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Darin Majnarić
E-mail: dmajnaric@riteh.hr
Davor Bolf
E-mail: dbolf@riteh.hr
Albert Zamarin
E-mail: zamarin@riteh.hr
Faculty of Engineering University of Rijeka, Vukovarska 58, Rijeka, Croatia

Structural Analysis of Hybrid Ro-Pax Ferry

Abstract

With the aim of improving the environmental sustainability in the field of maritime transport and with special reference to multimodality and 'green' solutions for coastal transport, within the *METRO* project (Maritime Environment-friendly TRanspOrt systems), funded under the Interreg VA CBC Programme Italy-Croatia, a project of a hybrid Ro-Pax medium range ferry for coastal navigation in the Adriatic area is developed. The paper presents a part of the conceptual design for the assessment of the global hull structure strength, which is not common for this phase of the project, and that is the structural analysis of the complete ship. For this purpose, a detailed computer model of the geometry of the whole ship was made, which includes all primary and basic secondary structural elements, with the aim that such a model can serve later as a good basis for classification and workshop documentation production during contract phase. Additionally, a preliminary calculation of the scantlings of the complete ship was performed according to *BV* rules and regulations using the *MARS2000* software package, with regard to bending and buckling. Loads were modeled according to real conditions for two unfavorable loading conditions, and static linear analysis was performed using the *LS-DYNA* software package. The global analysis of bending strength in still water could reveal problematic areas in the structure.

Keywords: preliminary design, Ro-Pax, hull structure, *FEA*

1. Introduction

Within the process of conceptual designs of ships, one of the basic activities is the design of the structure, which should within the first round of the design spiral define the basic structural layout, preliminary dimensions of all structural elements as a basis for estimating mass and cost of materials and hull construction. In the standard commercial procedure, the next step would be the preparation of complete classification documentation, selection of investors/owner followed by signing of the contract and finally production of the workshop documentation. As this paper is result of a research project, so the investor / shipowner is unknown, the project did not aim to prepare a workshop or complete classification documentation, nor its confirmation by the classification society. Therefore, it was decided to make a structural analysis of the complete ship, and the goal was to check the global strength and confirm the calculation of the dimensions of structural elements against yielding and buckling. The remaining structural design assessment activities, such as fatigue assessment and ultimate strength calculation, have been omitted as they belong to the final, detailed structure assessment. It should be noted that this scope of work, modeling and structural analysis of complete ship, is not common at this stage of the conceptual design, due to the high consumption of human and computer resources, but it is still done because there is a lack of data to assess the load capacity of superstructures. The analysis of the structure is based on the initial calculations of the structure made by *Tehnomont shipyard Pula* and *Flow Ship Design* where the midship section are defined. Based on these data, the remaining parts of the structure were defined and dimensioned by the authors, as well as rest of *FEA* with the aim of verifying the calculated scantlings of the hull and superstructure [1]. Since the project did not envisage the preparation of hull classification documentation, and therefore no drawings such as *Shell expansion*, *Decks plans*, *Watertight and longitudinal bulkheads, Engine room structure*, *Superstructure*, it was necessary to determine the preliminary dimensions of the structure of other parts of the hull and superstructure outside the midship. This problem was solved by using the classification society Bureau Veritas software package MARS2000, which using the rules and regulations of the same classification society provides for class [2], supervision and possible construction, and which are integrated into the software package, all in order to determine the scantlings of the remaining part of the hull structure. This was done in such a way that the minimum required dimensions were determined for additional cross-sections with regard to the requirements such as longitudinal strength, minimum section modulus of cross-sections, minimum structural dimensions, as well as checking of structural elements against buckling. Later on, geometric model could be meshed and the elements could be given specific dimensions in terms of material type, as well as scantlings for plating thickness and dimensions of stiffeners based on their actual section modulus of cross section. After meshing and defining the physical properties of the material, the boundary conditions and loads were determined. The real load modelling approach was used, which included modelling the hydrostatic load according to the actual drought, and the load from the vehicle for the specific loading condition. Hydrodynamic analysis as well as accelerations were not considered. A static analysis was performed in the elastic region using the LS-DYNA software package [3], based on FEM, [4], [5]. Through analysis, the two most unfavourable loading conditions were observed, according to the recommendations of the classification society. Additionally, the possible influence of the superstructure above the main deck on the longitudinal strength was observed, but due to lack of time, detailed analysis was not performed, as well as racking phenomena, [6], although the designer takes into consideration racking stiffens where front and sides of superstructures and deckhouses is to be extra stiffened wherever necessary by racking bulkheads, [7]. Results of the global strength analysis that taking into account only static load are presented in form of displacements and stresses with aim to spot high stress area as a base for further structural analysis involving wave load and buckling strength criteria.

2. Vessel structural arrangement

The designed vessel presented is a Ro-Ro passenger ship, Figure 1, Table 1, compliant with SOLAS regulations for Short International Voyages (excluding US waters), in accordance with builder's standards and to comply with the listed Rules and Regulations. The Vessel is a twin screw, twin rudder, dual fuel-driven ship of welded steel construction including superstructure and wheelhouse, with one cargo deck and one hostable deck for cars. The hull with bulbous bow, transom stern, twin skegs and lines is so designed to ensure good seaworthiness and maneuverability. The hull under the freeboard deck is divided into sufficient watertight compartments, to satisfy damage stability as well as SRtP requirements according to the SOLAS regulations. The vessel shall have a capacity of abt. 630 lm for trailers or area of abt. 2020 m^2 for cars and transporters on the level of main garage decks. In addition to that, the area of abt. 1865 m^2 for cars on hostable car deck is ensured. Further, it will accommodate abt. 1340 passengers and 75 crew members. The cargo section consists of fully enclosed main cargo hold suitable for storing of trucks and other wheeled cargoes, as well as hostable car deck for stowage of cars only. Loading and unloading of wheeled cargo is performed by two ramps, one stern and other bow with hinged arms. All vehicle decks are designed to carry vehicles with fuel in their own tanks. Hull of the vessel is divided on following main compartments: fore and aft peak, double bottom / side tanks, engine rooms. The double bottom is extended between fore and aft peak bulkheads and subdivided as shown in *GAP*, Figure 1. Double bottom is provided in engine rooms for storage of water, lubricating oil and other service tanks. The vessel including its hull, machinery and equipment is to be constructed in accordance with the Rules of the Classification Society of Bureau Veritas to obtain the following Class notations: I ✠HULL ✠MACH; Ro-Ro Passenger Ship, Unrestricted navigation, SRTP, POWERGEN(DUALFUEL), ✠AUT-UMS, ✠SYS-NEQ, ELECTRIC HYBRID (PM, ZE), MON-SHAFT, INWATERSURVEY. The hull is arranged with transverse watertight subdivision below main deck. Passenger deck and Main deck are supported by transverse frames. Pillars are arranged in the service spaces below the Main deck and in the superstructure in order to minimize steel weight and structure height. The cargo area is arranged without pillars. Structural arrangement is based on longitudinal framing system. Transverse framing system is arranged for superstructure sides. Bilge keels 2 x HP320, having abt. 35% of ship length. Frame spacing is 800 mm. Main transverse frame spacing is 3200 mm. Longitudinal stiffener spacing on decks is generally 600 mm. Material main hull in general is mild steel (MS). Cargo area will have one fixed deck and one hostable deck for Ro-Ro cargo. Cargo hold is made as fully enclosed Ro-Ro space. Bow ramp with suitable bow door and stern ramp will be implemented for facilitated loading/unloading.

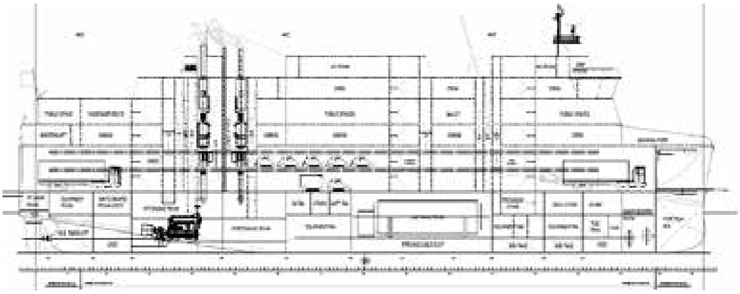

Figure 1: General arrangement plan of Ro-Pax ferry

The front and sides of superstructures and deckhouses is to be extra stiffened wherever necessary by racking bulkheads. The funnel will be made of steel plates and properly stiffened from the inside.

Table 1: Ro-Pax ferry main particulars

Length, overall	129.27	m
Length, between perpendiculars	124.45	m
Breadth, moulded	23.60	m
Hull depth to freeboard deck (midship)	8.00	m
Draught, scantling	5.60	m
Draught, design	5.25	m
Deadweight (at scantlings draught)	abt.2240	t
Deadweight (at design draught)	abt.1400	t
Gross tonnage	15040	GT
Main engines MCR	2x4000	kW @ 750 rpm
Design speed (design draught)	abt.15.5	knots
Maximum trial speed (design draught)	16.1	knots

3. Structural model

Modelling the structure for FEM analysis differ from the standard structural modelling for basic and detail production. In order to prepare graphical and surface model of the ship some necessary simplifications needed to be made and model was adjusted to easily mesh the surfaces and proceed with the structural analysis. Upon completion of the project setup, the hull shape was inserted into the model. Following the methodology presented in [8], and adopted to FEM modelling, first hull plating and decks were created using the available 3D software for modelling of the vessels. Later on, watertight bulkheads and longitudinal bulkheads were modelled. After the bulkheads, all primary structure was modelled (deck girders and beams as well as web frames and floors). Structure was modelled from double bottom to the wheelhouse deck, creating the structure one deck at the time. In order to prepare the model for meshing, all plates needed to be cut at the intersections and prepared for meshing. All major openings were created, but not the manholes, lightning holes in floors and beams and doors in the bulkheads. Hull and deck longitudinals were also modelled, thus creating the structure from first two stages of modelling presented in [8], while structural details were not modelled. Entire geometry of the ship is presented on Figure 2 and Figure 3 through section rings.

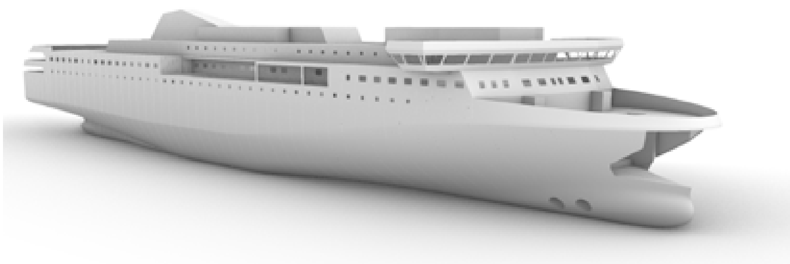

Figure 2: Hull 3D render geometry model of the whole ship

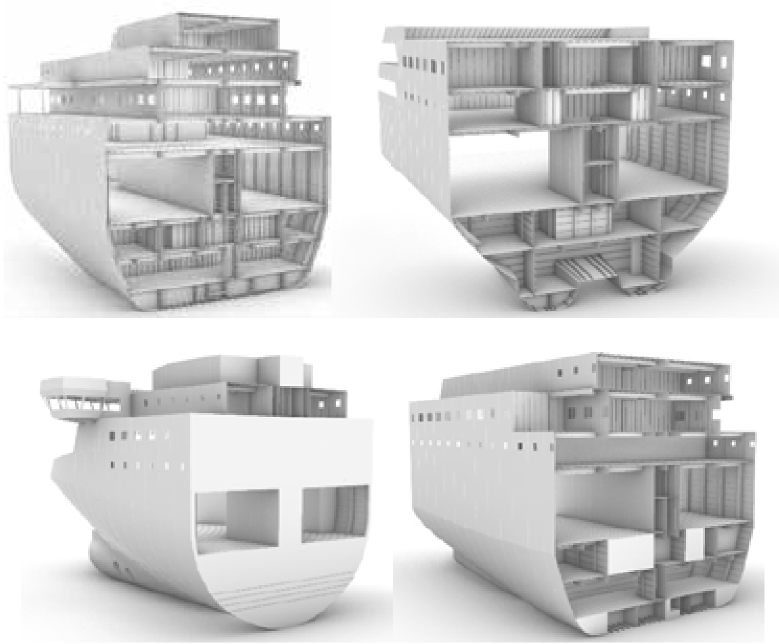

Figure 3: Internal structural geometry, frames FR0-FR30 (top left), FR30-FR70 (top right), Fr70-Fr110 (bottom left) and Fr110-Fr130 (bottom right)

4. Preliminary structural design

In order to model the structure within the *FEA* procedure, it is necessary to determine the dimensions of all structural elements. The standard design procedure would include the production of basic classification drawings of the structure from which all dimensions of the primary and secondary hull elements can be listed, [9], [10]. As this was not provided, the scantlings of the structural elements on the midship section (midship section preliminary draft) were first determined on the basis of the trim and stability book document over the longitudinal strength calculation. Input data for scantlings calculation are still water bending moment obtained from the mentioned calculation/document and wave vertical bending moment determined according to the rules and regulations of BV classification society [2] and are shown in Table 2 (left).

Table 2: Hull girder loads (left) and section modulus and inertia (right)

Vertical Bending Moment

	Hogging (kNm)	Sagging (kNm)
S.W.B.M. Builder's proposal in Basic Ship Data	300 200.	0
S.W.B.M. Builder's proposal at X = 61.5 m	.	.
S.W.B.M. preliminary value at midship	344 410.	-256 411.
S.W.B.M. preliminary value at X = 61.5 m	344 410.	-256 411.
Rule Vertical Wave Bending Moment at X = 61.5 m	345 327.	-432 927.

The hereabove wave bending moments have been calculated with Cb = [illegible]

Design Hull Girder Loads at X = 61.5 m

	Hogging (kNm)	Sagging (kNm)
S.W.B.M.	300 200.	0
Wave bending moment (Rule)	345 327.	-432 927.
Horizontal wave bending moment	127 267.	

	Positive (KN)	Negative (KN)
Vertical still water shear force	7 500.	
Vertical wave shear force	6 699.	-6 699.

Admissible Vertical Shear Forces

Total Admissible Vert. Shear Force	(KN)	34 912.
Positive Admissible Vert. Still Water Shear Force	(KN)	26 213.
Negative Admissible Vert. Still Water Shear Force	(KN)	26 213.

Rule section moduli

	Deck (m^3)	Bottom (m^3)	Top (m^3)
Modulus based on design BM, Hog. (645 927.4 kNm)	3.6910	3.6910	3.6910
Modulus based on design BM, Sag. (- 433 926.5 kNm)	2.4796	2.4796	2.4796
Rule Modulus	3.6910	3.6910	3.6910

Check of section moduli and inertia

		Rule	Actual
Deck	(8.000 m k = 1.00)	3.6910	66.3737
Bottom	(0.000 m k = 1.00)	3.6910	7.7894
Top	(16.800 m k = 1.00)	3.6910	5.7851
Inertia		14.6344	55.7699

Check of Net/Gross Moduli

		Actual Gross	Actual Net	%
Deck	(8.000 m)	66.3737	73.1267	110.2
Bottom	(0.000 m)	7.7894	6.9746	89.5
Top	(16.800 m)	5.7851	5.3639	92.7

Using the remaining data on material type (MS) and yield strength (s_y) and considering of the above rules and regulations, the minimum structural dimensions on the midship section is determined, using the classification society Bureau Veritas software package MARS2000, which in the assumed structural arrangement meet the required minimum section modulus of the midship section and are shown in Table 2 (right) and Figure 4.

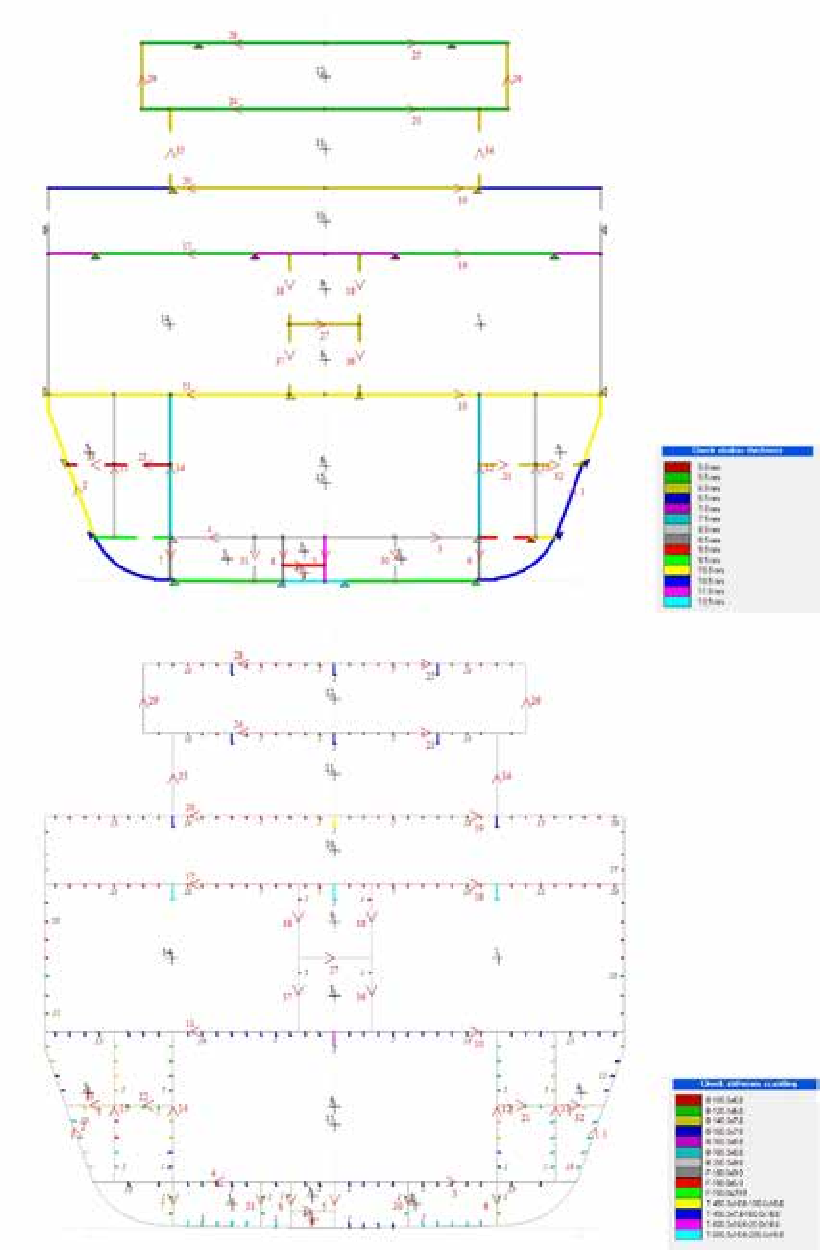

Figure 4: Plating(top) and stiffener (bottom) scantling on Midship section

Within yellow boxes, on Figure 5 and 6, plating thickness in millimetres and, on the left side, the required scantlings of the girders and stiffeners are given.

As the load varies along the length of the ship, it was necessary to repeat this procedure for a number of characteristic cross-sections in order to obtain the dimensions for the structure model and FEA as accurately as possible. The sections considered are: FR20, FR41, FR98, FR119, FR137, only two are presented due to limited space, Figures 7, and 8.

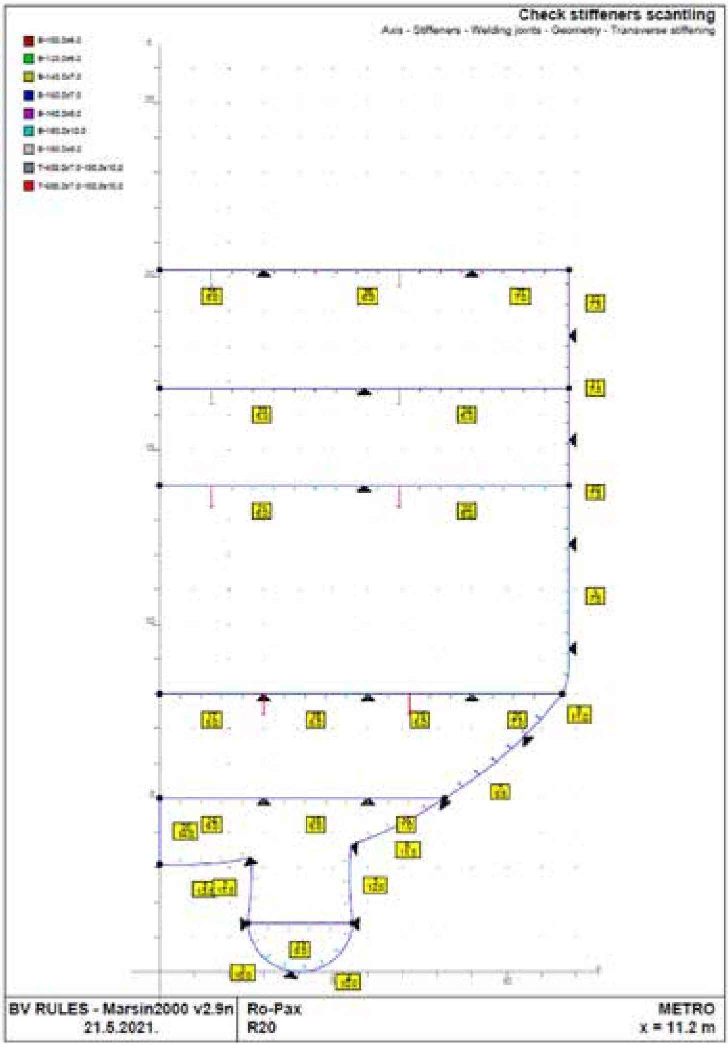

Figure 5: Plating and stiffeners scantlings on FR20

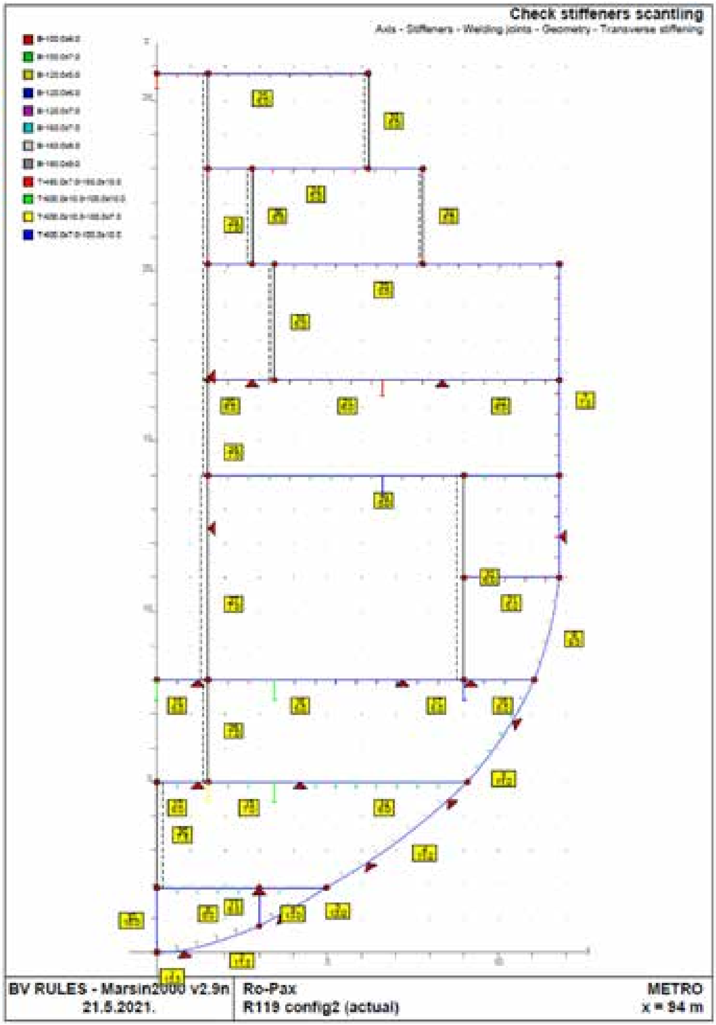

Figure 6: Plating and stiffeners scantlings on FR119

In addition, it should be noted that the dimensions are determined for the middle-low efficiency of the superstructure in longitudinal strength, Figure 7. This could be investigated later in more detail through different models of the hull and part of the superstructure with the aim to point out the possible stronger positive influence of the superstructure on the longitudinal strength, which can be proven only by direct calculation methods (FEM) and presentation to the classification society as a possible basis for optimizing the dimensions of hull structure elements, [11], [12], [13].

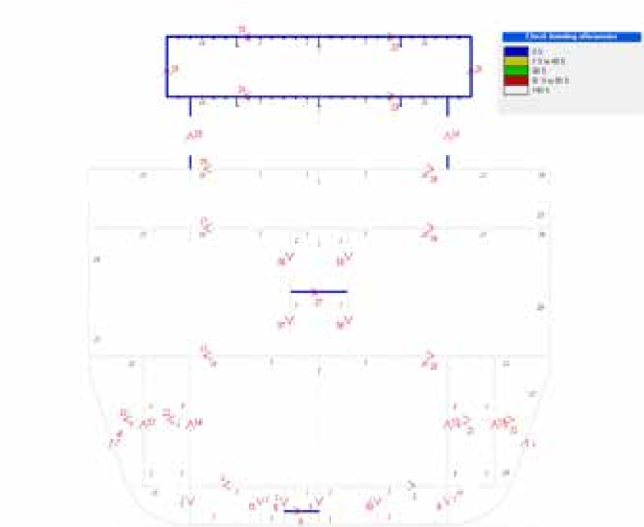

Figure 7: Midship section bending efficiency

The resulting scantlings of the plating and stiffening of transverse structural elements such as the bow watertight bulkheads (FR41 and FR 78) are shown on Figure 8.

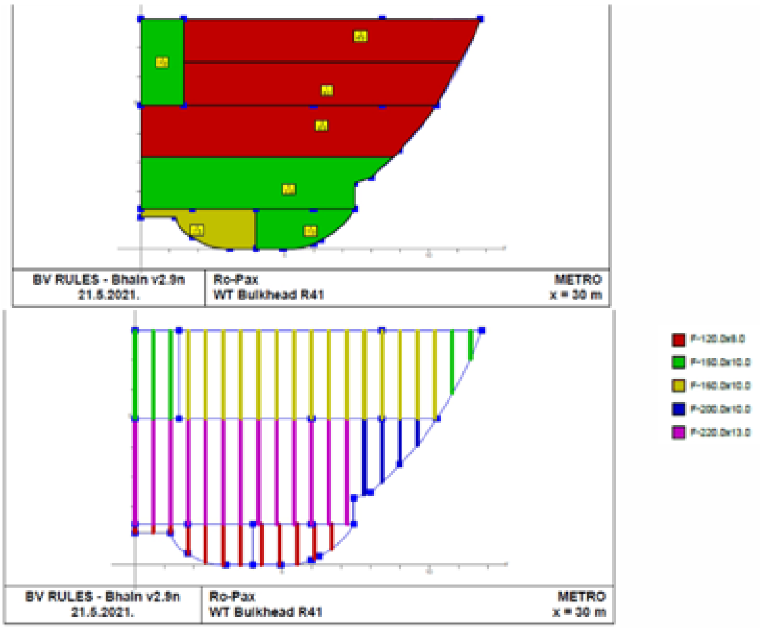

Figure 8: Plating and stiffeners on watertight bulkhead FR41

5. Global FE strength analysis

5.1. Referential Documents and 3D Model Description

A list of the main documents, named Referential Documents, used are:

Technical description:	ROPAX-METRO-Outline-REV2
General Arrangement Plan:	ROPAX-METRO-GAP-REV2
Body Lines:	METRO-RO-PAX-1101301-REV2
Midship section:	METRO-RO-PAX-1200301-REV2-Midship section preliminary
	METRO-Ropax-TRIM & STABILITY BOOK_REV1

Complete structure model (*CSM*) of Ro-Pax ship is created for the simulation purposes, Figure 9, [14]. Model is positioned in the working space (*FEM environment*) according to standard naval architectural practices in which x-axis is oriented aft to the fore in the longitudinal direction, y axis is oriented from starboard to the portside with its origin at the centreline of the vessel and z axis is oriented vertically to the base line of the ship with its positive direction from base to the top part of the ship, Figures 9. Model consists of 395 different FE parts, in which each part represents one structural element or in some cases a group of structural elements with same geometric properties. One type of steel is used, with following properties; Young's modules: E = 201 000 MPa, Poisson's ratio v = 0.29 and yield stress σ_Y = 235 MPa.

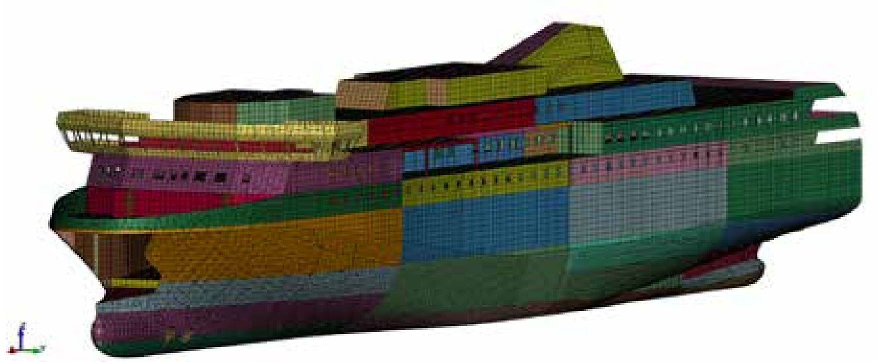

Figure 9: Isometric view on the model with the Coordinate system

5.2. Modelling of Loads

Presented Ro-Pax ferry is Passenger / Ro-Ro types of ship that have such a shape and distribution of their own weight (quite uniform along the ship) that they are always in a hogging condition on calm water, i.e. they have extra buoyancy in the middle and weights at the ends. Due to such static load distribution, they are usually loaded with a very high bending moment on still water. The combination of the maximum still water bending moment in hogging and the maximum wave bending moment in hogging gives maximum longitudinal stresses. The combination of the minimum hogging bending moment on still water and the maximum wave sagging bending moment gives the possibility of compressive stresses in the upper decks. This is to be avoided at all costs because the compressive stresses in the upper decks of the superstructure, which are mostly made of very thin plates (5-6 mm), can cause buckling problems. The shear force distribution on still water usually follows the theoretical distribution with maximum values in the range of about 0.25 *L* and 0.75 *L* of the stern vertical. Significant values of the shear force are obtained by summing the maximum value of the shear force due to the wave with the maximum value of the shear force on still water. This can cause large shear stresses on the side of the ship in areas of openings where shear stiffness is reduced, which is not the case of presented Ro-Pax ferry. Static load is divided into following groups:

- weight of structure, weight of paint, equipment, welds,
- weight of cargo per deck (usually default pressure per deck),
- cargo weight in cargo / ballast tanks,
- weight of supplies, fuel, lubricants, water,
- hydrostatic pressure due to buoyancy.

This part of analyse is accompanied by a detailed elaboration of Trim and Stability (T&S) book in which load cases of ship loading are defined. The static load of an idealized structure is increased and adjusted to the weight of the light ship according to the T&S book for the considered loading case. The shape of the FE model quite faithfully follows the actual shape of the ship, and differences in displacement of up to 2% are considered acceptable [15]. The hydrostatic pressure distribution is directly defined by the ship's draft and has to be checked also. The load on the decks is explicitly given in the form of pressure. The weight of the cargo in the tanks is derived from the volume of the tank and the density of the liquid. The mass of the main machine and larger equipment is defined at the exact position as concentrated mass. The self-weight of the idealized construction is calculated directly by FEM programs from the structural model and are increased by the weight of the neglected reinforcement, welds, paint, small equipment, inventory, etc. The difference is defined by the magnification factor which increases the density of the steel. In this case, the total weight distribution follows the own weight distribution of the idealized structure. The magnification is obtained in parallel with the adjustment of the weight curve obtained from the FEM program and that from the T&S book.

When modelling the wave load, it should be on mind that is generated with much more uncertainty than the structural model, and therefore was not considered at this stage of the analysis. Direct methods for calculating the wave loads of various authors still give large variations in the results of even the vertical wave moment [16]. For the practical implementation of wave loads on the 3D FE model of the whole ship, the design wave method [15] and [17] is usually used due to the speed and practicality of the calculation. They use elements of a deterministic and / or statistical approach in determining the equivalent design wave that will load the FE model. Two different loading cases were used in the analyses/simulations. In both simulations hydrostatic pressure is included which is changed depending on the draught. In the second loading case apart from hydrostatic load, load from the trucks on the deck is implemented. Hydrostatic load is set onto the hull surface in seven separated areas. So, each draught that is implemented into the simulation is separated by height into seven areas. For each areas pressure is calculated separately based on Bernoulli's equation. With explained approach hydrostatic load is set as distributed load on the hull surface which changes with the depth. Loads form the truck are imposed based on the inputs [2] (see Ref. Documents), Figure 10.

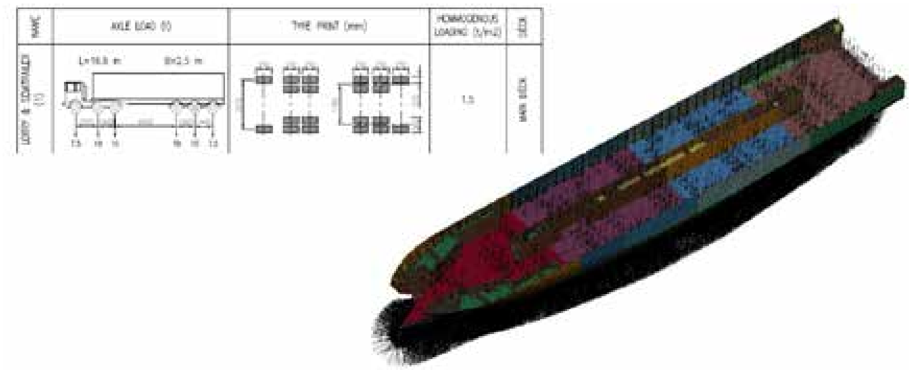

Figure 10: Permissible loadings from the trucks on the deck (left) and representation of hydrostatic and trucks load on the same model, section view

5.3. Loading conditions

Two different static loading conditions, Table 3, are used in the simulations according to T&S book as lightweight ship (LC1) and load case that correspond maximum value of stillwater bending moments (LC2) that reads kNm and shear force of kN. Load case LC1 has got only hydrostatic load, while LC2, has got hydrostatic load and cargo load from trucks on the Main garage deck, Figure 10.

All simulations are performed with the following assumptions; static analysis, small displacement and linear behaviour of materials.

Table 3: Schematic representation of load conditions

Load case		Displacement, t	Draught, m	Cars	Trucks
LC1	Trim&Stability Book	7210	4.619	-	-
	FEM*	6741	4.501	-	-
LC2	Trim&Stability Book	9246.5	5.536	-	Yes
	FEM*	9187.4	5.51	-	Yes

*Weights, t	LC1	LC2
FEM structure + main equipment	4575	4575
Cargo equipment	428	428
Ship equipment	300	300
Crew and Passengers equipment	1000	1000
Ship systems	438	438
Bunkers	-	45.6
Ballast waters	-	290.8
Deadweight	-	2110
Total:	6741	9187.4

5.4. Boundary condition

In order to prevent rigid body motions of the overall model, the constraints specified below are applied, Table 4, Figure 11. The model itself needs to be in quasi-static equilibrium so that the reactions in the nodes in form of displacement and rotation are minimal. A total unbalanced force below 2% of the displacement is considered acceptable according to BV [15], Table 3. The model balancing procedure changes two parameters, ship draft and trim angle, in the case of a symmetrical load case. By varying the above parameters in an iterative procedure (which is usually a preparation for FEM calculation), [18], the conditions of buoyancy and minimum reactions at the ends are met.

Table 4: Boundary conditions imposed on the model

Boundary conditions	Degree of freedom (DOF)		
	X	Y	Z
Fore node in CL, 1	fixed	fixed	fixed
Aft node in CL, 3	free	fixed	free
One node, portside, aft end, 2	free	free	fixed
One node, starboard side, aft end, 4	free	free	fixed

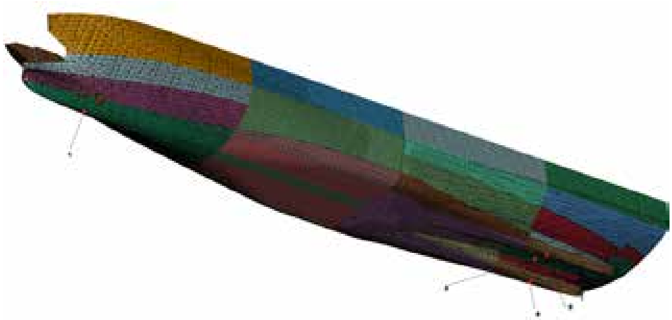

Figure 11: Boundary conditions positions

5.5. FE Modelling Characteristics and Checking Criteria

Mesh was created of the shell elements with the usage of the *Fully integrated shell element* formulation option. In creating mesh two elements types were used which are quadrilateral and triangular element, Table 5. Initial dimension of the mesh element is 600 mm, where that was necessary elements were smaller in order to better define geometry and to sustain mesh quality in problematic areas.

FE model is based on the scantlings with 50% corrosion deductions for primary supporting members analysed through complete ship model, according to the rules, [2] (Pt. B, Ch.4, Sec.2, Table2).

Hull girder bending strength checks within 0,4 L amidship are:

$s_1 = 175/k$, MPa - normal stress, where k=1 is material coefficient of mild steel,

$t_1 = 110/k$, MPa - shear stress, and

$f = l/200$ – deflection, where l is unsupported span.

Table 5: Number of elements for the model and their shape (formulation)

	No. of elements	Quads	Trias
Model	296780	*27430*	*269350*

Figure 12: Longitudinal global section views of the mesh

6. Results and discussion

Reviewing and evaluating the results on the global FE model of the whole ship due to the size and complexity of the model is a long and demanding job. Software packages that automatically check the suitability of all structural elements greatly speed up the work on the evaluation of results, but still is not completely automatic process. The analysis of the results is carried out on the prepared model for which two loading conditions are analysed. Results are presented globally for the whole model and both load cases, in case of resultant displacement, Figure 13, 14 and 15, and locally for some parts of the structure in case of effective stress response, Figures 16, 17, 18 and 19. Only those figures showing areas of the structure that are under significant or high stress are selected.

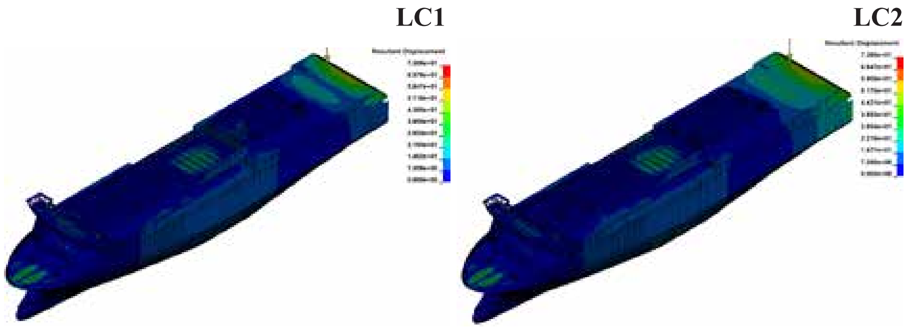

Figure 13: Resultant displacement of the model, Wheelhouse top

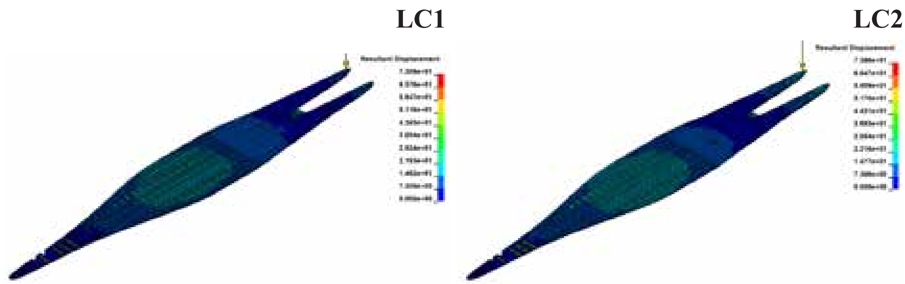

Figure 14: Resultant displacement of the model, Tank top

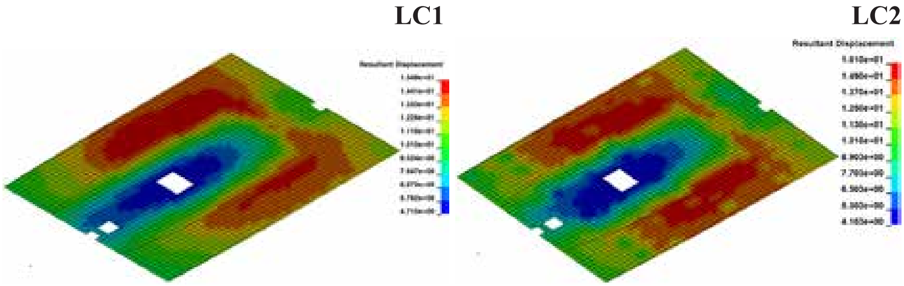

Figure 15: Resultant displacement for Main garage deck

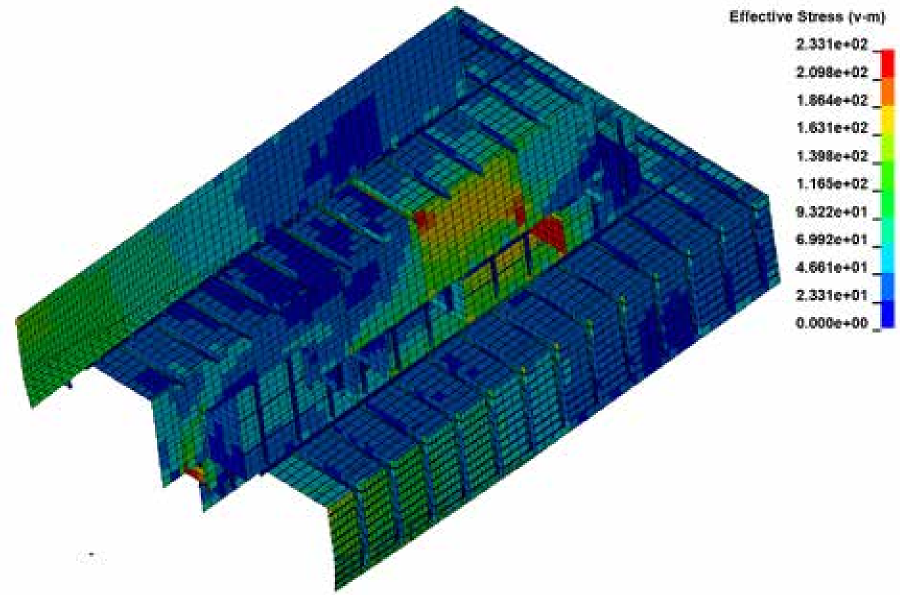

Figure 16: ***LC1*** *- Von Mises stress for structure between Fr70 -Fr110 and Main garage deck and 1st Accommodation deck*

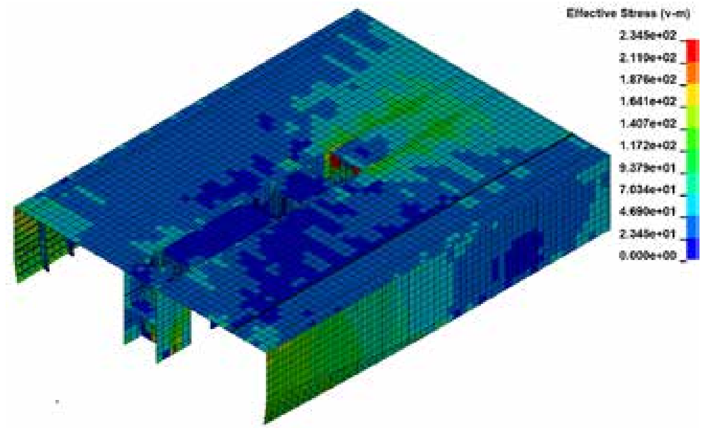

Figure 17: ***LC2*** *- Von Mises stress for structure between Fr70 -Fr110 and Main garage deck and 1st Accommodation deck*

LC1 **LC2**

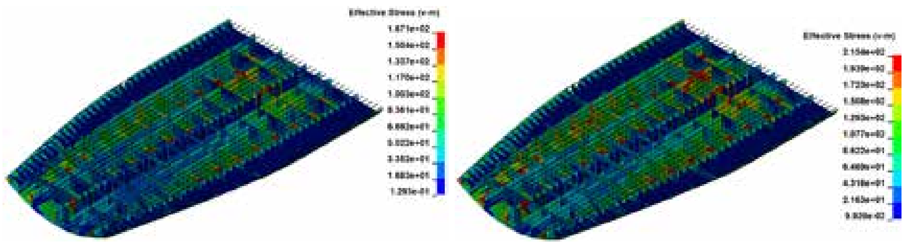

Figure 18: Von Mises stress for structure between Fr70 -Fr110 and from the bottom to the Tank top

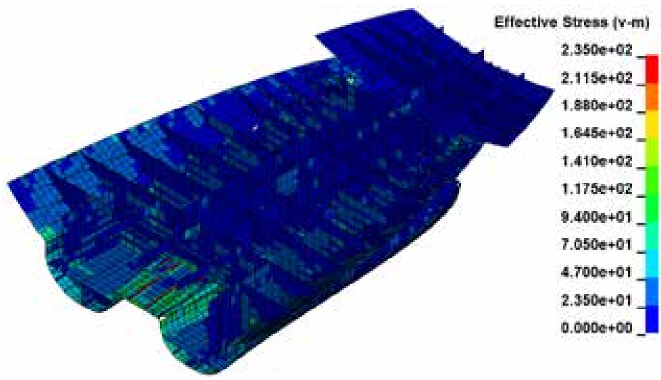

Figure 19: ***LC2*** *- Von Mises stress for structure between Fr0 -Fr30 and hull bottom under the Main garage deck*

7. Conclusion

In order to check part of the global ship strength related to static load of the Ro-Pax ferry hull structure, complete ship model finite element analysis is performed. Previously, minimal scantlings are determined in accordance to BV prescribed rules, where yielding and local buckling criteria were applied. Within FEA only global checking criteria regarding stillwater bending moment was applied. Two load cases are considered as most unfavourable ones from trim and stability book regard to lightweight ship and maximum vertical bending moment. Results are presented in form of displacement and stresses. Static loads are modelled as much realistic as possible from load cases. It means that distribution of weight is considered and consequently the buoyancy distribution at proper water line. Additional mass of engine, equipment and other groups are considered as well as loads from the car and trucks.

Stresses are presented in the form of equivalent stresses instead in the form of longitudinal (x) ones, which are lower in comparison to equivalent and might be more appropriate for global strength evaluation. Still, bearing in mind that the wave vertical bending moment is not included as load and therefore the stress response should be lower, leaving enough space for stresses due to wave bending moment, up to stress limit. Therefore, structural element showing stress value near to limit of 175 MPa were of interest. In general, the response, both deflection and stress, is small and within the expected range, and only some local structural elements show excessive stresses. After detailed inspection, following elements/positions are extracted from analysis, Table 6, as potential high stress area that would require more detailed analysis as a future work and are likely to be addressed by local reinforcements or local structural rearrangement.

Table 6: High stress structural positions / elements

Load case	Structural part	Position / Frame	Level of stress	Figure
LC1	Main garage deck	0 -30	High	18
	Bottom shell	0 - 30	High	20
	Bottom shell, double bottom	70 - 110	Significant	21
LC2	Main garage deck	70 – 110	High	19
	Hull bottom	0 - 30	High	20

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