

Vedran Žanić, FSB, I. Lučića 5, Zagreb
Dino Sponza, ULJANIK Shipyard, Pula
Jerolim Andrić, FSB, I. Lučića 5, Zagreb
Darko Frank, FSB, I. Lučića 5, Zagreb

HULL-SUPERSTRUCTURE STRUCTURAL INTERACTION BY FINITE ELEMENT CALCULATIONS

Summary

Prototype design of the wagon (tank car) carrier structure according to minimal scantling requirements of Russian Maritime Register of Shipping Rules (RS), designed by the ULJANIK Shipyard, is presented. To analyze realistic 3-D effects the full ship (coarse-mesh symmetric) 3-D FE model was developed. It simultaneously gave insight into all relevant critical areas especially regarding hull-superstructure interaction in sagging/hogging condition and racking forces. Five load cases, based upon T&S Book and RS Rules, were generated. The effectiveness of the very long superstructure (approximately 0.45 L) in longitudinal strength is discussed. Critical areas were identified in global model regarding: (a) deformations of accommodation and upper decks, (b) stress concentrations in superstructure openings and at its ends (c) buckling in shell plating amidships, etc. Optimization model was developed to minimize weight additions above minimal scantlings to satisfy structural requirements of RS and deck rigidity regarding deck deformations in wagon area. Based upon optimised dimensions, the structural modifications were inserted in full collaboration with the designer.

Key words: *full ship FEM model, hull-superstructure interaction, wagon carrier*

INTERAKCIJA TRUP-NADGRADE METODOM KONAČNIH ELEMENATA

Sažetak

Brod za prijevoz vagona projektiran je u brodogradilištu ULJANIK u skladu s minimalnim zahtjevima Ruskog registra brodova (RS). Za potrebe analize realističnih 3-D efekata izrađen je 3-D MKE model broda s *grubom* mrežom makroelemenata. Model istovremeno detektira i daje uvid u relevantne kritične zone s obzirom na interakciju trupa i nadgrađa u pregibnom/progibnom stanju kao i kod stanja nagnutog broda. Pet slučajeva opterećenja, temeljenih na knjizi Trima i stabiliteta i Pravilima RS, izdvojena su kao kritična te analizirana. Efektivnost vrlo dugog nadgrađa (cca 0.45L) i utjecaj na vertikalnu krutost kod savijanja broda detaljno je analizirana. Identificirane su kritični efekti: (a) deformacije gornjih paluba, (b) koncentracije naprezanja oko otvora u stjenkama te na krajevima nadgrađa, itd. Optimizacijski model je razvijen u cilju minimizacije prirasta težine za zadovoljenje strukturnih zahtjeva RS-a. Strukturne modifikacije temeljene na optimiziranim dimenzijama provedene su u dogovoru s projektantom.

Ključne riječi: *MKE model cijelog broda, trup-nadgrađe, brod za prijevoz vagona*

1. Introduction

At the request of ULJANIK SHIPYARD, Pula, the University of Zagreb, Faculty of Mechanical Engineering and Naval Architecture has carried out three dimensional finite element full ship analysis of the wagon carrier Yard No. 459- 462, [1].

The objective of the analysis was to investigate the structural strength in fulfillment of requirements of the classification society RUSSIAN MARITIME REGISTER OF SHIPPING [2] (in further text: Register) and to provide the minimum weight optimization of structural elements inside 0.4L amidships.

Special attention was focused on *strong* interaction between hull and superstructures due to the fact that very long superstructure (approximately 0.45 L) were designed as one part. Sensitivity study of alternative concepts via dividing superstructure in two and three parts was also performed for reference.

MAESTRO software [3] was used for calculation of the response of the full ship 3D FEM model.

2. Vessel description

The vessel is a WAGON CARRIER with the following principal dimensions:

Length overall	154.50 m
Length between perpendiculars	147.00 m
Breadth moulded	17.50 m
Breadth max.	18.30 m
Depth to upper deck	7.50 m
Depth to accommodation deck	13.35 m
Draught	4.50 m
Deadweight	5000 t
Main engines	2 X 2000 kW
Speed trial (80% MCR)	14.0 knots
Wagons	52



Fig. 1 General arrangement plan

Slika 1. Opći plan broda

Figure 1 shows an outline of the general arrangement of the vessel. Midship section geometry and main scantlings are shown in Figure 2.

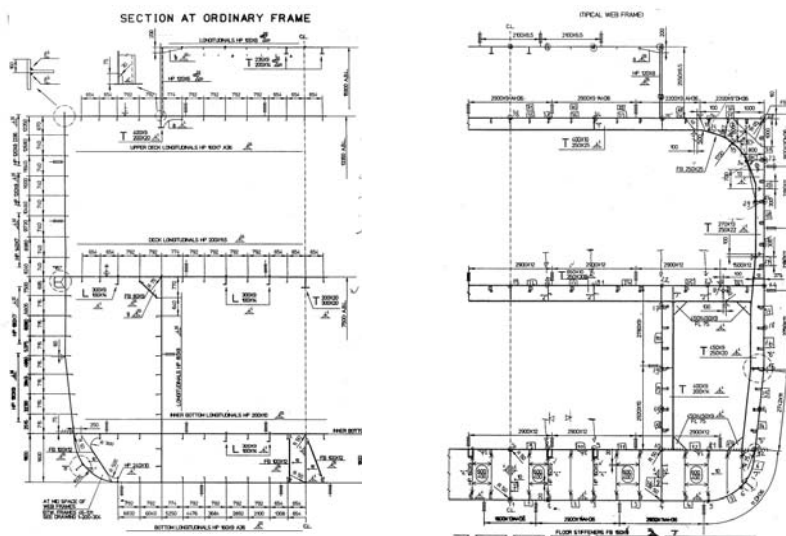


Figure 2. Midship section

Slika 2. Glavno rebro

3. Mathematical model

To analyze realistic 3-D effects the full ship, coarse-mesh, symmetric 3-D FE MAESTRO model was developed, Fig. 3. It simultaneously gave insight into all relevant critical areas especially regarding hull-superstructure interaction in sagging/hogging condition and due to racking induced forces. In the view of the symmetrical structure and non-symmetrical racking loads, the modeling was performed only for PS side of the structure. The non-symmetrical loading was applied by use of special MAESTRO option.

Ship 3-D FEM model has 11019 nodes and 7432 macroelements (4375 stiffened panels and 2385 beams, triangles 468, pillars 204). Plated areas such as decks, outer shell and bulkheads were represented by the special Q4 stiffened shell macroelements and each primary transverse frame or girder was modeled with special bracketed beam macroelement. TRIA membrane triangular elements were also applied with appropriate thickness.

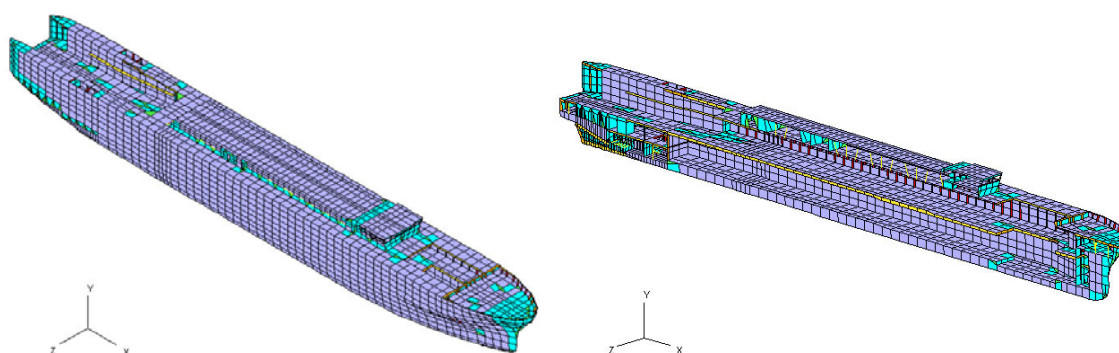


Figure 3. Full ship 3-D FE MAESTRO model

Slika 3. 3-D FE MAESTRO model cijelog broda

4. Loading

Five load cases for longitudinal and transverse strength were analyzed. The load cases (LC1-4) were based on the loading conditions described in TRIM AND STABILITY BOOK [4] and RS Rules. They are shown in Table 1:

Table 1. Load cases description

Tablica 1. Opis slučajeva opterećenja

LC	Main characteristic of load case	Loading condition description from [4]
1	Longitudinal / dynamic / hogging	WB10% - ballast condition – 10% of fuel and stores
2	Longitudinal / dynamic / sagging	W+100%ST – 52 PCS of 73.6 t wagons, 100% fuel and stores
3	Longitudinal / dynamic / hogging	W+10%ST – 52 PCS of 73.6 t wagons, 10% of fuel and stores
4	Transverse / racking / dynamic	Racking – 36 PCS of 93 t wagons, 2 locomot. of 16 t & 16 PCS of 23 t wagons
5	Transverse / racking / static	Racking – 36 PCS of 93 t wagons, 2 locomot. of 16 t & 16 PCS of 23 t wagons

The considered longitudinal load cases were defined according to Table 2:

Table 2. Vertical bending moments for longitudinal strength calculation**Tablica 2.** Vertikalni moment savijanja u proračunu uzdužne čvrstoće

LC	Max. still water bending moment (kNm) from [4]	Wave bending moment (kNm) according to Register	Total bending moment (kNm)
1	179900	506800	686700
2	-84760	-542980	-627740
3	60160	506800	566960

Transverse load case LC4 includes heeled water surface (heel angle $\theta = 19.9^\circ$). and dynamic forces in transverse sections. Transverse load case LC 5 was defined by static heeling of ship in still water. The heeling angle was 25° .

Based on the model geometry and elements scantlings, mass of the hull was generated within the program. Some bigger masses (main engines, etc) were included in model as concentrated masses. Lightship weight distribution was adjusted to loading condition LIGHTSHIP from TRIM AND STABILITY BOOK [4].

Two wagon distributions were applied (see Table 1). The load cases (LC 2, 3) were analyzed with wagons of the same mass. In racking load cases (LC 4, 5) heavier wagons were placed on the upper deck and lighter wagons on the inner bottom. Wagon masses were distributed in mesh nodes of the corresponding decks taking into account real position of each wagon centre of gravity and permitted directions of wheel reactions. The masses of water ballast and fuel were taken from longitudinal strength calculation for appropriate loading condition [4] and were generally placed in appropriate tanks, which were modeled inside the structure model.

Accelerations were calculated according to Register. The calculated accelerations were:

- horizontal-longitudinal acceleration $a_{cx} = 0.867 \text{ m/s}^2$
- horizontal-transverse acceleration $a_{cy} = 1.734 \text{ m/s}^2$
- vertical acceleration $a_{cz} = 1.734 \text{ m/s}^2$
- angular acceleration for pitching $a_{pa} = 0.06281 \text{ rad/s}^2$
- angular acceleration for rolling $a_{ra} = 0.08584 \text{ rad/s}^2$

Combined transverse acceleration were defined according to Rules and adopted to standard MAESTRO input. The external loading (including dynamic pressures) on ship's hull was calculated according to Rules and substituted with the equivalent wave pressure distribution calculated by MAESTRO. The wave pressure distribution was also used for achieving the demanded total longitudinal bending moment and for balancing of the full ship FE model.

5. Optimization model

Optimization was a very demanding design process performed interactively with the Yard designer.

Optimization model has been developed with objective to minimize weight (mass) additions above minimal required scantlings and simultaneously satisfying:

- structural requirements of Register
- deck rigidity regarding deck deformations in wagon area.

Control structure for optimization was the midship region of 0.6 L amidships (111 frame spacing starting at Fr. 38). It was selected as the most dominant w.r.t. structural weight / mass.

Design variables were scantlings of structural elements.

Starting dimensions were taken from PROTOTYPE-YARD (**P-Y**) documentation based on minimal requirements of the Register. Initial mass of material to be optimized was 817 t. Number of unsatisfied safety constraints (with minimal scantlings) was 37. Maximal deflection of the accommodation deck was 41.7 mm.

PROTOTYPE-0 (or **P-0**) is redesign of prototype **P-Y** to achieve required permissible displacements of upper and accommodation decks and to solve unsatisfied constraints. Its mass was 874 t. Deflection was reduced to 25 mm with all criteria satisfied.

Since **P-0** will be the final design if no optimization has to be performed, it was taken as a fair starting point for the optimization process (This is standard practice in optimization tasks). All achievements are therefore referenced with respect to feasible **P-0** design and not to infeasible design **P-Y**.

The designer specified parameters:

- (1) Basic geometry and topology
- (2) Basic web frame spacing: 2400 mm
- (3) Spacing of longitudinal
- (4) Position of all girders.
- (5) Fixed values for certain number of scantlings (bulkheads, bilge, double bottom, e.t.c.)
- (6) Material characteristics (MS, AH36)

Design requirements

Minimal and maximal nominal scantlings are prescribed by the head structural designer in Table 3a. They are corrected for the corrosion allowance according to Register [2].

Table 3a. Optimization model

Tablica 3a. Optimizacijski model

WAGON CARRIER: Optimization model												
Structure (Strake no.)	Plate thick.		Stiffeners HP		Longitudinal girder				Transverse frame			
	min	max.	min.	max.	HGW	TGW	BGF min-max	TGF min-max	HFW min-max	TFW min-max	BFF min-max	TFF min-max
Bottom (1-4)	9.5	15.5	140 x 9	180 x 10								
Bilge (5,6)	9.5	14.5										
Center bott. Gir. (7)	12	17	FIX 160 x 9									
Bottom girder (8,36)	12	17	FIX 150 x 12									
Inner bottom (9-11)	12	17	200 x 9	200x 1.5	FIX 300	FIX 9	60-100	12-16				
Inner bottom (12,13)	12	17	140 x 7	200 x 10								
Side (14,15)	9.5	14.5	160 x 7	200 x 10					FIX 450	8-13	200-300	18-22
Side (16,17)	9.5	14.5	160 x 7	180 x 10					FIX 450	8-13	200-300	18-22
Bulkhead (18)	8	13	140 x 7	180 x 10					350-450	8-13	150-250	12-14
Bulkhead (19-20)	8	13	140 x 7	180 x 10					350-450	8-13	150-250	12-14
Deck 7500 (22-25)	12	17	FIX 200 x 11.5		FIX 300	FIX 9	FIX100	FIX14	FIX 550	8-12	250-400	25-30
Deck 7500 (26)	12	17	FIX 200 x 11.5		FIX 550	FIX 10	FIX 100	FIX 20	FIX 550	8-12	250-400	25-30
Side (27,28)	9.5	14.5	120 x 7	140 x 8					270-365	10-13	200-300	18-35
Side (29,30)	9.5	14.5	120 x 7	140 x 8					FIX 365	FIX 12	FIX 250	FIX 35
Deck 13350 (31-33)	8	13	120 x 7	160 x 9	FIX 400	FIX 9	FIX 200	FIX 20	FIX 400	8-13	200-300	20-25
Deck 13350 (34,35)	8	13	120 x 7	160 x 9					FIX 400	8-13	200-300	20-25

Optimization process

The optimal (**O-1**) design was obtained using two optimization algorithms: Sequential Linear Programming (SLP) and Multi-criteria two level Evolution Strategy (ES) based on Fractional Factorial Experiments (FFE). Its mass was decreased to 808 t and number of unsatisfied, strength criteria was simultaneously decreased from 37 to 15. Deflection was unchanged (25 mm) and acceptable. In collaboration with head designer new designs (**D-1**) to (**D-3**) were developed and analyzed and new scantlings were chosen on the basis of optimal design (**O-1**).

The final selected design **D-3** had mass of 849 t and all safety criteria satisfied with deflection of 25 mm. This shows that addition of $849-808 = 41$ t was necessary to solve unsatisfied criteria caused by hull-superstructure interaction with respect to optimal design and to standardize scantlings according to shipyard practice.

It should be also mentioned that superstructure was not directly included in the initial optimization model and that its effective part may have contributed to further savings. New MAESTRO features permit multi-module optimization and such experiment will be performed in the near future.

Optimization process included 304 design variables of which 223 are active. The constraint set includes 446 min-max criteria and for each strake and 33 nonlinear safety criteria or in total 219 965 safety calculations for 5 load cases.

Constraint activity is monitored to enable designer to identify or modify criteria blocking further decrease in weight. Usage of Register minimal requirements has resulted in blocking of most variables on given minimal values, so that with respect to given strength criteria the design has some reserve strength. Stiffener and/or web-frame spacing may have influenced design weight if they were not fixed before optimization process.

Table 3b. Optimization results

Tablica 3b. Rezultati optimizacijskog procesa

MODEL	Mass of control structure (t)	Unsatisfied criteria		DEFLECTION (mm)	Description of MODEL
		No.	Mean value		
P-Y	817	37	-0.25	41.7	Yard scantlings based upon RS minimum requirements
P-0	874	0	/	25	Redesign of prototype P-Y to achieve required permissible displacements of upper and accommodation decks and to solve unsatisfied constraints/criteria
O-1	808	15	-0.19	25	Optimal design with some remaining unsatisfied constraints
D-3	849	0	/	25	Final design generated in collaboration with head designer with standardized scantlings according to shipyard practice.

Saving of about 3% steel weight was achieved for final standardized design (**D-3** → **849 t**) with respect to prototype design (**P-0** → **874 t**), simultaneously satisfying deflection and strength criteria, Table 3b.

Results of prototype and of structural redesign

Deformed plot of the complete model is shown for load case LC 2 (sagging), Fig. 4.

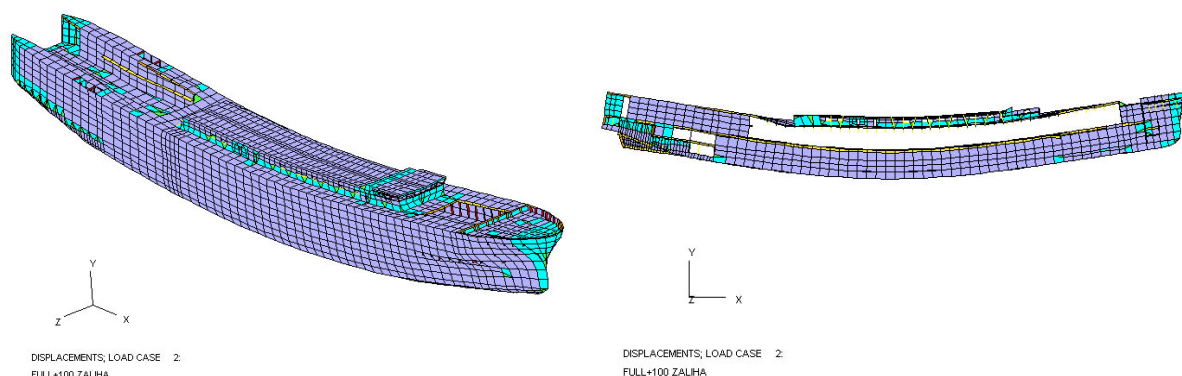


Fig. 4 Deformed plot of the complete model for loadcase LC 2

Slika 4. Prikaz deformacije kompletnog FE modela za LC2

Significant relative displacements are given in Table 4. for positions marked in the Fig. 5. Relative displacements specified by the designer (functionality requirements) allows for maximal $\delta_2 < 25$ mm in accommodation deck (1.5 ‰) and $\delta_1 < 10$ mm in upper deck (1 ‰).

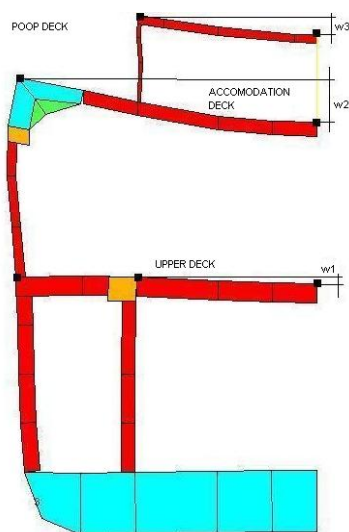


Fig. 5 Position of relative displacement

Slika 5. Pozicija očitavanja relativnih pomaka

		RELATIVE DISPLACEMENT IN VERTICAL DIRECTION (mm)							
		P-Y				P-0			
		LC1	LC2	LC3	LC4	LC1	LC2	LC3	LC4
	w ₁	0.8	3.0	6.0	5.0	0.6	3.5	4.4	5.1
FR.60	w ₂	9.7	41.7	11.5	28.7	13.2	21.6	15.1	15.6
	w ₃	/	/	/	/	/	/	/	/
	w ₁	0.3	6.5	6.6	7.5	0.3	5.7	6.6	7.2
FR.78	w ₂	22.8	7.5	28.6	8.6	17.9	2.8	22.5	4.5
	w ₃	12.3	2.4	13.5	4.6	10.8	0.3	9.0	2.3
	w ₁	0.9	8.0	5.8	7.0	0.9	6.5	5.7	7.2
FR.111	w ₂	35.0	10.8	32.1	9.6	25.2	7.4	22.7	6.3
	w ₃	15.8	7.3	14.5	5.7	11.8	5.5	10.6	5.1

Table 4. Significant relative displacements

Tablica 4. Značajni relativni pomaci

Relative displacements for design (P-Y) in accommodation deck were unacceptable in the region affected by the superstructure (Fr. 57-135). Based upon unacceptable displacements for (P-Y) design in accommodation deck (Table 4) the following changes were introduced in consultation with head designer and (P-0) design is generated:

- intermediate web-frames were inserted right and left of Fr. 63 (aft end of superstructure);
- flange of the accomod. deck transverses was increased for 4 long. spacings from C.L.;
- additional girder was applied at C.L. between Fr. 54-69;

- web-frame scantlings between upper and accomm. deck (Fr.54-135) were increased.

Using insight into MAESTRO results (stresses, deflections, adequacy parameters, optimal scantlings) the head designer was able to solve the problems in prototype structure (P-Y) and also achieve scantlings reductions through optimization based decision support process:

- Bottom structure (Fr. 60-135; 0.4 L amidships) has been strengthened against buckling by increased plate thickness and stiffeners.
- Additional longitudinal stiffener against buckling was inserted on center girder.
- Due to low stress levels, the thickness of floors was reduced to the optimal value.
- Due to 3D effects the high shear stress is recorded in deck transverses (/for LC 3) between Fr.42-48 (influence of longitudinal bulkhead bellow upper deck and the inner shell of stern machinery space above this deck). Thickness of web was doubled.
- High shear stress is recorded in longitudinal girder of upper deck between Fr. 10-18 due to weight of stern structure and influence of longitudinal and transverse bulkheads. Modifications include replacement of centerline girder with longitudinal bulkhead between platform and upper deck.
- Transition area of accommodation to forecastle deck from Fr.150-177 was locally strengthened (material quality, scantlings).

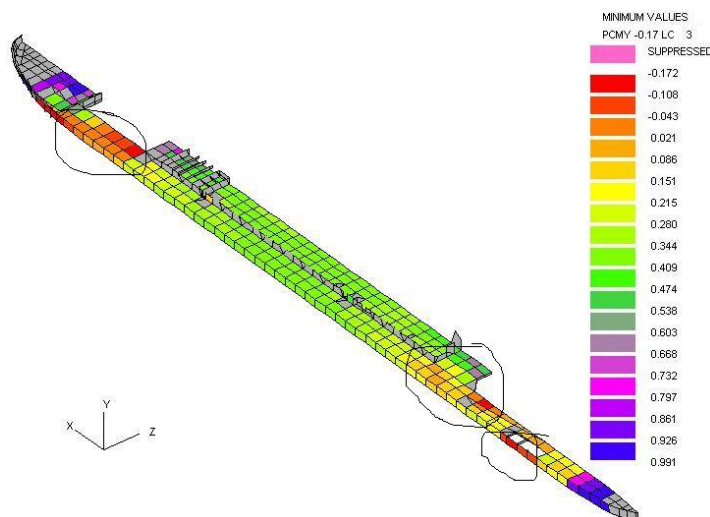


Fig. 6 Worst normalized safety factors PCMY achieved in the plating of accommodation deck

Slika 6. Najniže realizirani normalizirani factor sigurnosti PCMY postignuti u oplati palube

Hull-superstructure interaction

In order to present the effectiveness of the very long superstructure in vertical bending (long. strength) an overall view of normal (σ_x) stresses are presented for LC2, see Fig.7.

Due to stress distribution it is obvious that superstructure was effective in the midship region (Fr. 87-111). The effectiveness was analyzed with respect to stresses and displacement.

Distribution of σ_x stresses for LC1 along hull depth for the superstructure side (position 5250 mm from CL) is presented in Fig. 8 for the chosen design and alternative concepts (2 or 3 parts with 1 or 2 expansion joints) generated in the sensitivity study:

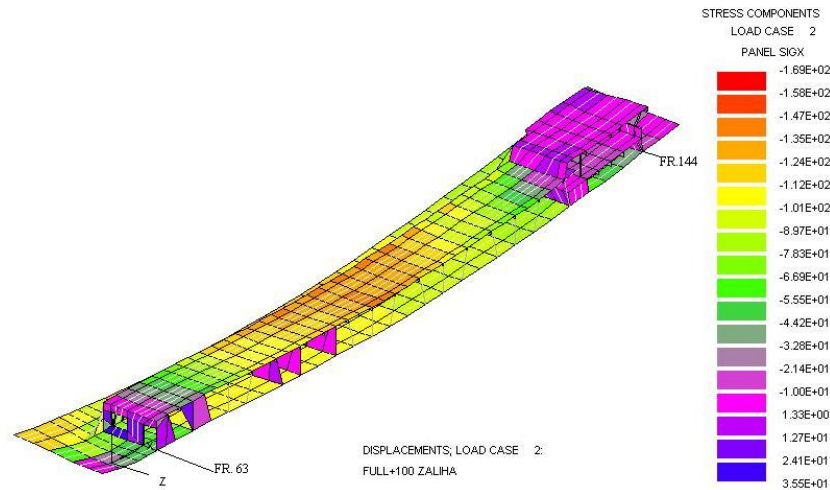


Figure 7. Normal (σ_x) stresses of hull girder for LC 2

Slika 7. Normalna (σ_x) napreznja u gornjim palubama za LC2

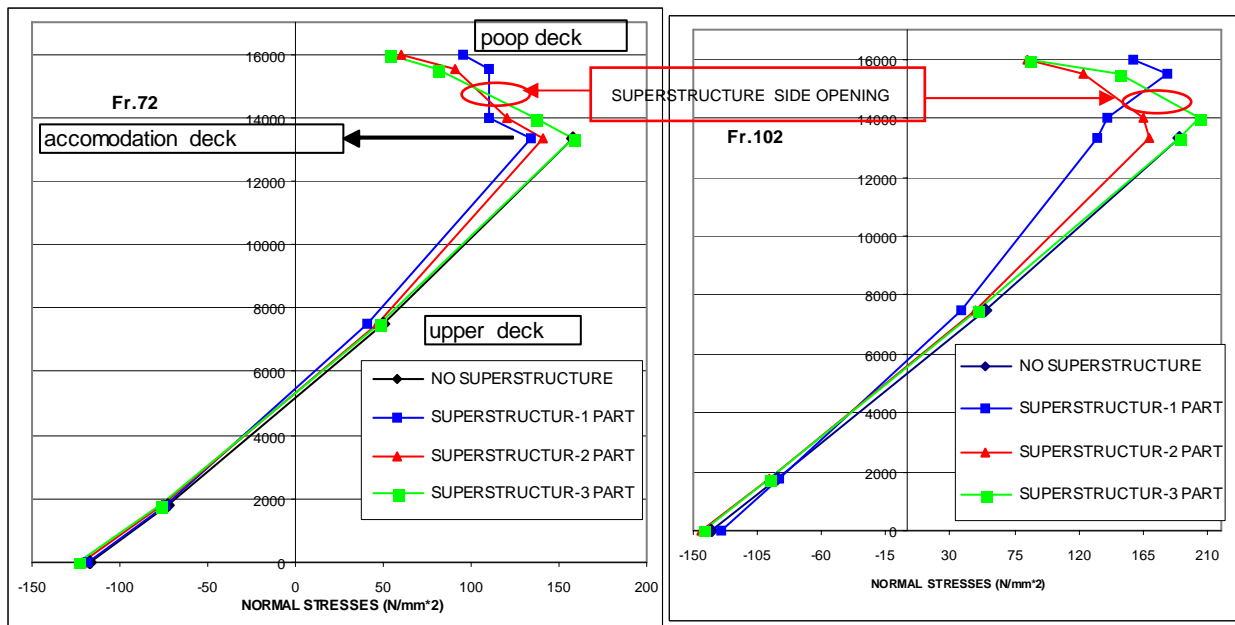


Figure 8. Stress distribution of normal (σ_x) stresses along hull depth for Fr.72 and Fr.102

Slika 8. Distribucija normalnih (σ_x) napreznja po visni poprečnog presjeka za R.72 I R.102

- Concept with expansion joints solved the problems (compressive stresses) of poop deck.
- Stress concentrations at openings in superstructure sides were of the similar intensity as in solutions without expansion joints, see Fig 8.
- Stress levels in accommodation deck were higher, for concepts with expansion joints, especially for solution with two joints, where stress levels were similar to the levels obtained for the hull without superstructure.
- Also, the potential problems with the expansion joints construction, production and maintenance have to be taken into account.

It appears that the concept of superstructure in one part was the most rational solution for this ship.

Efficiency of superstructure was analyzed in the term of stresses proposed by Cadwell [5] and displacement proposed by Mackney and Ross [6]. Efficiency in the terms of stresses [5]:

$$\eta_s = \frac{\sigma_{x0} - \sigma_x}{\sigma_{x0} - \sigma_{x1}}$$

σ_{x0} – max. stresses on the hull main deck without superstructure;

σ_x – max. stresses on the hull main deck with superstructure;

σ_{x1} – max. stresses on the hull main deck calculated with beam theory considering superstructure fully effective.

Efficiency in the term of displacements [6]:

$$\eta_d = \frac{w_o}{w_s}$$

w_o – max. displacement of the hull at main deck without superstructure;

w_s – max. displacement of the hull at main deck with the superstructure;

The results regarding superstructure efficiency are summarized in Table 5.

Vertical displacements along hull for two positions (CL and side) at main deck for LC 1 are presented in Fig. 9. (Note: NO SS means hull without superstructure).

Table 5. Superstructure efficiency for different concept

Tablica 5. Efektivnost nadgrađa za različite koncepte

SUPERSTRUCTURE CONCEPT	Efficiency in the terms of stresses- η_s	Efficiency in the terms of displacements - η_d
1 SS- superstructure in 1 part (without expansion joints)	0.65	1.099
2 SS- superstructure in 2 part (1 expansion joints)	0.21	1.022
3 SS- superstructure in 3 part (2 expansion joints)	0.11	1.004

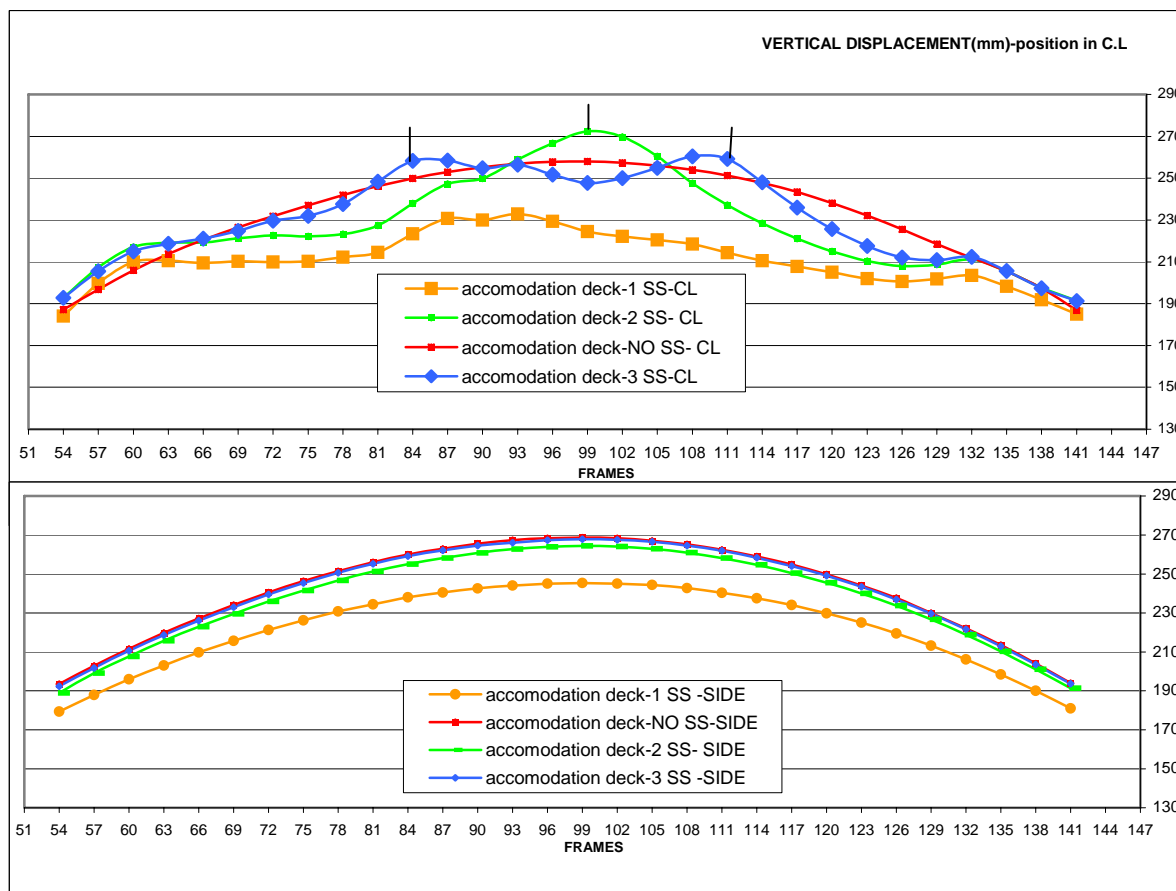


Fig. 9 Distribution of vertical displacements of accomodation deck along hull
Slika 9. Raspored vertikalnih pomaka na palubi duž trupa

Since the superstructure in one part was adopted for the ship the detailed analysis of structural problems was performed:

Buckling criteria were not satisfied in poop deck and superstructure side for LC2 (sagging), particularly around openings. Redesign includes:

- spacing of longitudinals in poop deck was changed and the profile size was increased,
- increase of poop deck plating thickness for different zones was adopted.
- regarding bi-axial buckling the inter-costal stiffeners in the superstructure side were applied at selected heights to decrease the unstiffened areas.

Yield criteria were not satisfied in (coarse mesh modeled) side bulkhead, particularly around openings. Fine mesh analysis of side bulkhead using *top-down approach (global coarse-mesh FE model provided boundary conditions for fine mesh analysis)* was performed for the final position of side openings, Fig 10. Stress concentration areas for windows and doors were analyzed, Fig 11. Redesign includes: (a) inserted plates of AH36 material as reinforcement to avoid stress concentrations around window openings and (b) flanges around door openings.

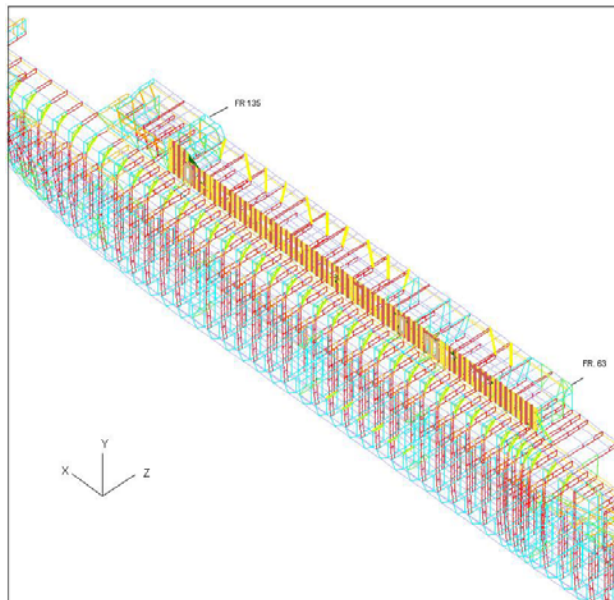


Figure 10. Fine mesh model inserted into coarse mesh MAESTRO model

Slika 10. FE model fine mreže uklopljen u MAESTRO model grube mreže

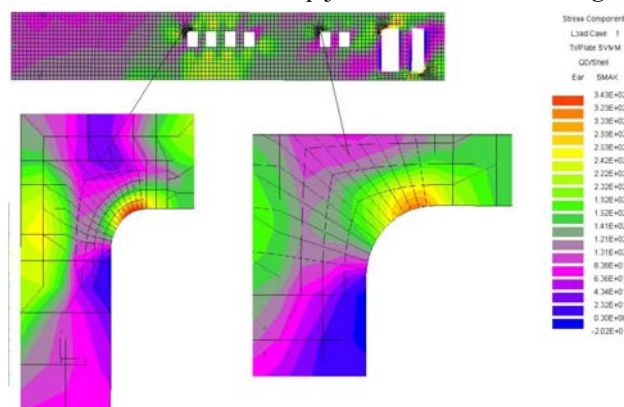


Figure 11. Von Mises equivalent stresses along side of the superstructure Fr.76-Fr. 85 for LC 1

Slika 11. Ekvivalentna Von Mises naprezanja duž bočne stranice nadgrađe između R.76-85 za LC1

6. Conclusion

Presented work represents the successful cooperation and joint work of Yard and Faculty design teams as an example of modern procedure in rational structural design. The conclusions are as follows:

- Decision support process with scantlings optimization gives to the head designer the rational basis for determination of the final design scantlings.
- Only the full ship FEM model is capable to simulated realistic 3D effect of hull/superstructure interaction without restricting assumptions. Effectiveness of superstructure in longitudinal strength was analyzed and efficient redesign was developed.
- Sensitivity analysis, based on parametric investigations of alternative superstructure concepts, has provided designer with rational arguments regarding benefits/drawbacks of the selected designs.
- Fine mesh analysis using *top-down approach* (implemented for superstructure side openings) was found to be very efficient and rapid procedure for solving the stress concentration problems.

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