceptable. Predominant stress is global, not local. Higher stresses occur where cross-sections change abruptly, like at salon window edges. Hence, window edges have rounded corners to reduce stress concentration.

6. Conclusion

Ro-Ro and Ro-Pax ferries have unique design focused on accommodating wheeled cargo efficiently. This involves optimizing decks for maximum vehicle capacity while ensuring smooth traffic flow.

The process of designing the hull structure of double-ended ferries in this paper is divided into three phases. The first phase involves calculating the dimensions of structural elements and strength according to the CRS rules and regulations. The main goal is to meet the minimum allowable deck and bottom section modulus.

Second one comprise calculation and verification of the primary structures of the main deck, side frames, and superstructure, as well as the assessment of the bottom structure during docking. These segments of the second design phase were carried out using the DNV 3D Beam software, in which dimensions are automatically checked in accordance with DNV rules and verified in accordance with HRB rules.

Longitudinal strength is of great importance since the length dimension is significantly larger compared to height and width. When analysing the longitudinal strength of a ship, it is typically viewed as a beam. However, by using advanced software packages that employ the finite element method, it is possible to determine the longitudinal strength of a highly complex ship hull structure. Therefore, in the third design phase, a check of the distribution of global longitudinal stresses in the area of the centreline was conducted using the finite element method with *DNV SESAM* as one of the tools for structural analysis of ships

As a result, all relevant aspects and procedures for preliminary structure design phase are accomplished. The final result is double-ended ferry hull structure ready for next phase; contractual and detailed design.

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