UDC 629.5.023.46:519.6

Jerolim ANDRIĆ
Vedran ŽANIĆ
Mate GRGIĆ

Structural Optimization of Corrugated Transverse Bulkheads Made of Stainless Steel

Professional paper

The article describes structural optimization applied to the minimum weight design of corrugated transverse bulkheads made of the duplex stainless steel. The study presented in this paper was carried out within the EU FP6 project IMPROVE as a sub-task of multi-level structural optimization that was performed with the aim of development of a new innovative design of chemical tanker. This task can result in large benefits, because the unit price of duplex stainless steel is very high (5000 ÷ 6000 €/tons), and even the small savings of material can result in significant cost savings. Corrugated transverse bulkhead structure of chemical tanker (CT) was developed, analyzed and optimized using partial 3D FEM model, with the objective to achieve improved and competitive design. Two types of corrugations: (1) horizontal-HC and (2) vertical-VC, were investigated, optimized and compared to enable rational selection of the preferred design. Final solutions, satisfying all structural constraints, resulted in 7% savings in structural mass. The total savings (five duplex-steel made transverse bulkheads) of about 25 t can be expected with the cost benefit of up to € 150 000.

Keywords: *structural optimization, corrugated bulkheads, FEM, chemical tanker*

Strukturna optimizacija naboranih poprečnih pregrada izrađenih od nehrđajućeg čelika

Stručni rad

Opisuje se strukturna optimizacija s ciljem minimiziranja mase poprečne pregrade tankera za prijevoz kemikalija izrađene od nehrđajućeg *duplex* čelika. Studija predstavljena ovim radom dio je EU FP6 projekta IMPROVE i predstavlja pod-zadatak u sklopu višefazne strukturne optimizacije čiji je cilj bio razvoj inovativnog projekta tankera za prijevoz kemikalija. Zbog vrlo visoke cijene nehrđajućeg čelika (5000÷ 6000 €/t) i male uštede materijala mogu rezultirati znatnom uštedom u cijeni. U cilju postizanja kompetitivnog projekta razvijen je 3D parcijalni MKE model kemijskog tankera koji je postao osnova za strukturnu optimizaciju i donošenje odluka. Razmotrena su dva tipa naboranih pregrada: 1) s horizontalnim i 2) s vertikalnim naborima. Oba modela su analizirana, optimizirana, te je proveden odabir najboljeg. Konačno rješenje koje zadovoljava sva strukturna ograničenja ima oko 7 posto manju masu od početnog. Može se očekivati ukupna ušteda (za pet poprečnih pregrada od nehrđajućeg čelika) od 25 tona što rezultira uštedom od oko 150 000 €.

Ključne riječi: *strukturna optimizacija, naborane pregrade, MKE, tanker za prijevoz kemikalija*

Authors' address (Adresa autora):
University of Zagreb, Faculty of Mechanical Engineering and Naval Architecture
Ivana Lucica 5, 10000 Zagreb, Croatia;
e-mail: jerolim.andric@fsb.hr; vedran.zanic@fsb.hr; mate.grgic@fsb.hr

Received (Primljeno): 2009-10-06
Accepted (Prihvaćeno): 2009-11-03
Open for discussion (Otvoreno za raspravu): 2011-03-31

1 Introduction and objective

Corrugated transverse bulkhead (TBHD) is a preferred structural solution for chemical tankers, compared to the flat stiffened bulkhead, due to several reasons: lower mass, easier maintenance, smaller corrosion problems, etc. Use of stainless steel for corrugated TBHD is rather rare and is used only for a small number of special purpose chemical tankers. Stainless steel has great advantages by requiring lesser maintenance and avoiding larger corrosion problems, but it also has a disadvantage in much higher cost compared to standard shipbuilding steel. Also, special know-how in welding technology is needed during production process. Traditionally, austenitic stainless steel grades such 316L, 317L, 316LN and 317LN were used. The properties of these austenitic stainless steel grades (e.g. corrosion resistance, weldability and good ductility) make them well suited for use in chemical tankers [1]. Recently, duplex stainless steel grades have become the material of choice for cargo tank plating. Duplex stainless steel, which is austenitic-ferritic stainless steel, has greater overall corrosion resistance and higher strength than the austenitic grades. The greater strength of duplex stainless steel as compared to austenitic grades also permits a reduction in scantlings which can results in reduced steel weight and increased cargo capacity [1].

The work presented in this article has been performed as a part of the EU FP6 project IMPROVE [2, 3]. The article summarizes work done on structural optimization of transverse bulkheads, made of duplex stainless steel, as a sub-task of multi-level structural optimization that was performed in the development of a new innovative 40000 DWT Chemical Tanker. Optimization of the bulkheads structure is recommendable regarding high structural cost. Even small reduction of structural mass can results in high cost benefits due to very high unit price of duplex stainless steel (5000÷ 6000 €/tons). Corrugated transverse bulkhead structure of the chemical tanker (CT) was optimized (based on partial 3D FEM model) in order to achieve improved and competitive design. Two different types of corrugations, vertical and horizontal, were optimized, evaluated and compared to enable a rational selection of the preferred design.

Generally, structural design procedure may be divided into concept, preliminary and detail design phases. Concept design phase is defined as the phase when geometry and topology are open to modifications and structural variants are analyzed in accordance with the needs of the head designer. The structural response needed for scantling determination is calculated mainly by use of Rule based formulae (analytical models) in that phase. It means that accuracy is lower due to simplification of the boundary conditions used in model definition. Several authors performed optimization to define an optimal geometry using that kind of approach. Lee and Kim in [4] used genetic algorithm to define an optimal geometry of corrugation of a 70 000 DWT bulk carrier. Kim and Shin in [5] studied a minimum weight design of corrugated bulkhead for a bulk carrier based on CSR (Common Structural Rules) and the optimal shape and size of corrugation has been defined using ES (Evolution Strategy) as an optimization algorithm.

During the concept design phase *Szczecin Shipyard* from Poland (*SSN*) developed preferable corrugation geometry for both corrugation types and defined initial scantlings based on Rules formulae [6]. Starting from the suggested geometry the design team from the University of Zagreb performed the preliminary design phase optimization to reduce the bulkhead structural weight/cost and find optimal scantlings. Structural response was calculated using direct approach (FE method) which is characterized with high accuracy regarding response calculation, while for optimization algorithm the well proven SLP (Sequential Linear Programming) with dual formulation was used [7, 8]. This approach is extremely efficient in weight/cost optimizations. It is also acceptable for the final determination of structural scantlings, according to the classification society requests for structural evaluation, using direct calculation, where FEM based check becomes mandatory [9]. For this particular type of problem, the weight optimal solution is almost directly linked with the cost optimal solution due to the nature of investigated structure (no frames and stiffeners, just plating). MAESTRO structural design software [10], capable of imbedding multiple quality criteria in structural design objective, was used. It provided the decision support rationale for optimization of the bulkhead variants.

2 Design procedure

The general procedure developed for design includes the following tasks:

- Formulation of design support problem (DSP):
  - o identification of design problem (variables, attributes, constraints),
  - o formulation of analytical model (response and feasibility modules),
  - o selection of synthesis model and its manipulation into mathematically simpler form (using e.g. decomposition into coordinated sub-problems) and final selection of the solution strategy for the manipulated problem.
- Analysis of prototype structure $\mathbf{P^0}$

To enable fair comparisons with other concepts denoted $\mathbf{P^J}$, where index **J** denotes a design variant (sometimes it is the ship cycle no., denoting the design obtained in J-th cycle of the optimization procedure). $\mathbf{P^J} = \{\mathbf{d}\}^\mathbf{J}$ is a set of descriptors d_p, where p = 1,…n descriptors, defining uniquely the design. Note: $\mathbf{d} = \{d_p\} = \{\mathbf{d}_{fix}, \mathbf{x}\}$; where $\mathbf{d}_{fix} \equiv \bar{x} = \{x_m\}$; m=1,...n fix descriptors and $\mathbf{x} = \{x_n\}$ n = 1,...n free variables.

- Design problem solution is denoted $\mathbf{P^{OPT}}$ (or $\mathbf{O^K}$)

from which standardized version is generated (only a subset of variables, e.g. flange width is used) in optimization problem to generate $\mathbf{D^N}$ from mathematical optimum $\mathbf{O^K}$.

- Comparison of $\mathbf{D^N}$ with $\mathbf{P^0}$ is then performed to validate the new solution.

2.1 Design problem identification

(a) **Design variables**:

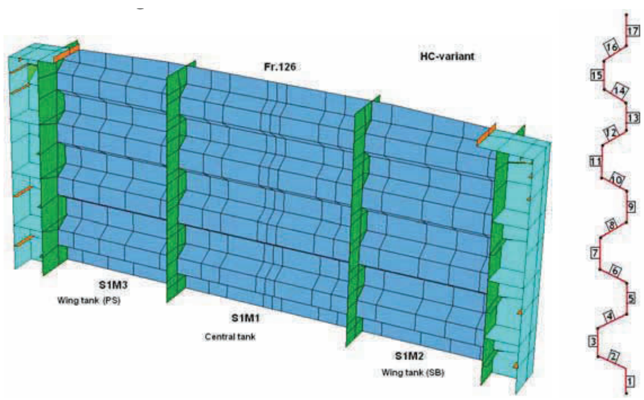
$$\mathbf{x}^{\mathbf{Total}} \subseteq \mathbf{P^j} = \{\, \mathbf{x}^{\mathbf{Ship}}, \{\mathbf{x}^{\mathbf{Subset\ -i}}\}\}$$

where n-tuple $\mathbf{x^{Total}}$ includes all design variables in the area under consideration. It can be decomposed into subsets of variables $\mathbf{x^i}$ and each of those subsets can be further decomposed into elements of sets related to topology $\mathbf{x^{(T)}}$, geometry $\mathbf{x^{(G)}}$, scantlings $\mathbf{x^{(S)}}$ and material $\mathbf{x^{(M)}}$.

For the preliminary design phase problem considered through this task, the topology/geometry and material (duplex steel) of corrugations were defined by *SSN* during concept design exploration. They were kept fixed during optimization process. Solution without lower/upper stools was also chosen by the shipyard, as preferable concept. Therefore, this optimization was mainly

Figure 1 **Optimization sub modules and strake identification for HC variant**

Slika 1 **Optimizacijski moduli i identifikacija vojeva za HC varijantu**



devoted to the scantling optimization of the corrugation plating (t_{pl}) for the characteristic bulkheads at Fr.126. Scantling variables, according to definition given in Figure 1, were associated to a specific strake. Also, strakes were grouped according to two structural areas: central tank and wing tanks. Plate thickness was unchanged over the whole tank breadth for the HC variant. Also, for the HC variant, the geometry of corrugations was changed in a way that depth of corrugations was increased from top to bottom.

Number of design variables (thickness of corrugation plating) in central tanks is $n_v^{CT}=17$ and in each wing tank $n_v^{WT}=18$.

(b) **Design attributes set,** whose elements are expressed as functions of design variables, is denoted as:

$$a(x^{\mathbf{Total}}) = \{a_{WEIGHT}(\mathbf{x}^{\mathbf{Total}}),\ a_{COST}(\mathbf{x}^{\mathbf{Total}}),\ a_{VCG}(\mathbf{x}^{\mathbf{Total}}),\ \mathbf{a}_{SAFETY}(\mathbf{x}^{\mathbf{Total}})\}$$

The first two attributes are additive functions of subsets of design variables and are minimized (objective y_1 = minimize a_{WEIGHT} and y_2 = minimize a_{COST}) or maximized (objective y_4 = maximize a_{SAFETY}). Structural mass and cost were directly linked because of the fixed geometry (length of weld, etc.) for this design problem. Measure of safety is defined via mean value of total number of unsatisfied constraints (gM), total number of unsatisfied constraints (TNUC) and relative adequacy index (RAI). RAI is calculated using histogram of values of various constraint functions, as ratio between the area under the distribution of positive values and total area consisting of area under positive and negative values of constraints.

(c) **Design constraints**:

Design constraints and requirements are determined in several ways.

(1) Minimum and maximum values were specified by the shipyard:
- bounds: $\mathbf{x}^{\mathbf{Total}}_{max} \geq \mathbf{x}^{\mathbf{Total}} \geq \mathbf{x}^{\mathbf{Total}}_{min,}$

(2) Structural constraints that include collapse and serviceability constraints (buckling and yield) are in-built in MAESTRO software and are adjusted to fit BV rules. They are given in Table 1. Their general form reads:
- $g_i(\mathbf{x}^{\mathbf{Total}}) \geq 0$, i= 1,…,*n constraints*.

For the purpose of the presentation of results, the strength ratio R, whose normalized form of g(x) is needed, is defined as follows:

$$R(\mathbf{x}) = Q(\mathbf{x}) / Q_L(\mathbf{x});$$

where: **x** is vector of current values of structural descriptors including scantlings, Q(**x**) is load effect and, $Q_L(\mathbf{x})$ is its limit value for particular failure mode. Failure criterion is given by:

$$\gamma R(\mathbf{x}) < 1 \text{ where: } \gamma \text{ is prescribed safety factor}$$

or in normalized form using 'adequacy parameter' the constraint now reads g(R(x)), where

$$g(R(x)) = (1 - \gamma R) / (1 + \gamma R)\ ;\ \text{note: } -1 < g(R(x)) < 1.$$

The structural adequacy parameters have to be equal or greater than zero, or $g(R(x)) \geq 0$, to satisfy necessary structural strength requirement.

Table 1 **MAESTRO structural constraints [7, 8, 10]**
Tablica 1 **Strukturna ograničenja u programu MAESTRO [7, 8, 10]**

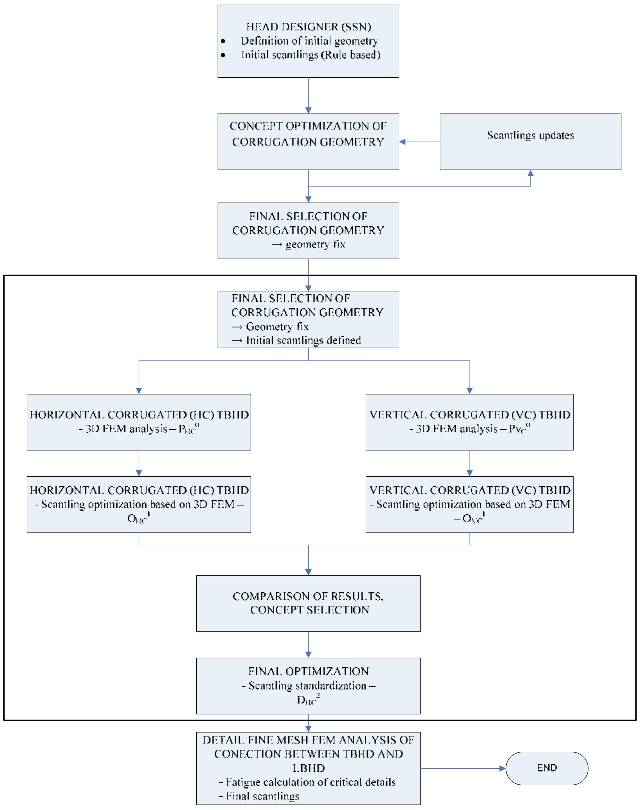
Item	Limit state	Description	Safety factor, γ
1	PCSF	Panel Collapse - Stiffener Flexure	1.04
2	PCCB	Panel Collapse - Combined Buckling	1.04
3	PCMY	Panel Collapse - Membrane Yield	1.224
4	PCSB	Panel Collapse - Stiffener Buckling	1.04
5	PYTF	Panel Yield - Tension Flange	1.04
6	PYTP	Panel Yield - Tension Plate	1.224
7	PYCF	Panel Yield - Compression Flange	1.04
8	PYCP	Panel Yield - Compression Plate	1.224
9	PSPB	Panel Serviceability - Plate Bending	1
10	PFLB	Panel Failure - Local Buckling	1

Constraints regarding structural strength were used in design procedure via safety factors defined according to BV Rules [6].

2.2 Preliminary design problem formulation - Synthesis modules

Problem can be fully decomposed regarding local variables and attributes but coupling is present in calculation of design criteria. Each of them is dependent on stress fields obtained from FEM analysis and is therefore dependent on structural stiffness

Figure 2 **Design procedure flow chart**
Slika 2 **Dijagram toka projektne procedure**



and load vector. Convergence of the process is obtained via unified response analysis of all modules. Accordingly, the design procedure was performed in several steps and design phases. The design procedure flow chart to obtain minimum weight design is presented in Figure 2 and work performed through this study is marked with rectangular.

3 Analysis modules (structure and load models)

3.1 Ship description

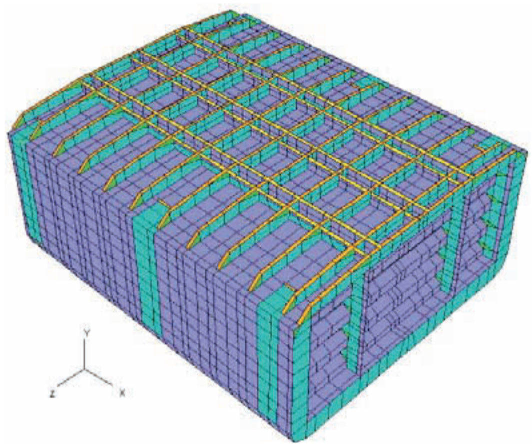
The studied ship is a 40 000 DWT ocean-going Chemical Tanker with the propulsion system consisting of a low speed single diesel main engine driving directly a fixed pitch propeller. The vessel is designed to carry a large variety of different cargoes in thirty cargo tanks. About 60% of the ship cargo volume is distributed in eighteen tanks made of duplex stainless steel, while the remaining 40% of the tanks are made of standard shipbuilding steel. The duplex stainless steel cargo tanks are separated from the mild steel cargo tanks by cofferdam structure. The main particulars of the vessel are as follows [11]:

- Length overall: 182.88 m,
- Length between perpendicular: 175.25 m,
- Beam moulded: 32.20 m,
- Depth to main deck: 15.00 m,
- Scantling Draught: 11.10 m,
- Cargo tanks capacity (total): 44 000 m^3,
- Capacity of duplex cargo tanks: 26 800 m^3,
- Service speed: 15.0 knots

3.2 FE model of chemical tanker (CT) structure

Two-hold, coarse mesh, FE model of both sides, used for prototype analysis and optimization, was developed using MAESTRO software [10], see Figure 3. Stiffened plated areas such as deck, inner shell and outer shell were represented by the special stiffened shell macro-elements [7, 8]. MAESTRO stiffened macro-element uses the *NASTRAN* type Q4 4-node shell elements. They are enhanced with stiffeners in their proper geometrical position regarding axial and bending energy absorption/detailed stress output. Corrugated bulkheads plating was represented by the standard Q4 4-node shell elements (*NASTRAN* type).

Figure 3 **Two hold FE model of chemical tanker**
Slika 3 **MKE model dva skladišta tankera za kemikalije**



Transverse bulkhead at Fr.126 was selected as the characteristic one to perform structural optimization. Full model consisted of six tanks to enable simulated chessboard and alternate loading conditions, with the extent from Fr. 104 to Fr. 144. Due to the request that two directions of corrugation had to be investigated, two FE models with different types of corrugations were developed. The model with horizontal corrugation (HC) is presented in Figure 4 and the model with vertical corrugation (VC) is presented in Figure 5.

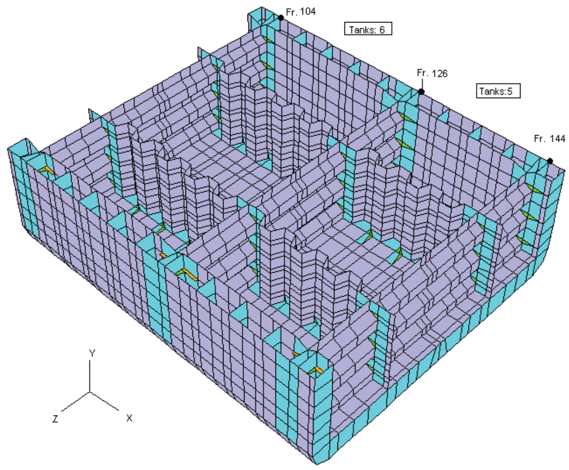


Figure 4 **Two hold FE model horizontal corrugation (HC) - structure below deck**
Slika 4 **MKE model dva skladišta s horizontalno naboranom poprečnom pregradom – konstrukcija ispod palube**

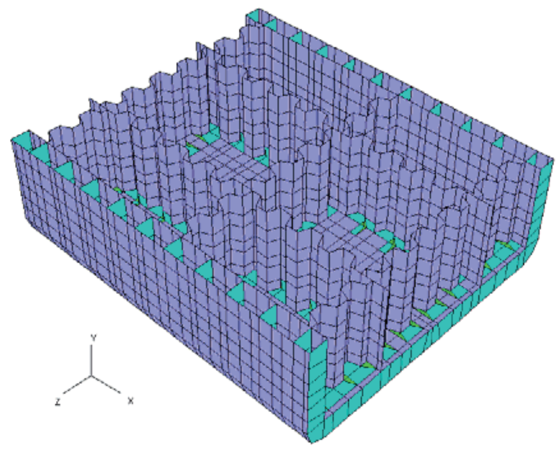


Figure 5 **Two hold FE model vertical corrugation (VC) - structure below deck**
Slika 5 **MKE model dva skladišta s vertikalno naboranom poprečnom pregradom – konstrukcija ispod palube**

Optimization modules are shown in Figure 1 for the HC-variant. They consist of three modules: S1M1 represents part of the bulkhead in the central tank; S1M2/M3 represents part of the bulkhead in the PS and SB wing tanks. Similar decomposition is performed for the VC variant.

3.3 Axes definition and boundary conditions

The global axes system referenced the longitudinal centerline at base as X, positive forward; Z transverse, positive to starboard; and Y vertical, positive upwards from the base. The origin is located at frame 104 at the keel. To prevent rigid body motion of the model and singularity of the stiffness matrix, the boundary conditions were implemented in accordance with IACS Common Structural Rules for Oil Tankers (Appendix B, 2.6) [9].

3.4 Loading conditions and load case components

A total number of four critical loading conditions were defined according to Trim and Stability (T&S) book [11] and, based on them and on the BV requirement, twelve load cases were generated. Loading conditions are summarized in Table 2. Chessboard fill and alternative loading were recognized as the most critical for transverse bulkhead optimization. In Figure 6 the chessboard loading condition is presented [11].

Each loading condition comprises four load sets: 1) lightship weight, 2) deadweight, 3) accelerations and 4) buoyancy loading including dynamic pressures. Based on the model geometry and scantlings of the elements used, a mass for the hull model was generated automatically. The distribution of cargo loading in tanks was defined by Yard, following T&S book [11]. Cargo masses were placed in appropriate tanks, which were modeled inside the ship structure model. Density of fluid (Phosphoric Acid) in all tanks had specific mass of 1.50 t/m^3 (for all load cases) and tanks filling was 98% [11]. Each of four loading conditions was exposed to three different BV design load cases, marked as "a", "b", "d" in BV rules (Pt. B, Ch.5, Sec.4) [6]. Summary of load cases is presented in Table 2.

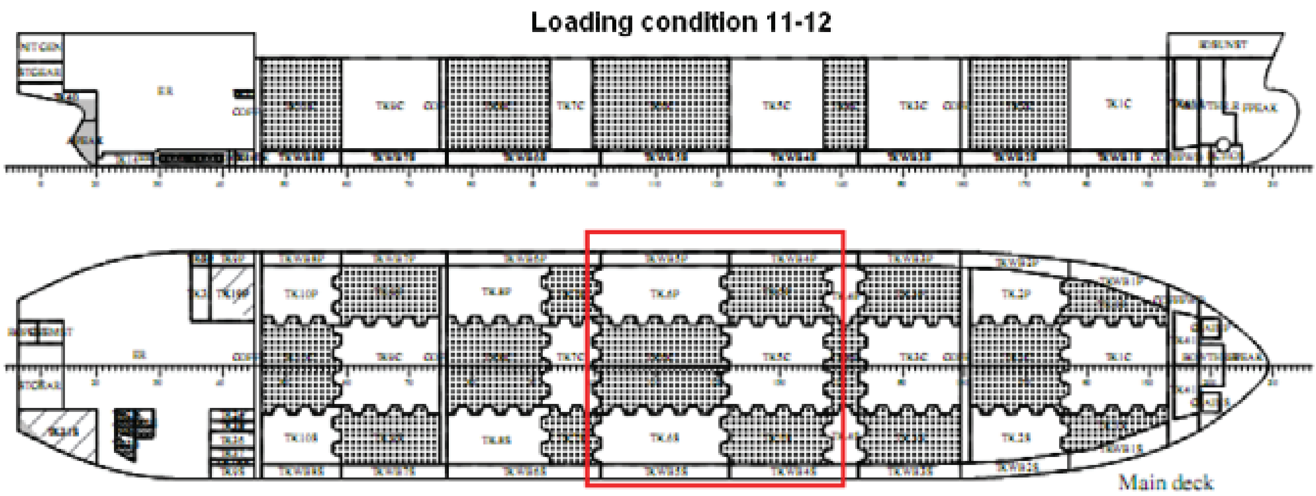


Figure 6 **Loading condition 11-12 chessboard fill - Version I [11]**
Slika 6 **Stanje krcanja šahovsko polje - Verzija I [11]**

Table 2 **Load cases definition**
Tablica 2 **Definicija slučajeva opterećenja**

Loading condition	**LOAD CASE**	BV load case definition	T-draught [m]	M_{static}-max [kNm]	Maximum achieved internal pressure (static + dynamic+ p_{pv}) [kN/m^2]
Loading condition 11-12 **chessboard-Version I**	1	case "**a**"	9.9	$3.16 \cdot 10^5$	214
	2	case "**b**"			280
	3	case "**d**"			260
Loading condition 13-14 **chessboard-Version II**	4	case "**a**"	10.2	$3.69 \cdot 10^5$	214
	5	case "**b**"			278
	6	case "**d**"			238
Loading condition 17-18 **alternate tank -Version I**	7	case "**a**"	10.8	$9.15 \cdot 10^5$	214
	8	case "**b**"			278
	9	case "**d**"			261
Loading condition 17-18 **alternate tank -Version II**	10	case "**a**"	10.5	$6.54 \cdot 10^5$	214
	11	case "**b**"			280
	12	case "**d**"			238

Inertial forces were generated using ship masses and their accelerations. Accelerations for all modelled masses were calculated from ship acceleration vector (ship is treated as a rigid body) as defined in the Rules. Accelerations in upright and inclined conditions were calculated according to BV Rules, (Pt B, Ch 5, Sec 3) [6]. Sea pressures were combination of static pressure and dynamic pressure (Smith's theory) depending on wave height. External and internal pressure were calculated following BV Rules (Pt. B, Ch.5, Sec.5) [6] and implemented into the FE model. In all load cases the preset pressure of safety valves (p_{pv} = 0.2 bar = 0.02 N/mm^2) was implemented as addition to the total internal pressure (static + dynamic).

4 Analysis of prototype structure

Analysis of prototype structures (HC and VC) was conducted in order to assess the adequacy of the initial models of CT structure and to rate the starting point for the design problems. Structural adequacy was checked using library of failure criteria inbuilt in MAESTRO (see Table 1).

4.1 Prototype analysis of horizontal corrugated (HC) type of TBHD- P_{HC}^{0}

Structural response via different stress components of prototype structure was evaluated, see Figure 7. Structural feasibility was checked based on normalized adequacy criteria specified in Ch.2. In Figure 8 the worst of all adequacy criteria for all LCs is presented. It represents the envelope created by the worst criteria that were identified for all structural elements by checking all load cases and all structural criteria.

In parallel, the influence regarding stiffness of support in double bottom structure was examined through complete 3D FE analysis of two proposed solutions: (a) with floors at Fr.125 and Fr.126 and (b) without the floor at Fr.125 (only at Fr.126). No significant changes in structural feasibility were identified and all of the following calculations were performed for the HC variant without the floor at Fr.125.

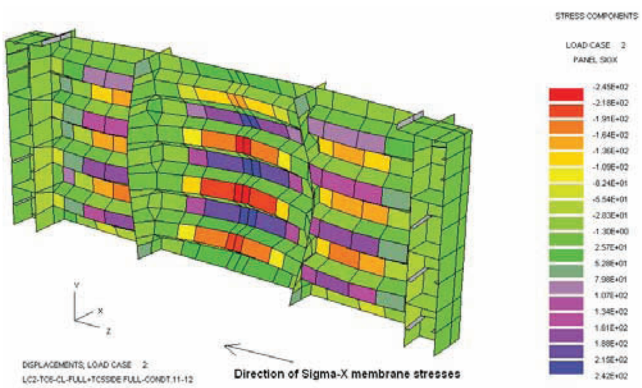
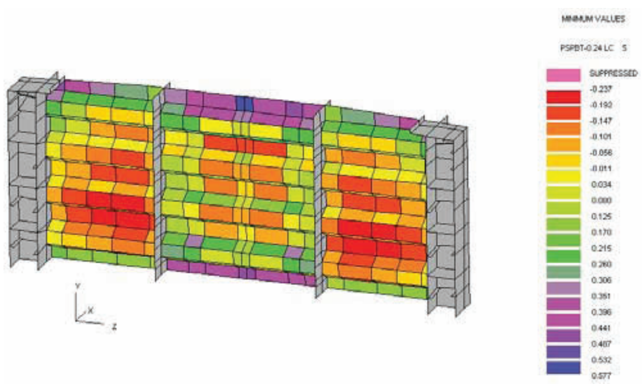


Figure 7 Prototype analysis – HC version - LC2 - σ_x membrane stresses (N/mm^2)
Slika 7 Analiza prototipa – HC verzija - LC2 - σ_x membranska naprezanja (N/mm^2)

Figure 8 Prototype analysis – HC version - the worst of all adequacy criteria for all LC
Slika 8 Analiza prototipa – HC verzija - ovojnica najgorih kriterija podobnosti za sve LC



4.2 Prototype analysis of vertical corrugated (VC) type of TBHD- P_{VC}^{0}

Similar investigation was performed for the VC structural variant. Structural response, based on different stress components of prototype structure, was evaluated. Figure 9 presents membrane σ_x stress. Structural feasibility was checked based on normalized adequacy criteria specified in Ch.2. In Figure 10 the worst of all adequacy criteria for LC2 and all structural criteria is presented.

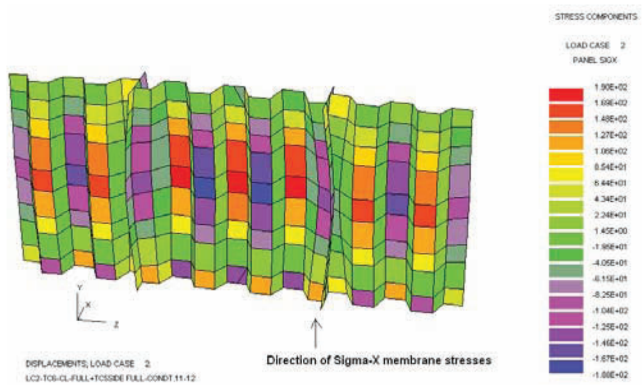
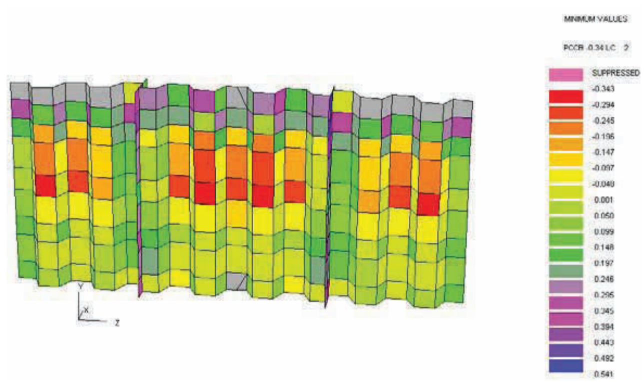


Figure 9 Prototype analysis – VC version - LC2 - σ_x membrane stresses (N/mm^2)
Slika 9 Analiza prototipa – VC verzija - LC2 - σ_x membranska naprezanja (N/mm^2)

Figure 10 Prototype analysis – VC version - the worst of all adequacy criteria for all LC
Slika 10 Analiza prototipa – VC verzija - ovojnica najgorih kriterija podobnosti za sve LC



4.3 Conclusion on the prototype structures

It can be conclude that the HC prototype structure has some problems especially in part of the bulkhead in the wing tank region and also in some middle width region of the central tank. On the other hand, the VC prototype structure has some problems especially in the middle height part of the bulkhead structure and along the whole ship breadth (including the central tank and wing tanks) where high possibility of combined buckling was identified. The following criteria were identified as most critical: PCCB, PSPBT, PSPBL, PFLB (see Table 1 for criteria description) for both structural variants. Also, some regions that are over satisfied regarding structural safety were identified in both variants.

5 Preliminary structural optimization of transverse bulkhead (TBHD)

Optimization of a real ship can offer a significant help to the ship designer because it can optimally redistribute material, reducing weight of initial model and increasing its safety [12, 13]. The described model of chemical tanker was optimized using MAESTRO software. Mathematical model of the optimization problem was formulated according to the described design procedure, using the defined sets of design variables, constraints and attributes. The problem was solved using dual formulation of the sequential linear programming method (SLP) in-built in the MAESTRO software [7, 8].

5.1 Design variables and constraints

The design variables are plate thicknesses for both types of corrugation as $\mathbf{X}^S$ $\{t_{pl\,i}\}$; i = 1,..,n strakes. Minimal (8 mm) and maximal (35 mm) values of the plate thickness were defined by the shipyard as min-max constraints. Regarding equality restrictions, the following relations were applied:

1. For horizontal corrugated (HC) TBHD: plates in the central tank and wing tanks at the same height could have different thickness,
2. For horizontal corrugated (HC) TBHD: plate thickness is unchanged over whole tank breadth,
3. Geometry of longitudinal bulkhead is the same for both variants (HC) and (VC),
4. For the HC variant the floor only exists at Fr.126.
5. For the VC variant two floors at Fr.125 and 126 support the connection of corrugations.
6. Yielding stress of duplex stainless steel was taken as 370 N/mm^2.
7. For differences between plate thicknesses (BV rules were followed) the shipyard specified maximum of 4 mm.

5.2 Structural optimization of horizontal corrugated (HC) type of TBHD

Design cycle history of design attributes (structural mass and safety) for optimization problem is given in Figure 11. Structural mass and cost are directly linked for fixed geometry (length of weld, etc.) at this stage. Safety is measured using the mean value of the total number of unsatisfied constraints (gM) and total (negative) number of unsatisfied constraints (TNUC).

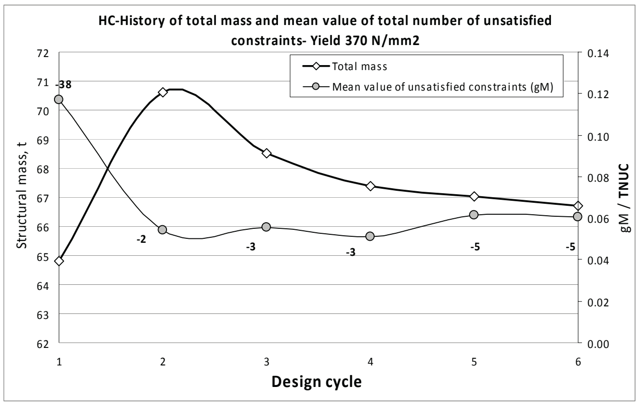


Figure 11 **HC variant – History of structural mass with the mean value (gM) and (TNUC) of unsatisfied constraints through design cycles**

Slika 11 **HC varijanta – Promjena strukturne mase te srednje vrijednosti (gM) i broja nezadovoljenih kriterija (TNUC) kroz projektne cikluse**

Number near each point in gM/TNUC diagram represents total number of unsatisfied constraints (TNUC), e.g. for 1st cycle TNUC=-38.

Active constraints were mainly those previously identified in prototype analysis (PSPBT, PSPBL, PFLB, see Figure 12) and the type of constraints does not change significantly through design cycles.

Figure 12 **HC – Active constraints for central tank (S1M1) in the first design cycle**

Slika 12 **HC – Aktivna ograničenja za centralni tank (S1M1) u prvom projektnom ciklusu**

```
+------------------------------------------------------------------------------------------------------+
| STR |                  ACTIVE CONSTRAINTS AFTER DESIGN CYCLE  1;  MODULE  1 OF SUBSTRUCTURE  1        | CONV.|
|------------------------------------------------------------------------------------------------------|
|  1  | PSPBT |   |   |   |   |   |   |   |   |   |   |   |   |   |   11 |
|  2  | PFLB  |   |   |   |   |   |   |   |   |   |   |   |   |   | 1110 |
|  3  | PSPBL |   |   |   |   |   |   |   |   |   |   |   |   |   | 1111 |
|  4  | PFLB  |   |   |   |   |   |   |   |   |   |   |   |   |   | 1110 |
|  5  |       |   |   |   |   |   |   |   |   |   |   |   |   |   | 7777 |
|  6  | PFLB  |   |   |   |   |   |   |   |   |   |   |   |   |   | 1110 |
|  7  |APSPBL |   |   |   |   |   |   |   |   |   |   |   |   |   | 1111 |
|  8  | PFLB  |   |   |   |   |   |   |   |   |   |   |   |   |   | 1110 |
|  9  |       |   |   |   |   |   |   |   |   |   |   |   |   |   | 7777 |
| 10  | PFLB  |   |   |   |   |   |   |   |   |   |   |   |   |   | 1110 |
| 11  | PFLB  |   |   |   |   |   |   |   |   |   |   |   |   |   |   10 |
| 12  | PSPBT |   |   |   |   |   |   |   |   |   |   |   |   |   | 1110 |
| 13  | PFLB  |   |   |   |   |   |   |   |   |   |   |   |   |   |   10 |
| 14  |APFLB  |   |   |   |   |   |   |   |   |   |   |   |   |   | 1111 |
| 15  | PSPBT |   |   |   |   |   |   |   |   |   |   |   |   |   |   11 |
| 16  |APFLB  |   |   |   |   |   |   |   |   |   |   |   |   |   |   11 |
| 17  |APFLB  |   |   |   |   |   |   |   |   |   |   |   |   |   |   11 |
+------------------------------------------------------------------------------------------------------+

CONVERGENCE CODE
----------------

      1*** - DESIGN VARIABLES ARE STATIONARY.
      *1** - OBJECTIVE FUNCTION IS STATIONARY.
      **1* - NON-LINEAR CONSTRAINTS ARE SATISFIED.
      ***1 - DID NOT REQUIRE FULL NO. OF STRAKE CYCLES.
      7777 - DESIGN FROM EARLIER DESIGN CYCLE IS STILL OPTIMAL
      8888 - ALL DESIGN VARIABLES FIXED.
      9999 - FEASIBLE NEW DESIGN UNOBTAINABLE; NO CHANGE.
NOTE: BLANK OR ZERO INDICATES CONDITION NOT TRUE.
```

A large number of unsatisfied structural constraints (TNUC = 38) in the first design cycle corresponds to prototype ($\mathbf{P}_{HC}{}^{0}$), with the mean value of unsatisfied constraints (gM = -0.12) and mass of 64.8 t. Definition of adequacy parameter g is given in Ch.2. Due to the reason that the prototype structure had failed in a large number of structural constraints, no reduction of weight was achieved through optimization process. Instead, MAESTRO algorithm was solving the structural adequacy problem with minimal mass addition. To achieve a feasible solution, with only five (TNUC = 5) of unsatisfied constraints (to be solved in the detail design phase), the optimization algorithm minimally increased mass (about 2 t in total). So, the total mass of optimal solutions $\mathbf{O}_{HC}{}^{1}$ is 66.7 t.

5.3 Structural optimization of vertical corrugated (VC) type of TBHD

History of design attributes (structural mass and safety) of the optimization problem is given in Figure 13 with respect to the design cycles. Structural mass and cost are directly linked due to the fixed geometry (length of weld, etc.) and safety is measured using the mean value of the total number of unsatisfied constraints (gM) and total number of unsatisfied constraints (TNUC).

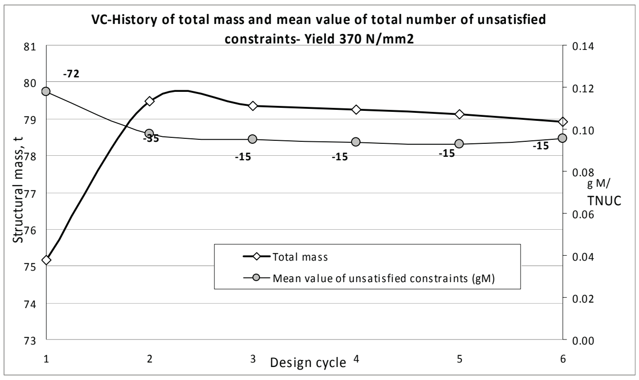


Figure 13 **VC variant – History of structural mass with the mean value (gM) and (TNUC) of unsatisfied constraints through design cycles**
Slika 13 **VC varijanta – Promjena strukturne mase te srednje vrijednosti (gM) i broja nezadovoljenih kriterija (TNUC) kroz projektne cikluse**

Number near each point in gM/TNUC diagram represents total number of unsatisfied constraints, e.g. for 6th cycle TNUC=-15.

Similar situation was obtained for the vertically corrugated design variant. Active constraints are mainly those that were previously identified in prototype analysis (PSPBT, PSPBL, PFLB) and the type of constraints were not changed significantly through design cycles. The only difference was that Von Mises (PCMY) criterion was identified due to large equivalent stresses recorded in the middle height area as well as the possibility of plate buckling (PCCB and PSCF). A large number of unsatisfied constraints (TNUC=72) in the first design cycle could also be examined, corresponding to prototype ($\mathbf{P}_{VC}{}^{0}$) with the mean value of unsatisfied constraints (gM = -0.12) and the mass equal to 75.1 t. Due to the reason that prototype structure failed in a large number of structural constraints, no reduction of weight was achieved through optimization process in this case, too. To achieve a feasible solution, with fifteen (TNUC =15) of unsatisfied constraints, the optimization algorithm minimally increased mass (about 4 t in total). So, after six optimization cycles the total mass of optimal solutions $\mathbf{O}_{VC}{}^{1}$ reached 78.9 t.

5.4 Comparison of HC & VC solutions and variant selection

In the end, two evaluated variants were examined according to their mass/cost and safety characteristics. Results are presented in Figure 14.

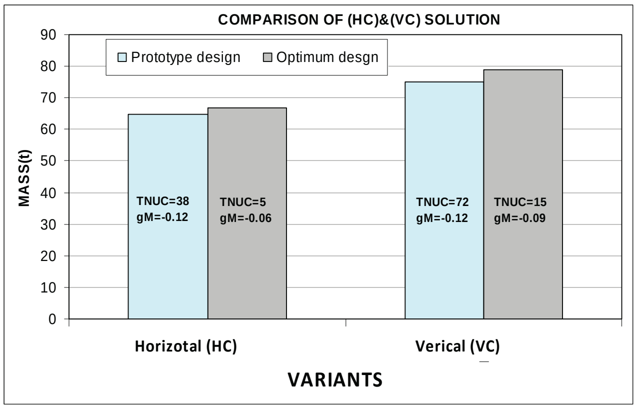


Figure 14 **Comparison of structural variants HC & VC**
Slika 14 **Usporedba strukturnih rješenja HC & VC**

It can be seen that the horizontally corrugated (HC) TBHD resulted in approximately 10 t smaller mass than the VC design. Also, regarding production, the HC-solution was preferred by the shipyard due to the reason that for each corrugation step, the same thickness was generated along the whole breadth. For the VC solution, the thickness changed from top to bottom and made production more complicated. On the other hand, the connection of the HC transverse bulkhead with the vertically corrugated longitudinal bulkhead was considered more complicated and that aspect has to be examined through the detail design phase. The HC variant was chosen and the final optimization was performed only for that variant.

6 Final optimization and standardization of HC variant of TBHD

The final optimization with standardization of the proposed solution was performed for the HC variant.

6.1 Sensitivity analysis due to duplex stainless steel characteristics

The loading, discharging and carriage temperature of cargoes affect the structural design. Elevated temperature has an impact on the mechanical properties of structural material and reduction of maximum allowable stresses [1]. Prior to final optimization runs, the fast sensitivity analysis was performed to investigate the influence of different allowable yield stresses of the duplex stainless steel on the bulkhead mass. At shipyards request, two variants were optimized, evaluated and compared: (1) allowable yield stresses equal to 370 N/mm^2 which correspond to maximum allowable temperature of 90°C; (2) allowable yield stresses equal to 420 N/mm^2 which correspond to maximum allowable temperature of 70°C. Results are presented in Figure 15. It can be seen that the second variant results in mass reduction of about 4 t. So, additional 6% of savings in mass can be obtained. Final optimization run was performed for duplex stainless steel with the allowable yield stresses of 420 N/mm^2.

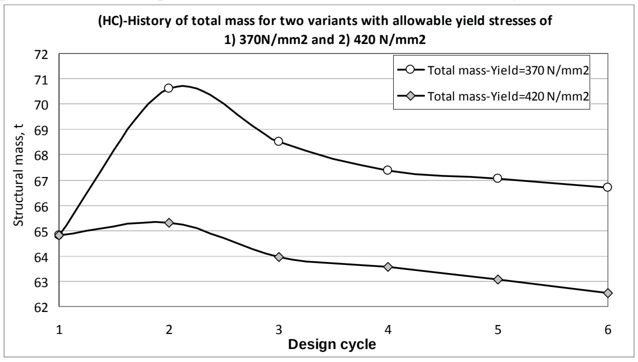


Figure 15 **HC – History of structural mass of variants with σ_{yield}= 370 N/mm^2 and σ_{yield} =420 N/mm^2**

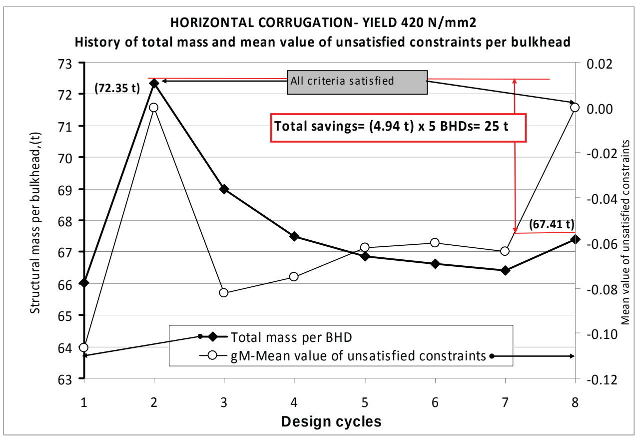
Slika 15 **HC – Promjena strukturne mase kroz projektne cikluse za varijante sa σ_{yield}= 370 N/mm^2 i σ_{yield} = 420 N/mm^2**

6.2 Final optimization and standardization

Final optimization run was performed for the chosen HC variant. Design variables were linked according to production requests and shipyard preferences. Also, some small improvements in model definition of prototype structure were implemented due to realistic position of weld seems. In the previous optimization steps the real variables were used to generate optimal solution. In the final optimization steps discrete variables were used. Standard value of plate thickness was used with a step of 0.5 mm.

Figure 16 **HC variant – History of structural mass with the mean value (gM) of unsatisfied constraints for the final optimization run**

Slika 16 **HC varijanta – Promjena strukturne mase te srednje vrijednosti (gM) kroz projektne cikluse za finalnu optimizaciju**



History of design attributes (structural mass and safety) for optimization problem is given in Figure 16 with respect to optimization cycles. Safety is measured using the mean value of the total number of unsatisfied constraints (gM). The last optimization cycle, no. 8, corresponds to the standardization of final scantlings. It was performed according to the shipyard ordinary practice.

Final standardized solution $\mathbf{D}_{HC}{}^2$ resulted in all constraints satisfied and in a total mass of 67.4 t per bulkhead. If that solution is compared with the one of the same feasibility from the 2nd design cycle (mass of 72.4 t), savings in the mass of 5t can be identified. It represents savings in the structural mass of about 7%.

7 Conclusion

Decision support procedure (including structural optimization) for a real ship structure can offer a significant help to the ship designer since the procedure can optimally redistribute material, reducing weight of initial design and increasing its safety.

Structural optimizations of corrugated transverse bulkheads (TBHD) made of duplex steel were performed. Two directions of corrugation were investigated: (1) horizontal (HC) and (2) vertical (VC). In that respect two 3D FE models, with different type of corrugations were developed, optimized and compared, to make rational selection of the corrugation direction. The variant with horizontal corrugations (HC) was chosen as preferred solution.

Through the final optimization run, the total mass of strakes of the HC variant was decreased successfully for 5 t, (or 7 % compared to the prescribed prototype design), with all structural constraints being satisfied. The total savings (for five duplex steel transverse bulkheads) of about 25 t can be expected with cost benefit of up to € 150 000, due to very high prices of duplex steel (5000÷6000 €/tons).

Proposed solution represents the basis for more detailed FE calculations (using very fine mesh models) in the subsequent detail design phase. Special considerations have to be devoted to the connection between transverse and longitudinal bulkheads, where high local stresses can be expected. These connection details have to be examined with respect to fatigue strength.

Through this paper the rationale of preliminary design phase optimization procedure has been proven. Through the IMPROVE project, the special finite macro-element for the concept design of corrugated transverse bulkheads has been developed [14], enabling corrugation geometry (width of flange, width of web plating and depth of corrugation) to be treated as design variables for each type of corrugation waves. If the exploration search for optimal corrugation geometry had been included in the concept design phase, savings might have been even larger than those presented here for the preliminary design phase only.

Acknowledgement

The European Commission under the FP6 Sustainable Surface Transport Programme, namely the STREP project *IMPROVE* (www.improve-project.eu), Contract No. FP6-031382 supported the study present in the paper. Thanks are due to the long-term support of the Croatian Ministry of Science, Education and Sport: projects 120-1201829-1671. Thanks also go to Krzysztof Kapuscik head designer of *Szczecin Shipyard* for his support through optimization process. Thanks are due to all members of the *OCTOPUS group* (www.fsb.hr/octopus).

References

[1] WERNER, M.R.: "Chemical Tankers", in: Ship Design and Construction, Vol.II, Ch.31, SNAME, 2004.

[2] RIGO, P., DUNDARA, D., KARCZEWICZ, A., KLANAC, A., ROLAND, F., TURAN, O., ZANIC, V., AMRANE, A., CONSTANTINESCU, A.: "Improve - Design of improved and competitive products using an integrated decision support system for ship production and operation", 7th Conference on Computer and IT Applications in the Maritime Industries (COMPIT 2008), Liege, p.92-106.

[3] ZANIC, V., PREBEG, P., ANDRIC, J., KITAROVIC S., GRGIC, M.: "Multicriteria structural design of RoPax ship: specification of design problem roadmap for EU FP6 Project IMPROVE", XVIII Symposium on the Theory and Practice of Shipbuilding -SORTA 2008, p.267-278, Pula, CROATIA, 2008.

[4] LEE, K-Y., ROH, M-I.: "An Efficient Genetic Algorithm Using Gradient Information for Ship Structural Design Optimization", Ship Technology Research, Vol. 48, p. 161-170, 2001.

[5] KIM, S-Y., SHIN, S-H.: "A Study on the Minimum Weight Design of Corrugated Bulkhead for Bulk Carrier based on Common Structural Rules", 10th International Marine Design Conference, IMDC 2009, Trondheim, Norway, Vol. 2, p.734-743, 2009.

[6] BUREAU VERITAS: "Rules for Steel Ships, Part B - Hull and Stability", April 2007.

[7] HUGHES, O. F.: "Ship Structural Design", SNAME, New Jersey, 1988.

[8] HUGHES, O. F., MISTREE, F., ZANIC, V.: "A Practical Method for the Rational Design of Ship Structures", Journal of Ship Research, Vo. 24(1980), No. 2, p.101-113.

[9] MAESTRO Version 8.9.3, Program documentation, Proteus engineering, Stevensville, MD, USA, 2008.

[10] IACS, Common Structural Rules for Double Hull Oil Tankers, January 2006.

[11] SSN, Information on Stability and Longitudinal Strength: Chemical Tanker 40000 DWT, IMPROVE/042-3, Version 09/12/2008.

[12] JANCIJEV, T., ZANIC, V., ANDRIC, J: "Mathematical Models for Analysis and Optimization in Concept and Preliminary Ship Structural Design", Proceedings of IMAM 2000 Congress, p.15-22, Napoli, Italy, 2000.

[13] ZANIC, V., ANDRIC, J., PREBEG. P. KITAROVIC, K., PIRIC, K.: "Multi-objective optimization of ship structural topology and scantlings", International Marine Design Conference, IMDC 2009, Vol. 2, p.789-803, Trondheim, Norway, 2009.

[14] JANCIJEV, T., GRGIC, M.: "Finite macro element for corrugated bulkhead modeling in ship design phase", Proceedings of IMAM 2009 Congress, Vol. I, p.103-110, Istanbul, Turkey, 2009.