(2.31)

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STRUCTURAL ANALYSIS OF LIVESTOCK CARRIER

Summary

The main results of structural analysis of livestock carrier designed in ULJANIK shipyard (Yard no. 486-487) have been presented. The most important aspects in a rational structural design of this kind of ships have been underlined. The ship structure is characterized with large openings in the superstructure side shell and with the absence of transverse bulkheads in superstructure part (zone above Deck 6). Ventilations tubes (channels) are integral load carrying part of the structure. Two main structural problems have been evaluated: (1) longitudinal strength, with the appropriate level of superstructure participation in the hull girder bending; (2) transverse/racking strength, where the capability of transverse structure has been evaluated. The strength calculation has been carried out according to RINA Rules using FE coarse mesh approach. Superstructure participation in hull girder longitudinal bending has been evaluated and longitudinal stress distribution over ship height has been analyzed for the prototype and the proposed model. Critical locations (where a fine mesh FE analysis is needed) with the high stress concentrations have been identified. Gain in structural weight has been achieved in the superstructure due to the rational redesign procedure.

Ključne riječi: *livestock carrier, structural design, full ship FE model, longitudinal and transverse strength*

STRUKTURNA ANALIZA BRODA ZA PRIJEVOZ ŽIVE STOKE

Sažetak

Svrha rada je prikazati najvažnije rezultate strukturne analize broda za prijevoz žive stoke projektiranog u brodogradilištu ULJANIK (Gradnja 486-487). Prikazani su glavni aspekti koje je potrebno razmotriti prilikom racionalnog projektiranja konstrukcije ovakvih tipova broda. Struktura broda odlikuje se velikim otvorima u boku iznad najgornje palube trupa, te nepostojanjem poprečnih pregrada u strukturi nadgrađa (između paluba 6 i 10). Cijevni ventilacijski kanali su integralni, nosivi dio strukture. To zahtjeva pažljivo razmatranje dva globalna strukturna problema: (1) problem uzdužne čvrstoće uz sudjelovanje paluba nadgrađa; (2) problem poprečne čvrstoće i nosivost poprečnih elemenata. Proračun čvrstoće je proveden je prema Pravilima klasifikacijskog društva RINA koristeći postupak modeliranja cijelog broda 'grubom' MKE mrežom. Sudjelovanje paluba nadgrađa u uzdužnoj čvrstoći izraženo je preko stupnja efikasnosti nadgrađa, te su analizirani dijagrami distribucije primarnih naprezanja po visini trupa za nekoliko karakterističnih presjeka, za početni model i predloženu varijantu. Identificirane su kritične točke u kojima se pojavljuju koncentracije naprezanja za koje je potrebno provesti proračun 'finom' MKE mrežom u dogovoru s klasifikacijskim društvom. Racionalnim dimenzioniranjem ostvarene su značajne uštede u težini nadgrađa i gornje palube trupa.

Key words: *brod za prijevoz žive stoke, strukturna analiza, MKE, uzdužna i poprečna čvrstoća*

1. Uvod

The extensive superstructure characterizes some ship types: cruise ships, passenger ferries, RoPax ships, car carriers, etc. Examined livestock carrier can be classified as a ship with a strong hull-superstructure interaction. The height of the superstructure is approximately equal to the height of the lower part of the hull and its influence on longitudinal strength of the ship is very important. Thus, it should be taken into consideration during a design and dimensioning of the structural elements.

A term strength deck, which is obvious for ships with a single deck, in this case is obsolete. The design of the structural elements on the assumption that only the lower part of the hull participates in the longitudinal strength is not rational and it could cause an excessive scantlings of structural elements in the lower part of the hull. The assumption that the superstructure is 100% effective and that a classical Bernoulli beam could be applied for estimation of primary stresses also is not valid for this type of the structures. Nonlinear distribution of the primary stresses in the hull is caused by many factors such as reduced shear stiffness of the side shell due to large openings, a shift of the side wall line of the hull or superstructure due to recess, the free end effect of short superstructures, influence of length, breadth and height of the superstructures, etc. For the rational structural design of these kinds of vessels, the correct primary stress distribution amidships along the height of the cross section (lower part of the hull+superstructure) should be determined. Scantlings of structural elements around midship calculated in the early design phase have a huge impact on the further process of the project. The effective superstructure design is very important because of a regulation of weights and vertical position of gravity, due to speed and stability requirements. Relatively large ship's height (hull + superstructure) could cause a large reduction of the primary stresses in upper lower hull decks if the superstructure only partially participates in longitudinal strength of ship.

Also, this kind of ship is characterized with the absence of transverse bulkheads in the superstructure part, so special care has to be focused also on transverse strength (racking) calculation due to non-symmetrical load cases.

Nowadays, most suitable and accepted method for final checking of structural adequacy of ships with large superstructures is the 3D FEM coarse mesh model of a complete ship.

In the cooperation with the ULJANIK Shipyard, Pula, the University of Zagreb, Faculty of Mechanical Engineering and Naval Architecture has carried out the full ship 3D FEM analysis of the complete hull of Yard number: 486-487 designed in ULJANIK Shipyard [2]. Presented research represents continuations of previously presented work, see [7], on similar ship already built by ULJANIK (Yard no.428) and long-term effort in structural design improvement of ULJANIK vessels.

The objective of the analysis was to investigate the structural strength in fulfilment of the requirements for direct calculation of the classification society Registro Italiano Navale (RINA) [3], including: (1) longitudinal strength analysis, (2) double bottom analysis, (3) transverse strength analysis, (4) detail stress analysis of structure around openings in deck 6, side shell, etc. The main results of those investigations have been summarized through this paper. MAESTRO software [4] was used for calculation of the structural response of the full ship 3D FEM model.

2. Vessel description

The vessel is a LIVESTOCK CARRIER 24 000 sq. meters with the following principal dimensions:

Length overall	185.20	m
Length between perpendiculars	169.26	m
Breadth moulded	31.10	m
Depth moulded to DECK no.6	14.53	m
Depth moulded to DECK no. 10	24.33	m
Draught design moulded	7.70	m
Draught scantling moulded	8.70	m
Deadweight at design draught	10800	t
Deadweight at scantling draught	14700	t
C_B at d=8.70 m	0.54	
Main engine MCR	MAN B&W 7S50 MC-C	
Output	116200 kW/127 r.p.m.	
Speed trial (90% MCR)	19.8	knots

Ship has 10 decks and a deck house. The pen and access arrangement defines the layout of ordinary and primary pillars in transverse direction. The arrangement is based on *AMSA* (*Australian Maritime Safety Authority*) Rules: the breadth of a single pen is limited to 4.5 m and minimal access breadth between stores for food and water is 0.7 m. Based on these constrains 6 pens (layout: 1+2+2+1) and 3 access are arranged in transverse direction.

The ship is longitudinally framed with the exception of ship sides above Deck 1, some areas within the engine room, fore and aft peak structures. The ship structure is characterized with large openings in superstructure side shell and with the absence of transverse bulkheads in superstructure (zone above Deck 6). Large ventilations tubes (channels) are integral load carrying part of the structure. Two RINA approved material qualities were used:

Steel Grade	NSS	Minimum yield stress = 235 N/mm^2
Steel Grade	AH36	Minimum yield stress = 355 N/mm^2

Fig. 1 shows an outline of the general arrangement of the vessel.

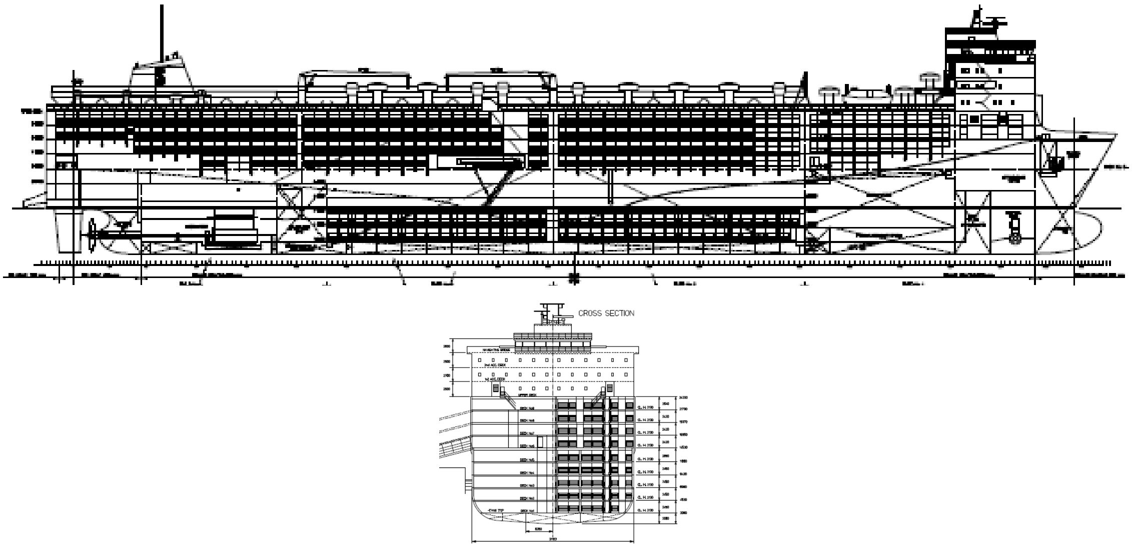


Fig. 1 General arrangement of livestock carrier

Slika 1. Generalni plan broda za prijevoz žive stoke

3. Mathematical Model and Boundary Conditions

In the view of the non-symmetrical structure and racking loads, the entire full ship FEM model was performed to give deflection, stress and adequacy results and simultaneously provide boundary conditions for further fine mesh analysis of all critical areas. The coarse-mesh, full-asymmetric, global livestock carrier FE model for Yard no. 486 was developed, see Figs.2 and 3. FE modeling details are as follows:

(a) Plated areas such as decks, outer shell and bulkheads were represented by the special stiffened shell macroelements. MAESTRO stiffened macroelement uses the NASTRAN type **QUAD4** 4-node shell elements enhanced with stiffeners in their proper geometrical position regarding axial and bending energy absorption / detailed stress output.

(b) TRIA triangular 3 node elements were also applied with appropriate thickness.

(c) Smaller primary transverse frames or girders were modeled with bracketed beam macro-elements (where beam theory is applicable).

(d) Larger web frames or girders were modeled with elements as ad (a) or (b).

Full ship 3D FEM model had 52 827 nodes and 77 722 macro-elements (stiffened panels and bracketed beams). Ventilation ducts (tubes) were in general modeled with the eight plate segments and are penetrating respective decks with a ‘collar’ of plate elements. Element thicknesses and properties were calculated from the scantlings shown on the structural plans supplied by the Yard. Net scantling approach was implemented based on complete ship model in accordance with reference [5], (see, Pt. B, Ch 4, Sec. 2.) Manholes (and similar) in the webs of primary supporting members (particularly in double bottom floors) were disregarded [3] and element thickness has been reduced in required proportion.

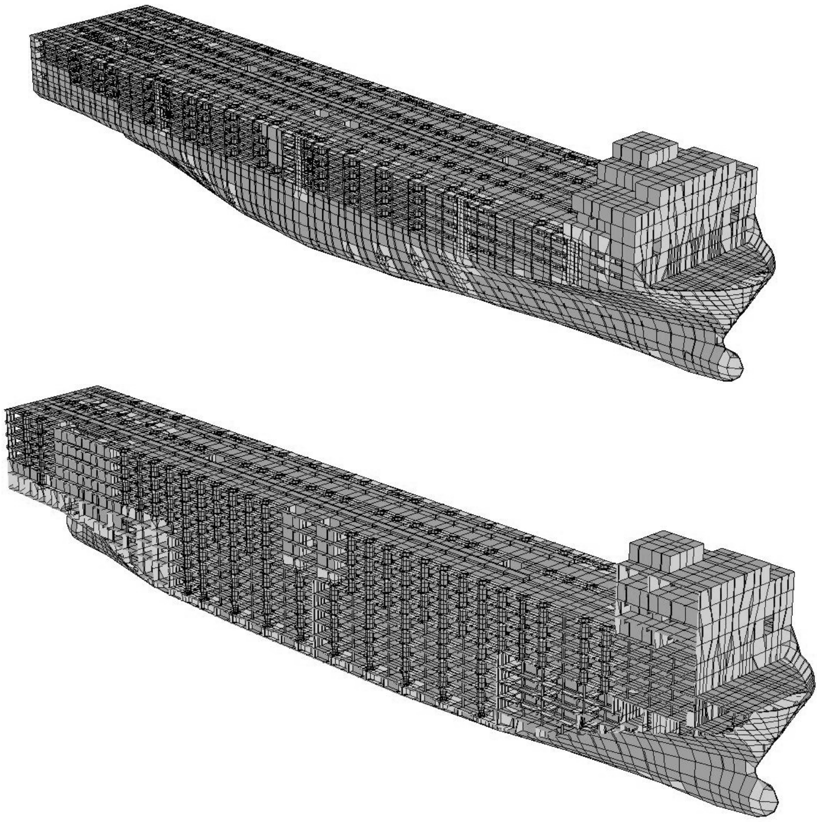


Fig. 2 Full ship FEM model of livestock carrier

Slika 2. MKE model cijelog broda za prijevoz žive stoke

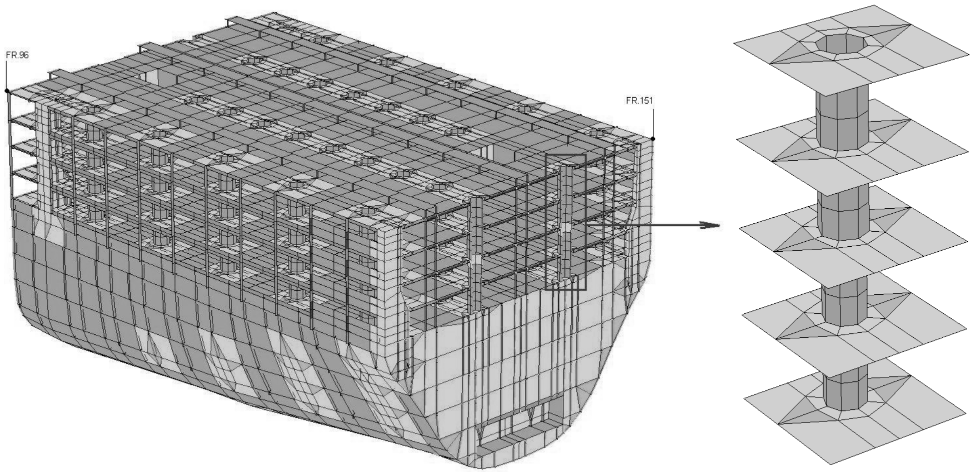


Fig. 3 Part of the full ship FEM model - area between Fr.96 and Fr.151 and ventilation tubes detail

Slika 3. Dio MKE model cijelog broda - područje između R.96 i R.151 i detalj ventilacijskih cijevi

To prevent rigid body motion of the model and singularity of the free ship stiffness matrix boundary conditions were implemented in accordance with RINA Rules [3], see Fig.4.

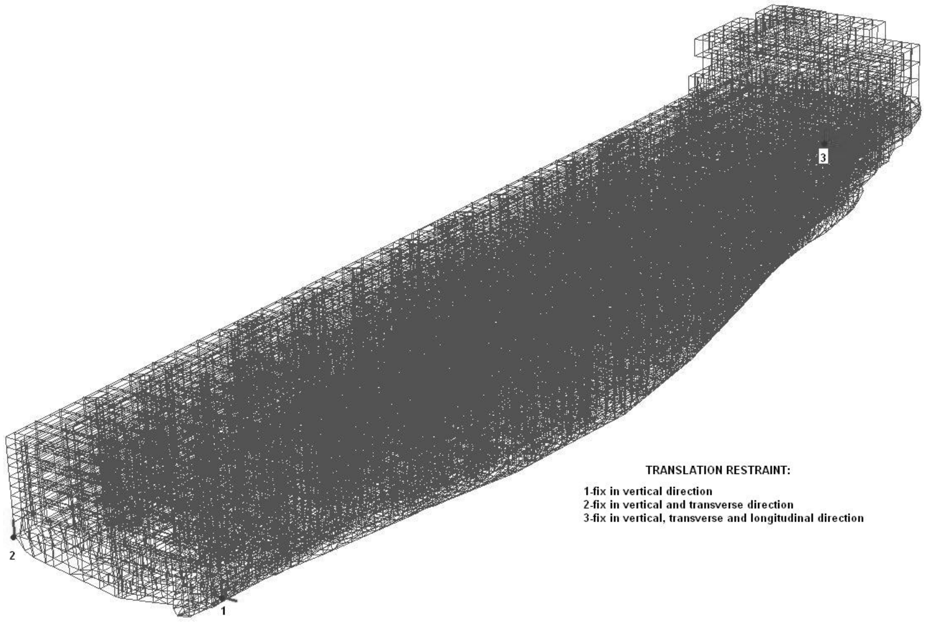


Fig. 4 Boundary conditions

Slika 4. Rubni uvjeti modela

Quasi static balancing of the full ship FEM model was performed using MAESTRO automatic balancing option (changing heave, trim and heel) to achieve permitted reaction force levels on the restrained nodes. Reactions obtained for the balanced ship in all load cases were below RINA requirements.

4. Loading

One of the characteristics of considered ship are relatively fine hull lines (low block coefficient) and continuous distribution of lightweight which imply that the ship is always in hogging condition at still water i.e. it has excess of buoyancy amidships and excess of weights at the ends. Due to this distribution of static loads, the structure is loaded by very large still water hogging bending moment. A combination of maximum still water bending moment and maximum wave bending moment in hogging condition produces the maximum longitudinal stresses. A combination of minimum still water bending moment in hogging condition and maximum wave bending moment in sagging condition could generate a compression stresses in upper decks. This should be avoided at any cost because the compression stresses could generate panel buckling problems on the upper decks which mostly consist of very thin plates. For this type of ship it is not a case and the structure is always in hogging condition. Nevertheless, the deck structure is designed in such way that stiffened panels withstand compression stress of minimum 30 N/mm^2. The still water shear force distribution is similar to a conventional distribution with the maximum values at positions 0.25L and 0.75L from aft perpendicular. The design values of shear force are obtained by summing the maximum value of still water shear force with the maximum value of wave shear force. The shear force could cause large shear stresses on the ship side in the areas where the shear stiffness is decreased. One of the advantages of 3D FEM complete ship models is an avoidance of defining force/displacement boundary conditions at the ends which are necessary for partial ship models. The complete models should be balanced such as the reactions in points where the boundary conditions are placed are negligible. A total bending moment (static and wave) and shear forces are derived from static and dynamic load components distribution. Each loading condition comprises of four sets: (1) light ship weight, (2) deadweight, (3) accelerations and (4) buoyancy loading including dynamic pressures.

Static load of an ideal structure is required to be enlarged and adjusted to the lightweight of a ship according to the trim and stability book (T&S) for considered load case. Based on the model geometry and the scantlings of the elements used, a modeled mass for the hull was generated within the program. Additional masses of machinery and equipment were added to the hull mass by concentrated masses at the appropriate nodes. Those masses include superstructure items (other than directly modeled), wheelhouse, stern ramp, rudder and steering gear, bow and stern thruster, diesel engine and transmissions, boiler, main electric power production, fooders. Cargo loading consists of masses of cattle and food. The distribution of cargo loading was defined by Yard in [6]. Cargo masses were concentrated in mesh nodes of the corresponding decks. The masses of water ballast, fuel oil, fresh water etc. were taken from [6]. These masses were generally placed in appropriate tanks, which were modeled inside the ship structure model. The main engine and massive equipment are defined as concentrated masses on their actual positions. Contents of some smaller tanks were idealized by the concentrated masses. The mass distribution defined above was corrected to achieve the distribution given in [6]. Total light ship mass was 11 150 t.

The hull shape of the 3D FEM model slightly differs from the original one, i.e. a difference of a displacement up to 2% are acceptable. A hydrostatic pressure distribution is defined directly by the ship's draught and it is implemented automatically by the software.

Wave induced loads and 3D FEM full ship model implementation

Upon the modeling of wave induced loads it should be mentioned that it is generated with much more uncertainty than the structural model. For a practical implementation of the wave loads on the 3D FEM full ship model there are various methods which use direct calculation of the loads [9, 10]. Design wave method [3] uses elements of deterministic approach in defining an equivalent design wave by which the FEM model will be loaded. This method is used in our case. The dominated load effect, i.e. the target value by which is loaded the FEM model, is the total vertical bending moment (static + wave) for hogging condition where the wave bending moment is calculated by the Rules.

Equivalent design wave is a regular sinusoidal wave (with Smith's effect included) with the following characteristics: length, height (twice the value of amplitude), phase which defines the position of a crest from the origin. It should be mentioned that due to the high nonlinearity of the hull form (deviation of a side shell from a normal above the waterline) at the ends the real wave bending moment is increased in hogging condition and decreased in sagging condition. Correction factor for hogging condition, regarding linear wave bending moment can be considered for this ship type. The value of vertical wave bending moment calculated according to expression from Requirement S11 is not scaled with calculated correction factor but the total value of the vertical bending moment is reduced according to the RINA requirement [3]. Acceleration components were also calculated according to Rules [5] and implemented in the model as an acceleration vector.

Set of critical load cases is selected aiming to maximize dominant load effects having dominant influence on the strength of some part of the structure, Table 1.

Table 1 Load cases description

Tablica 1. Opis slučaja opterećenja

CASE NO.	RINA [3],([5])	LOADING COND. [6]	TYPE OF ANALYSIS	M_{SW} (kNm)[6]	M_{Wave} (kNm)[5]	$M_{Total\ (max)} = M_{SW} + \gamma_{W1} \cdot k \cdot M_{Wave}$ (kNm),[3]	$\mathbf{M_{FEM\ (max)}}$ (kNm)
1	LC a-crest	11-Cattle 14000	Long. Strength	1 187 206	938 517	1 832 437	1 910 000
2	LC b-crest	11-Cattle 14000	Long. and Transverse Strength	1 187 206	938 517	1 832 437	1 870 000
3	LC a-trough	10a-Minimum Hogging	Long. Strength	570 726	-1 177 260	-482 838	- 482 000
4	LC a-crest	2-Ballast cond. 100% Cons.	Double Bottom	1 146 428	938 517	1 791 659	1 815 900
5	LC b-crest	4-IMO 100% Cons.	Double Bottom	1 136 351	938 517	1 781 582	1 760 000
6	LC a-crest	4-IMO 100% Cons.	Double Bottom	1 136 351	938 517	1 781 582	1 780 000
7	LC d- PS down	4-IMO 100% Cons.	Transverse Strength	1 136 351	938 517	1 370 980	1 4000 000
8	LC d- SB down	4-IMO 100% Cons.	Transverse Strength	1 136 351	938 517	1 370 980	1 410 000

The wave bending moment and the total bending moments were calculated according to RINA Rules, [5]. Implemented distribution of the total vertical bending moment and shear forces shows good agreement with the required/target values, see Fig. 5, for LC1 and LC2.

For transverse strength calculation two load cases "b" and "d" were selected. For the transverse strength calculation in the upright condition, the load case LC3 (RINA "b" case) was based on load condition 11 (14000 Cattle). It was chosen according to T&S book due to higher loads on the decks. LC8-IMO full load (Loading Condition 4 according T&S book) was chosen, for the inclined LC1 and LC2 (RINA "d” case), due to high GM that causes the highest transverse acceleration vector.

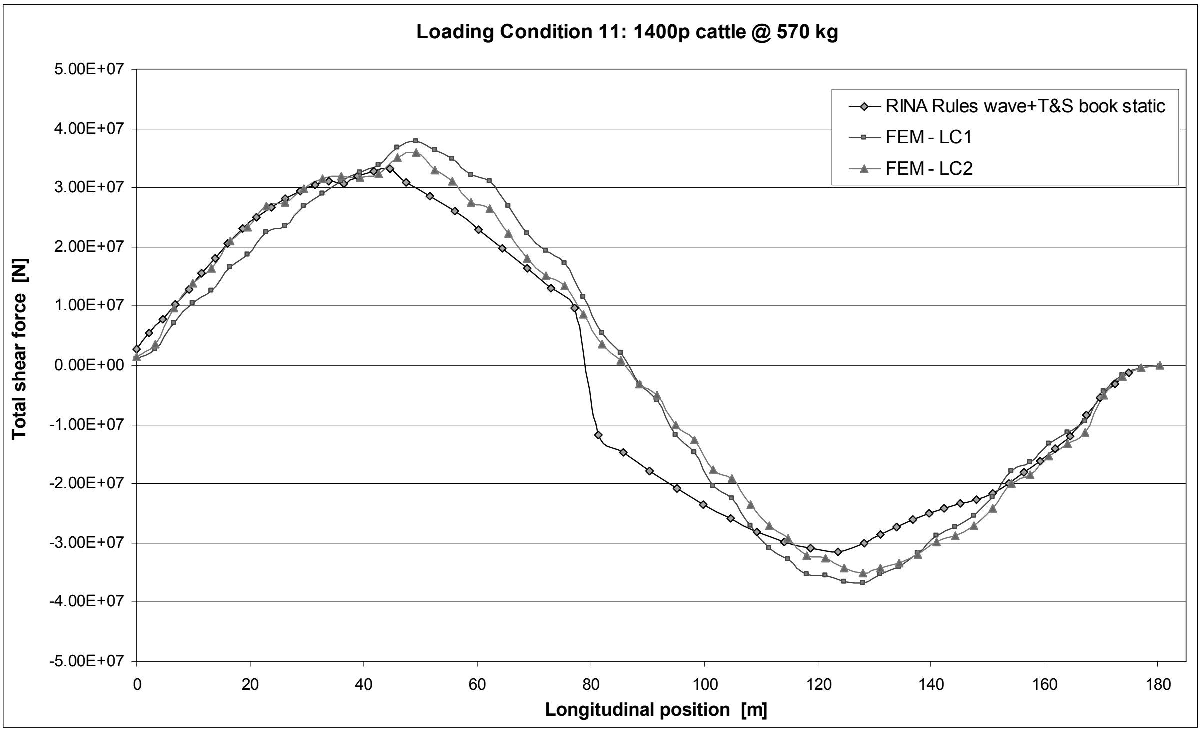


Fig. 5 Shear force distributions for LC1 and LC2 and comparison with RINA requirements

Slika 5. Dijagram poprečnih sila za LC1 i LC2 i usporedba s zahtjevima RINA-e

5. Results

5.1. Longitudinal strength analysis

The full ship 3D FE model provided results for the global deformations, the effectiveness of upper decks, the distribution of longitudinal stresses at each level, etc. as well as the boundary conditions for the fine mesh analysis of the critical details. The model used here, for the RINA analysis specified in [5], was sufficient for all those purposes. The selected load cases represented the approximation of the extreme condition in accordance with the RINA requests. All conclusions were based on the selected load cases. The behaviour of the ship's structure in terms of the global deformation is considered satisfactory from the structural aspect in all loading conditions considered.

Results obtained, confirmed the design assumptions that all continuous superstructure decks participated in the global hull girder bending, see Figs. 6 and 7.

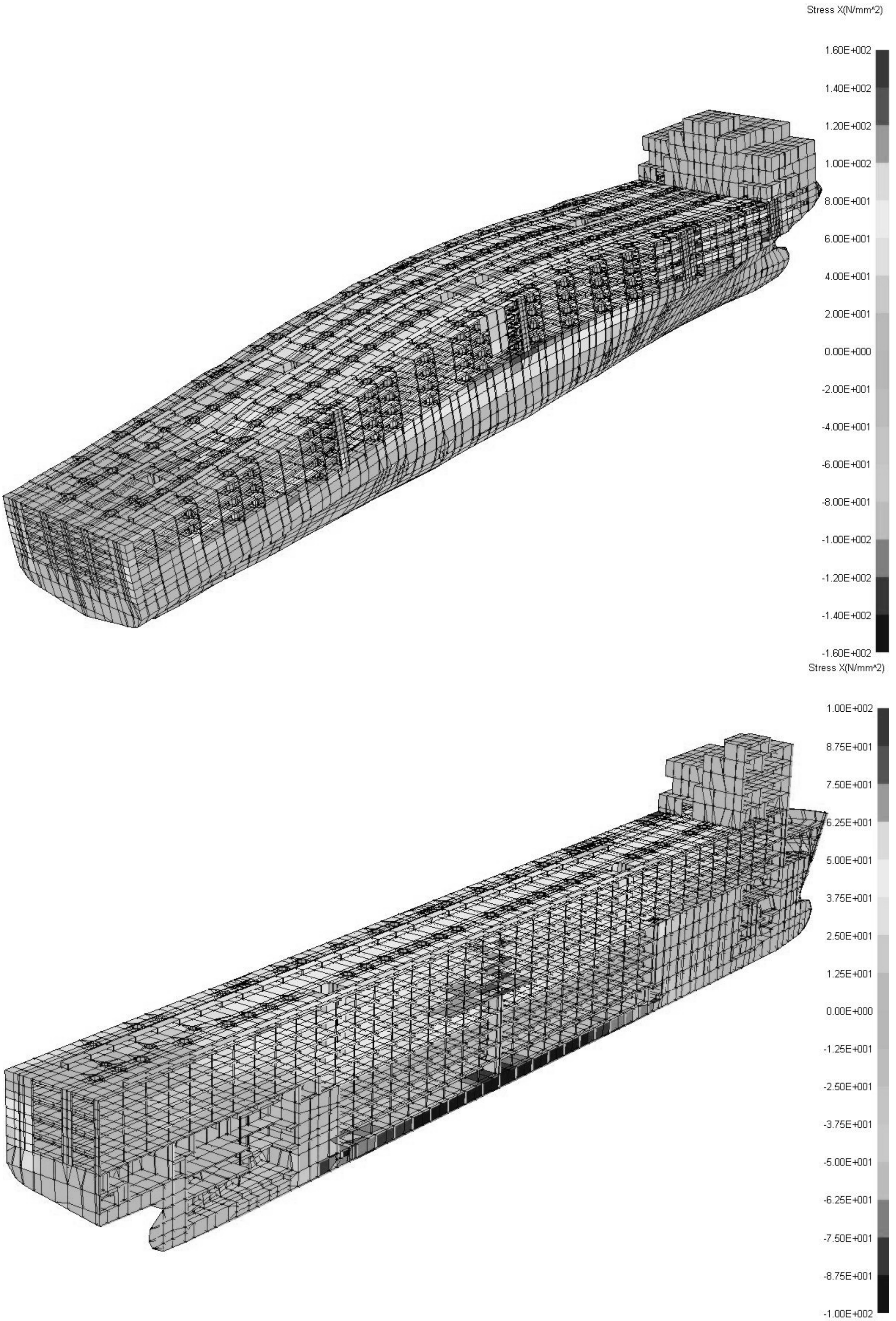


Fig. 6 Deformed full and half ship FEM model and normal $_{x}$ stresses for LC2

Slika 6. Deformirani model cijelog broda i normalna $_{x}$ naprezanja za LC2

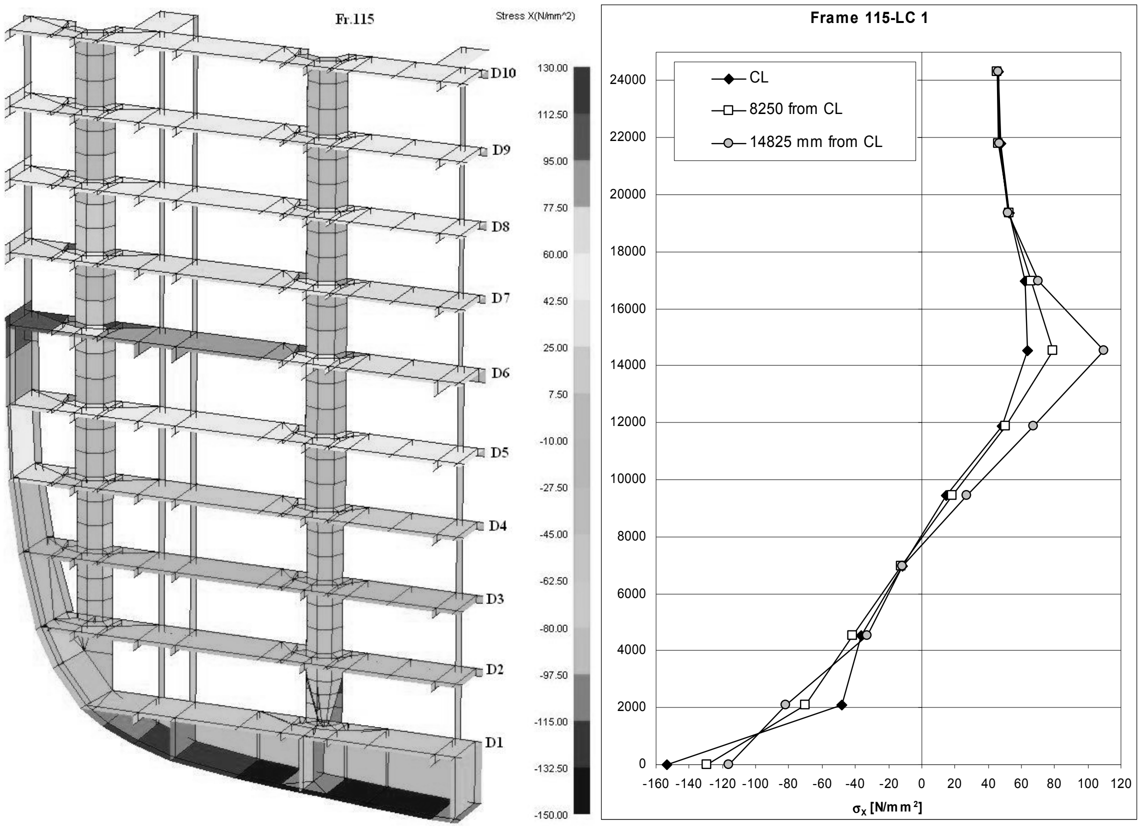


Fig. 7 Normal $_x$ stresses distribution over ship height at Fr.115 for LC1

Slika 7. Normalna $_x$ naprezanja po visini broda na R.115 za LC1

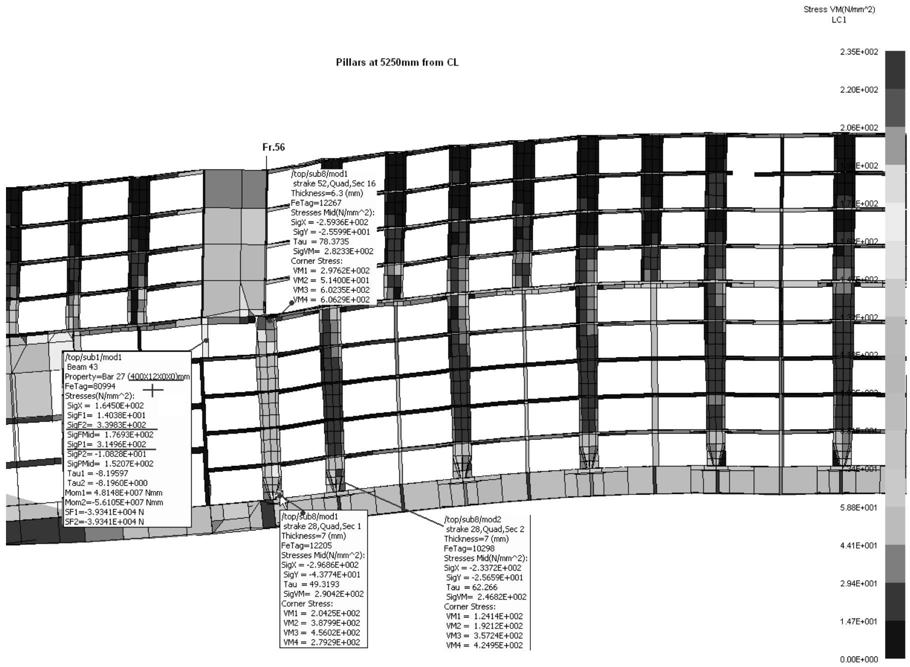
The implemented concept (partially effective superstructure) present an opportunity to reduce structural scantlings of superstructure decks (decks above D6) which are affected by the RINA requirements to increase cross section modulus by increased structural scantlings in superstructure decks. Based on RINA request, sensitivity analysis regarding increase of plating of deck 7 and 8 thicknesses has been performed. Very low influence was identified. Stress differences are below 10 N/mm^2 due to the increased plate thickness of deck 8, from tp=8 mm to tp= 11 mm. It has been verified that the level of normal $_x$ stresses for proposed lightweight solution satisfied RINA requirements. Maximum normal $_x$ stresses were below +160 N/mm^2 (connection of DECK 6 and the outer shell) and -160 N/mm^2 (bottom structure) in region 0.3 L - 0.65 L for LC1-3.

Special attention has to be taken to solve the stress concentrations problems that have been identified in several locations:

Connection of ventilation tubes and pillars with double bottom plating in aft and fore region and connection of ventilation tubes and pillars with deck 6, see Fig. 8. Also, rational selection of pillar profiles has to be taken due to bending (and not only axial stress) that occurs in specified position. Cross-like type of profile has been substituted with tube/ rectangular type of profile.

Side openings in superstructure in fore part of the ship and amidships between deck 6 and 7.

Large casings openings at deck 6.



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FeTag=12267
Stresses Mid(N/mm^2):
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 SigY = -2.5599E+001
 Tau  = 78.3735
 SigVM=  2.8233E+002
Corner Stress:
 VM1 =  2.9762E+002
 VM2 =  5.1400E+001
 VM3 =  6.0235E+002
 VM4 =  6.0629E+002
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FeTag=80994
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 SigF1=  1.4038E+001
 SigF2=  3.3983E+002
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 SigP1=  3.1496E+002
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Mom1= 4.8148E+007 Nmm
Mom2=-5.6105E+007 Nmm
SF1=-3.9341E+004 N
SF2=-3.9341E+004 N
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FeTag=12205
Stresses Mid(N/mm^2):
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 SigY = -4.3774E+001
 Tau  = 49.3193
 SigVM=  2.9042E+002
Corner Stress:
 VM1 =  2.0425E+002
 VM2 =  3.8799E+002
 VM3 =  4.5602E+002
 VM4 =  2.7929E+002
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 SigY = -2.5659E+001
 Tau  = 62.266
 SigVM=  2.4682E+002
Corner Stress:
 VM1 =  1.2414E+002
 VM2 =  1.9212E+002
 VM3 =  3.5724E+002
 VM4 =  4.2495E+002
```

Fig. 8 Maximum Von Mises equivalent stresses in ventilation tubes for LC1

Slika 8. Maksimalna von Mises ekvivalentna naprezanja u ventilacijskim cijevima za LC1

5.2. Double bottom analysis

The fine mesh model, between Fr.71 and Fr.91, was developed and imbedded into global coarse mesh model, see Fig.9.

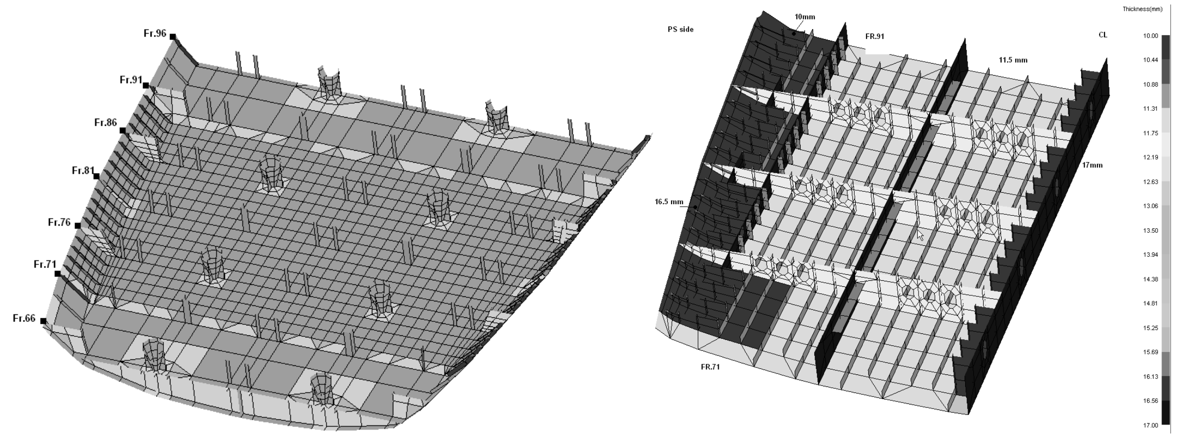


Fig. 9 Fine mesh FEM model of double bottom imbedded in global coarse mesh model and plate thickness

Slika 9. MKE fini model dijela dvodna uklopljen u globalni MKE model grube mreže i debljine limove

Two additional RINA load cases "a-crest" were implemented. Specifics of the examined double bottom structure are that pillars and ventilation tubes transfer cargo loading to the double bottom and support floors w.r.t to external pressure loading. This fact makes ballast condition critical. Several locations with high stress levels have been identified and evaluated/redesigned:

Higher stresses were recorded in the bilge region at the intersection of inner bottom plating, floor and partial transverse BHD supporting ventilation pipes (Fr. 76 and Fr. 86, see Fig. 10).

Very high stresses (at the free edge) were recorded in small brackets that connect the floor with the partial TBHD.

Around manholes (closest to bilge) local stress levels are increased.

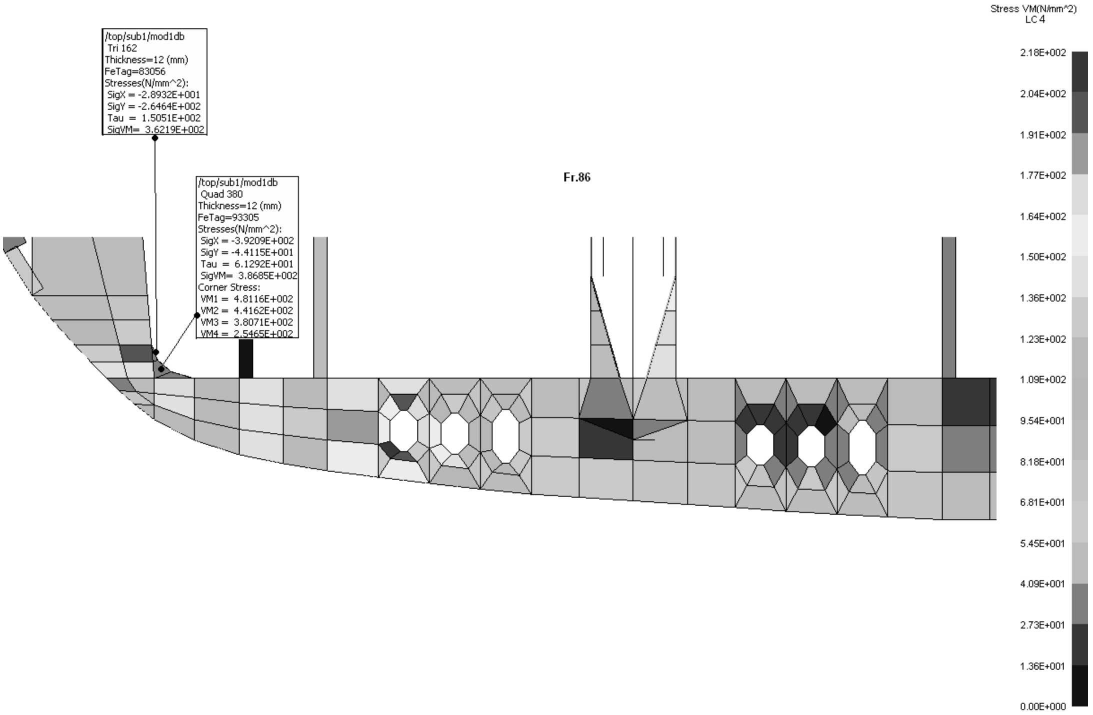


Fig. 10 Maximum Von Mises equivalent stresses at Fr. 86 for ballast load case LC4

Slika 10. Maksimalna von Mises ekvivalentna naprezanja na R. 86 za balastni slučaj opterećenja LC4

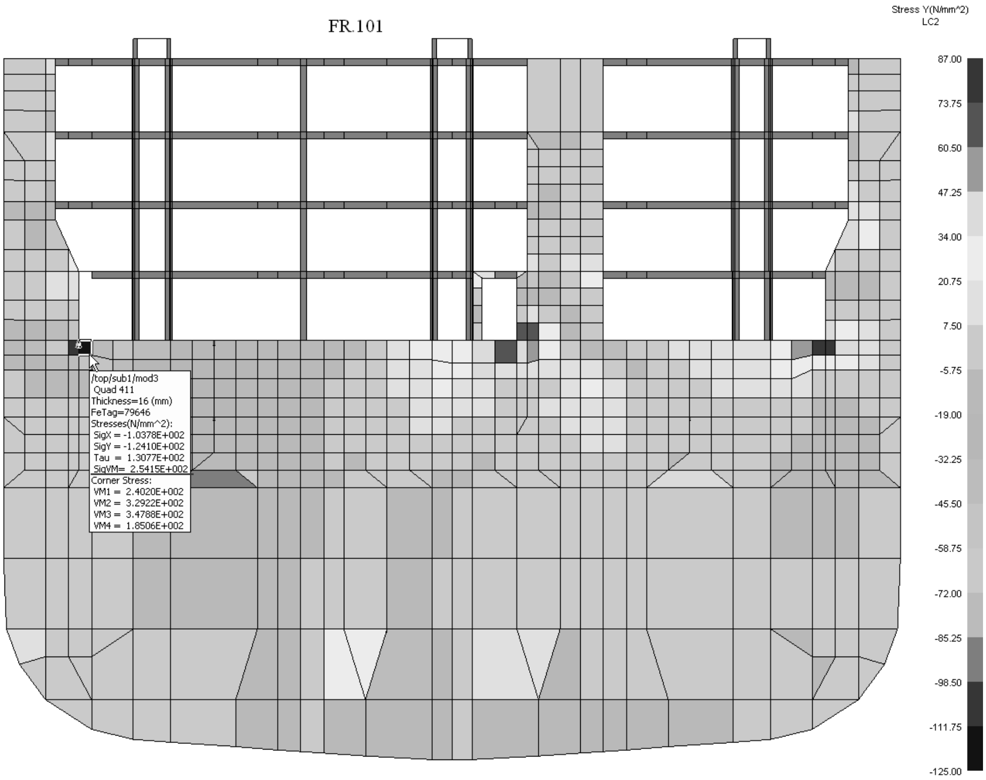
The comparable grillage (based on equivalent 3D beam model) calculation of double bottom structure using artificial boundary condition showed more conservative results.

5.3. Transverse strength analysis

Transverse strength analysis has been performed using presented global coarse mesh model to analyze several critical structural parts.

(a) Strength analysis of transverse bulkheads has been performed. The vessel has several waterproof transverse bulkheads from double bottom to D6 (Fr.51, 101,151 and 181). Fine mesh model was developed and imbedded into global coarse mesh model around specified transverse bulkheads. Model was balanced to achieve required transverse acceleration vector over the model height. Yield and buckling criteria were evaluated for the inclined "d" type load cases according to RINA Rules (LC7 and LC8).

Several high stresses areas have been identified on all examined transverse bulkheads mainly in connection with ventilation tubes, partial casing bulkheads and strong web frames above deck 6. Several highly stressed details are given on Figs. 11 to 13. Certain changes of plate thickness have been implemented following shipyard suggestions to achieve stress level bellow RINA limits (Pt B, Ch 7, Sec 1-3). Detail FEM analysis of critical structural details have been suggested to support local design.



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FeTag=79646
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 SigY = -1.2410E+002
 Tau  =  1.3077E+002
 SigVM=  2.5415E+002
Corner Stress:
 VM1 =  2.4020E+002
 VM2 =  3.2922E+002
 VM3 =  3.4788E+002
 VM4 =  1.8506E+002
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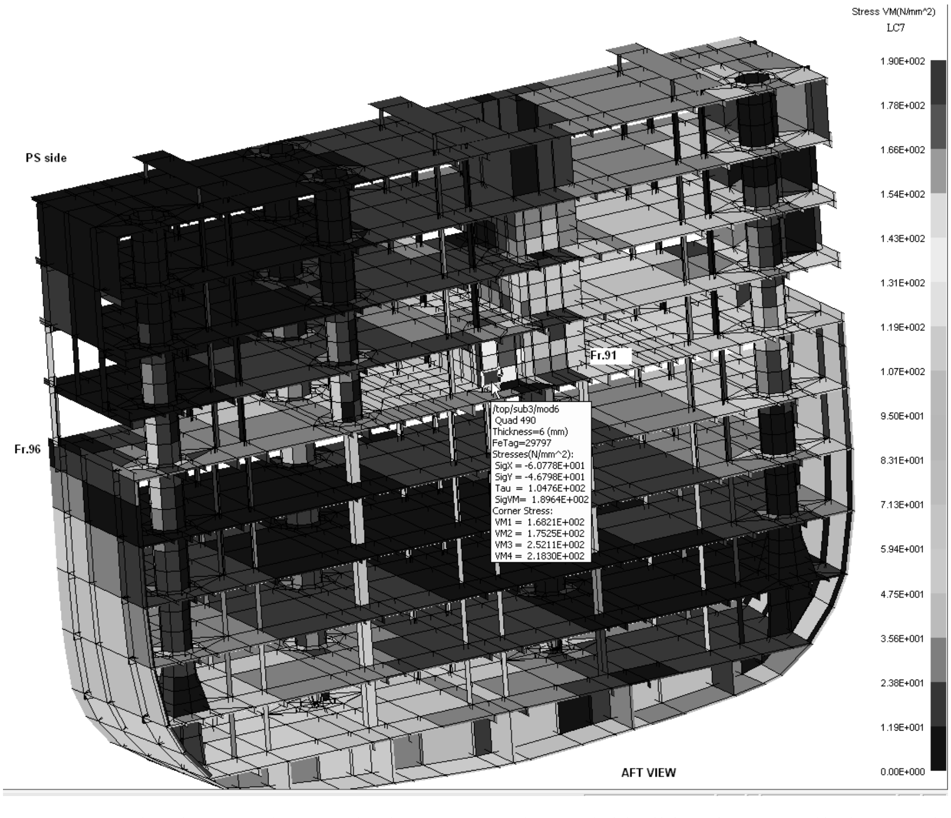
Fig. 11 Normal σ_y stresses in transverse bulkhead at Fr. 101 for non-symmetrical load case LC8

Slika 11. Normalna σ_y naprezanja u poprečnoj pregradi na R. 101 za nesimetrični slučaj opterećenja LC8



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Thickness=6 (mm)
FeTag=29797
Stresses(N/mm^2):
 SigX = -6.0778E+001
 SigY = -4.6798E+001
 Tau  =  1.0476E+002
 SigVM=  1.8964E+002
Corner Stress:
 VM1 =  1.6821E+002
 VM2 =  1.7525E+002
 VM3 =  2.5211E+002
 VM4 =  2.1830E+002
```
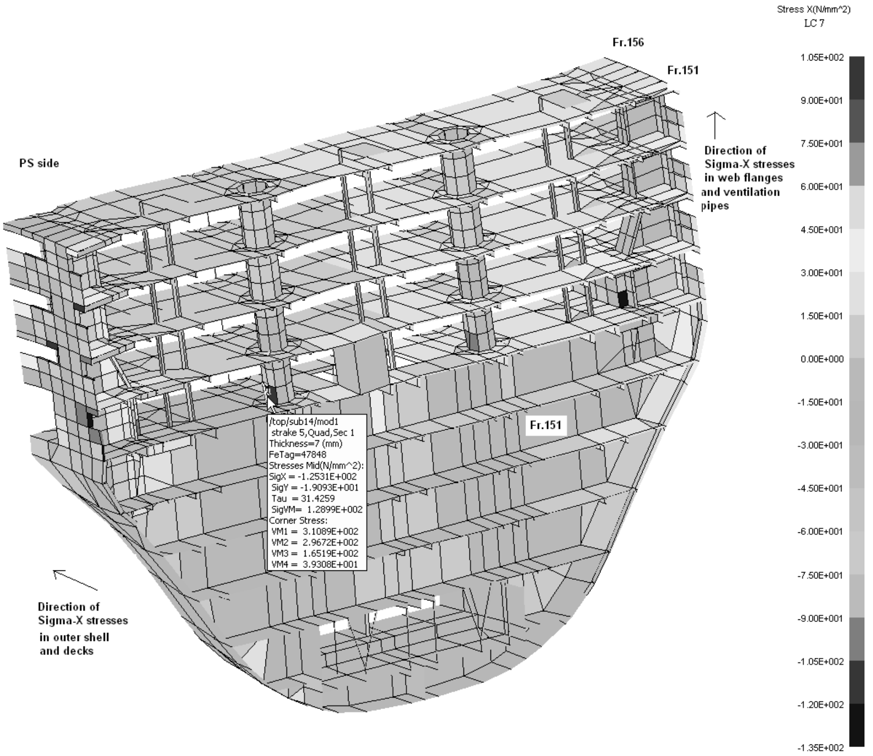

Fig. 12 Maximal Von Mises equivalent stresses in partial bulkheads of ventilation trunk
for non-symmetrical LC7

Slika 12. Maksimalna von Mises naprezanja u parcijalnoj pregradi ventilacijskog kanal za LC7

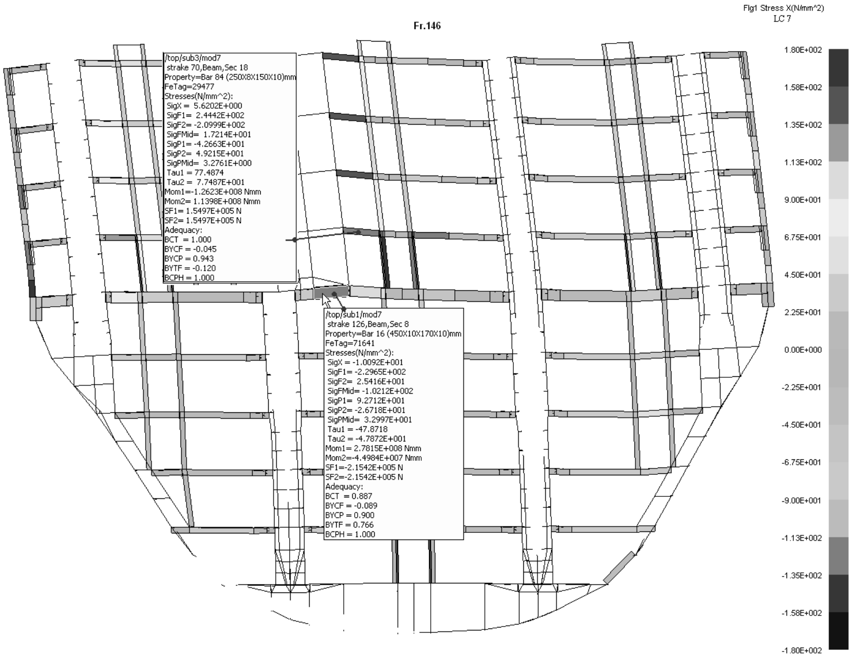


```
/top/sub14/mod1
 strake 5,Quad,Sec 1
Thickness=7 (mm)
FeTag=47848
Stresses Mid(N/mm^2):
SigX = -1.2531E+002
 SigY = -1.9093E+001
 Tau  = 31.4259
 SigVM=  1.2899E+002
Corner Stress:
 VM1 =  3.1089E+002
 VM2 =  2.9672E+002
 VM3 =  1.6519E+002
 VM4 =  3.9308E+001
```

Fig. 13 Normal σ_x stresses in transverse bulkhead at Fr. 151 for non-symmetrical load case LC7

Slika 13. Normalna σ_x naprezanja u poprečnoj pregradi na R. 151 za nesimetrični slučaj opterećenja LC7

(b) Strength of transverse beams and side frames have been evaluated in upright load case (LC2) and inclined load cases (LC7 and LC8), see Table 1. Critical locations have been identified and recommendations to solve identified problems have been suggested. Most critical locations for transverse deck beams are in connection to ventilation trunk bulkheads, ventilation tubes and pillars, see Fig.14.



```
/top/sub3/mod7
 strake 70,Beam,Sec 18
Property=Bar 84 (250X8X150X10)mm
FeTag=29477
Stresses(N/mm^2):
 SigX =  5.6202E+000
 SigF1=  2.4442E+002
 SigF2= -2.0999E+002
 SigFMid=  1.7214E+001
 SigP1= -4.2663E+001
 SigP2=  4.9215E+001
 SigPMid=  3.2761E+000
 Tau1 = 77.4874
 Tau2 =  7.7487E+001
Mom1=-1.2623E+008 Nmm
Mom2= 1.1398E+008 Nmm
SF1= 1.5497E+005 N
SF2= 1.5497E+005 N
Adequacy:
BCT  = 1.000
BYCF = -0.045
BYCP = 0.943
BYTF = -0.120
BCPH = 1.000
```

```
/top/sub1/mod7
 strake 126,Beam,Sec 8
Property=Bar 16 (450X10X170X10)mm
FeTag=71641
Stresses(N/mm^2):
 SigX = -1.0092E+001
 SigF1= -2.2965E+002
 SigF2=  2.5416E+001
 SigFMid= -1.0212E+002
 SigP1=  9.2712E+001
 SigP2= -2.6718E+001
 SigPMid=  3.2997E+001
 Tau1 = -47.8718
 Tau2 = -4.7872E+001
Mom1= 2.7815E+008 Nmm
Mom2=-4.4984E+007 Nmm
SF1=-2.1542E+005 N
SF2=-2.1542E+005 N
Adequacy:
BCT  = 0.887
BYCF = -0.089
BYCP = 0.900
BYTF = 0.766
BCPH = 1.000
```

Fig. 14 Maximum (axial+bending) stresses in transverse beams flange at Fr. 146 for non-symmetrical LC7

Slika 14. Maksimalna (uzdužna+savojna) naprezanja u prirubnicama sponja i rebara na R. 146 za LC7

(c) Strength of pillars and ventilation tubes have been evaluated in upright load case (LC2) and inclined load cases (LC7 and LC8), see Table 1. Critical locations regarding achieved stresses have been identified in details. Changes in type of profiles of pillar systems have been suggested. Pillars (with cross-like cross section) due to high participation of bending stresses (in racking and longitudinal strength load cases) should be replaced with rectangular or tube cross section.

5.4. Fine mesh analysis of critical details

Several critical structural details have to be evaluated using very fine mesh FE models (t x t). Those details very previously identified in the global-fine mesh model and presented through Ch.5.1 to 5.3:

Connection of web frame and transverse bulkhead;
Connection of ventilation tubes and Deck 6 plating;
Connection of ventilation trunk and Deck 6 plating;
Structure around openings at Deck 6 (amidships);
Side openings above Deck 6-transverse frame design

Very fine FE mesh (element size t x t) has been developed to support local design of side frames of large side openings above deck 6, see Fig. 15. Recommendations for solving those problems have been suggested.

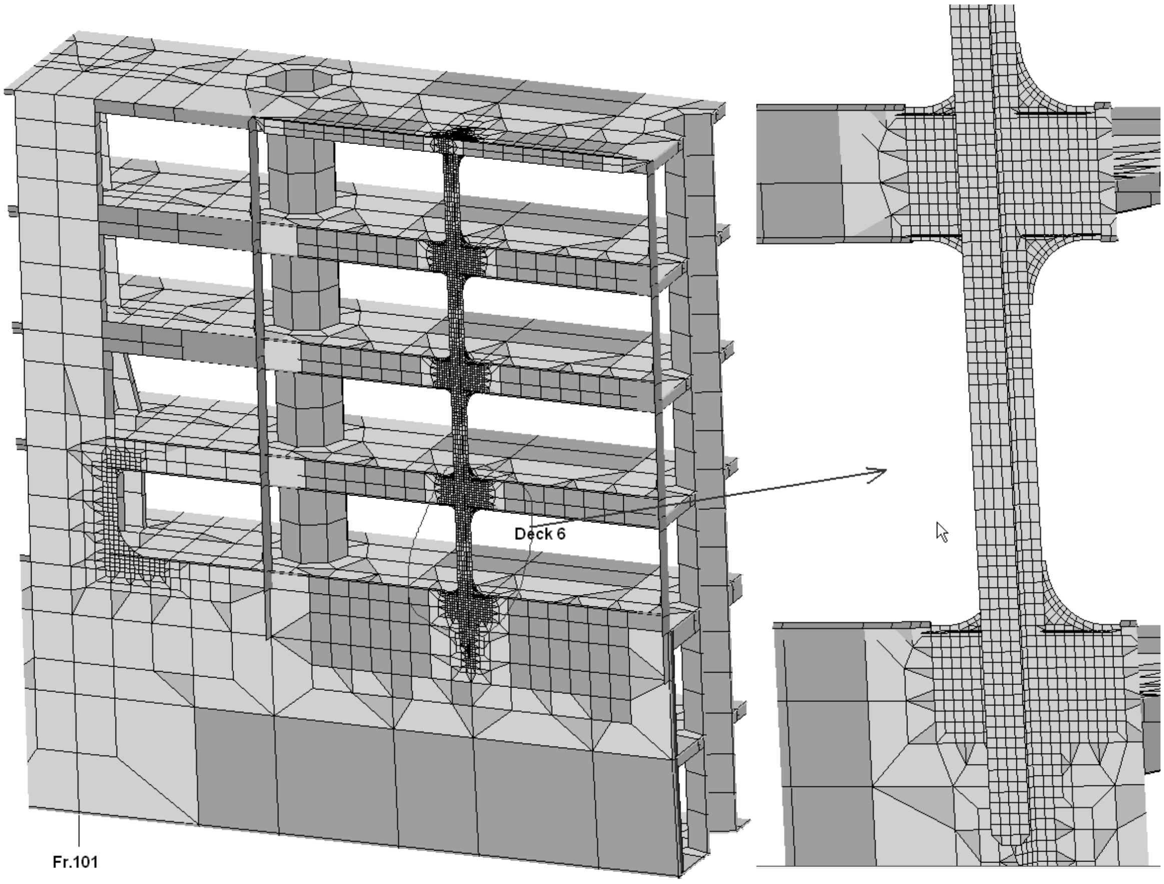


Fig. 15 Very fine mesh of superstructure side around Fr. 101 imbedded into global FE model

Slika 15. Vrlo fina MKE mreža područja boka nadgrađa oko R. 101 uklopljen u globalni MKE model

6. Conclusions

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. It also represents a progress in developing livestock carrier structural concept as a specific (tailor made) type of vessel offered by ULJANIK shipyard. The conclusions are as follows:

Only the full ship FEM model is capable to simulate realistic 3D effect of hull/superstructure interaction without the restricting assumptions. Effectiveness of the superstructure in longitudinal strength was analyzed and efficient redesign was developed.

Sensitivity analysis, based on parametric investigations of different scantlings of the superstructure, has provided the designer with rational arguments regarding benefits/drawbacks of the selected designs.

Complex transverse strength problems in non-symmetrical load cases, using presented models, can be rapidly solved and provides the head designer with the rational basis for determination of the final design scantlings.

Pillars have to be rationally designed not only for axial loading but also regarding bending stresses.

Fine mesh and very fine mesh FE analysis was found to be very efficient way for solving the stress concentration problems on previously identified critical locations.

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