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FE based structural optimization according to IACS CRS-BC

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Abstract

According to IACS CSR for Bulk Carriers, a direct strength analysis based on the three hold FE model of the cargo area is mandatory for all vessels above 150 m in length. Structural design according to those requirements is a challenging task that demands utilization of the integrated design system. To allow the designer to fully realize all benefits of the formal optimization procedure, an in-house structural design support system OCTOPUS-CSR was developed for concept and preliminary design phases. The developed design system was used for the structural design of the bulk carrier series to be built in ULJANIK Group shipyard 3.MAJ and the main achievements in the preliminary design phase are presented in this paper. Developed tools and methodology provides the shipyard and the ship-owner with the possibility of fully controlling structural scantlings while following the basic paradigm: lower ship production cost for the shipyard and a more profitable and durable ship for the ship-owner.

Keywords

Bulk carrier; FE analysis; structural optimization; IACS CSR-BC; in-house design system.

Introduction

Prior to the development of the harmonized IACS CSR for Bulk Carriers and Oil Tankers (i.e. from April 2006 until July 2015), structural design of bulk carriers was performed according to the IACS CSR for Bulk Carriers (CSR-BC), see (IACS, 2012). Direct strength analysis based on the three hold FE model of the cargo area was mandatory for all vessels above 150 m in length. All details of the requirements (regarding FE model, loads, evaluation criteria, etc.) were specified on both the global and the local level. Structural design according to those requirements is a challenging task that demands utilization of the integrated design systems for data transition between the different modules (loads-model-response-evaluation). To enable implementation of those requirements, classification societies developed their own software tools (e.g. VERISTAR developed by BV, CSR software developed by ABS and LR, etc.) Normally, shipyards and design offices use those tools for dimensioning of the transverse structure/grillages and to verify structural scantlings, previously defined by the prescribed rule requirements. Also, using the same tool as class society can speed up the process of classification drawings revision and finally design approval. A limitation of this approach is that the implementation of the formal structural optimization procedure is hard to achieve, since those systems are mainly closed (black box) to external data manipulation. Consequently, quality of structural design depends on the competences of the structural designer, his/her skills and talents to get the best from the *trial and error* approach of a limited number of different design variants that the designer generated in the limited time frame. To allow the designer to fully realize all the benefits of the formal optimization procedure, an in-house structural design support system OCTOPUS-CSR was developed for the concept and preliminary design phases. It combines several in-house developed modules containing CRS-BC requirements (loads, feasibility), a MAESTRO design system as a FE modeler and a structural response solver, an in-house developed multi-criteria optimization system DEMAK and an interactive GUI shell for data manipulation and post-processing of the results (3D View). The developed design system was used for the structural optimization of bulk carriers (Newbuildings 724-727) to be built in ULJANIK Group shipyard 3.MAJ in Rijeka, Croatia, and the main results and achievements are shortly presented in this paper. Alongside the shipyard and faculty design teams, the ship-owner team was actively involved in the design process with the intention to introduce the best practice from experience in ship operation into the new design solution.

Design support system OCTOPUS-CSR

To produce a competitive bulk carrier ship design, a rational structural design approach is of great importance. At the same time, a standard midship topology of the single skin bulk carrier (with wing and hopper tanks) constrained possible savings primarily on scantling reduction of structural elements. Direct application of structural design support techniques (structural optimization and FE analysis) during concept/preliminary design phase is usually performed with the objectives to reduce structural weight/cost, and in parallel to increase the overall structural safety. To allow designer to efficiently combine all benefits of the formal optimization procedure, a practical structural design support system is needed. The latest ship structural optimization examples and related developed optimization tools/systems, mainly dealing with midship section optimization based on prescribed rules, can be found in the literature (ISSC, 2012 and 2015). Design support system (DeSS) is a system of mathematical models and corresponding IT modules imbedded into the interactive design environment. It enables the design process evolution and development of efficient and competitive designs (Zanic et al 2009, 2013 and 2015). Fig.1. presents a schematic view of the Bulk Carrier Structural Design Process and tools implementation together with an explanation of data transfer between various tools and data sources. Suggested DeSS for the bulk carrier structural design, combines several main blocks:

1. MARS, Bureau Veritas software for Stage 1 CSR BC (Prescribed rule calculation);
2. MAESTRO design system as a FE modeler and solver (MAESTRO, 2014);
3. In-house developed modules containing CRS-BC requirements for direct strength calculation (loads, feasibility criteria, corrosion, ultimate strength, balancing procedure, etc.);
4. In-house developed multi-criteria optimization system DEMAK ;
5. In-house developed interactive GUI shell for data manipulation and post-processing of results (3D View).

While items 4 and 5 are already established in-house software tools used in previous research (Zanic et al. 2013, Prebeg et al. 2014), item 3 contains tools specifically developed for the bulk carrier design based on CSR BC requirements.

CRS-BC Loads and *CRS-BC Balance* are modules that enable automatic definition of loads prescribed by the CSR BC. Based on the loads prepared using those modules, load section of MAESTRO input file is automatically generated. *CRS-BC Local Adequacy* automatically checks stiffened panel adequacy prescribed by the CSR BC rules, while *CSR-BC HG Ult* is a module for hull girder ultimate strength calculation. The adequacy is checked upon the evaluation patches automatically generated in MAESTRO. In order to enable automatic preparation of the structural responses for the adequacy criteria, MAESTRO XMLSolver component is used instead of the standard MAESTRO application. MAESTRO XMLSolver component is modified in order to collect additional patch description data that are necessary for the CSR BC adequacy calculation. Module *CSR-BC Corrosion* automatically calculates corrosion allowance both for FE response calculation and for adequacy calculation.

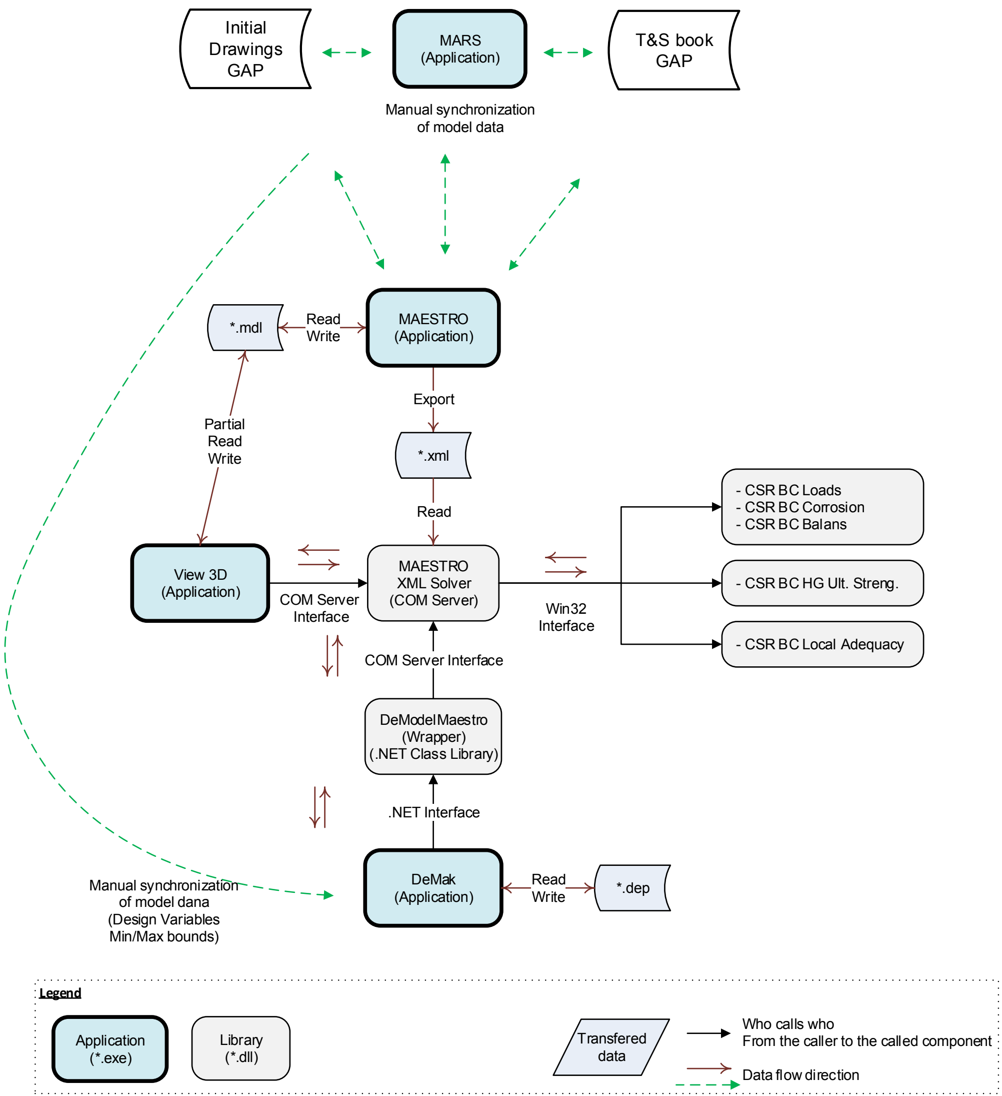

Fig. 1: Bulk Carrier Structural Design Process – Tools Implementation

Bulk Carrier Structural Design Process

One of the key challenges was to define a realistic procedure that could enable execution of the rule-based calculation, direct structural analysis and optimization simultaneously with the generation of the classification drawings in a limited time frame. The important goal was to ensure that the technical drawings (with structural scantlings definition) would be subject only to minor modification after revision by the class society (BV in this case). This approach enables the shipyard to have full control over the rational structural design generation process and to perform early material ordering. Additionally, the ship-owner's suggestions and requests were taken into account, considering their experience in ship operation practice. Fig.2. presents the design procedure flow chart of the Bulk Carrier structural design process, together with the OCTOPUS CSR DeSS tools used in a specific block.

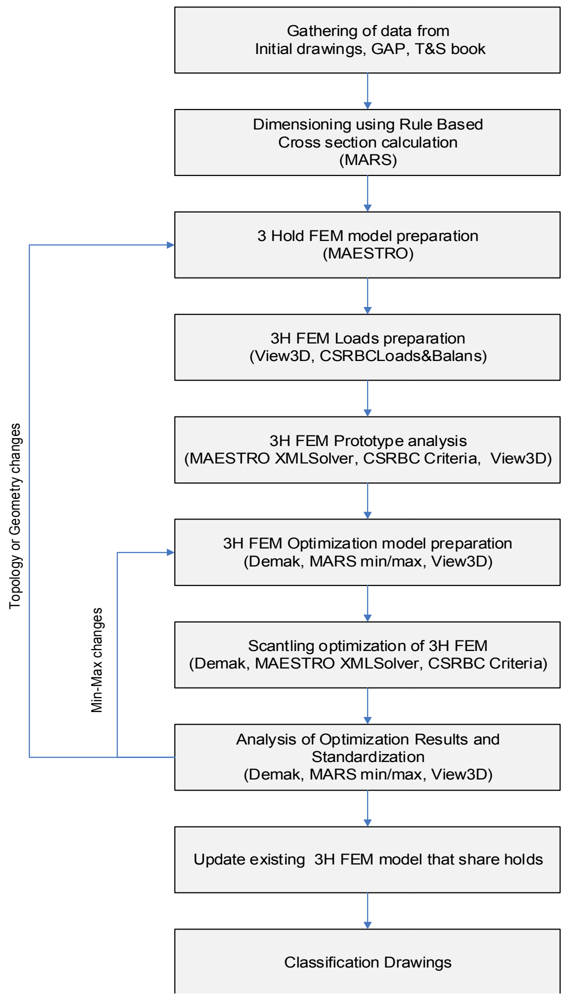

Fig. 2: Bulk Carrier Structural Design Process.

Direct application of the structural design support techniques (structural optimization and FE analysis) is performed with the objective to reduce structural weight with the simultaneous increase of the overall structural safety in fulfillment of the CSR-BC direct calculation requirements. Structural analysis and optimizations were performed for three cargo holds in the cargo area (Hold No. 2, 3 and 4), see Fig.3.

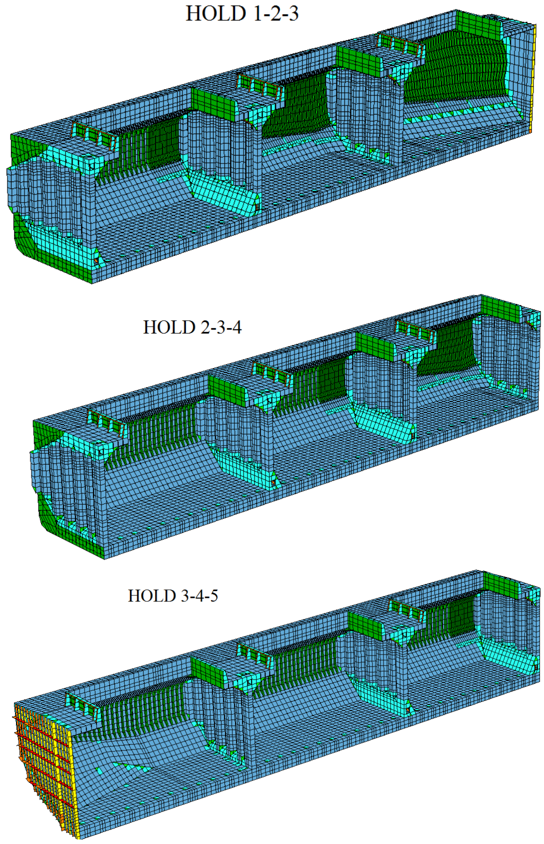

Fig. 3: Structural FE models in PDP phase

As a standard (see Zanic 2013), ship structural design process was performed through two phases: Phase I - Concept design phase (CDP) and Phase II - Preliminary design phase (PDP). Phase I is usually multilevel corresponding to design space exploration level and refinement level for the (interactively) selected designs.

Concept design phase

Concept design phase (CDP) is the most important one with regard to consequences, due to its fundamental influence on product quality, since most of the decisions regarding selection of topology and geometry variables are made in this phase. As usual, Stage I prescribed rule calculation software is used in this phase to investigate possible solutions. However, due to the limitations of this MARS model, additional global coarse orthotropic FE models are used (Hughes, 1983 and Hughes et al. 1980). The benefit of using coarse 3 hold FE models in this phase is the possibility of adequacy calculation of structural elements significantly influenced by secondary strength (bottom grillage, floors, etc.). Additionally, since in OCTOPUS CSR optimization (*DeMak*) is integrated with FEM structural response (*Maestro XMLSolver*) and adequacy calculation (*CRS-BC Local Adequacy*) it was possible perform structural optimization on this models.
Initial dimensions for this model are taken from the MARS model, which was generated using the standard yard practice. Parametric study w.r.t web frame/stiffener spacing was performed on the midship section level in order to determine longitudinal scantlings with minimal mass of cross section, based on prescribed CRS-BC requirement. Initial midship topology suggested by the

yard has the following characteristics:
• Ordinary frame spacing=800mm
• Web frame spacing of double bottom=3·800=2400mm
• Web frame spacing of deck structure=5·800=4000mm

For bottom grillage structure (floors and long. girders) and hatch coamings starting point was the minimum scantling requirement defined by CRS-BC. For the inner bottom structure, CRS-BC structural requirements regarding coils were taken into account. For the side structure within the defined ice belt region, BV ICE CLASS scantling requirements were used.

Preliminary design phase

Design optimization in this phase is based on the 3 hold FE models generated according to the CSR BC Stage 2 modelling rules, see Fig. 3. With respect to the 3 hold models used in CDP phase, these models are more detailed (regular shell elements are used instead of orthotropic macroelements, holes in webs are modeled directly instead of equivalent thickness approach, etc.). Starting points for this phase were structural scantlings defined through the optimization process in phase I (CDP). Due to the increased level of details, this model is much more demanding for optimization. However, since the majority of necessary decisions are made in CDP (that was enabled by usage of a simple 3 hold FE model), optimization in this phase only needs to make corrections that are results of higher fidelity/accuracy of PDP 3 hold FE model.

Vessel description

The vessel is the handymax bulk carrier with the following class specification and principal dimensions:

CLASS	:Bulk carrier CSR CPA (WBT), BC-A, ESP, GRAB (20), ICE CLASS 1A, Holds No.2 and No.4 may be empty
Length overall	: 183.00 m
Lpp	: 175.00 m
Rule Lenght	: 173.63
Breadth, moulded	: 30.00 m
Depth, moulded	: 15.60 m
Scantling Draught	: 11.30 m
Block coefficient- Cb	: 0.8068
Deadweight at Tscant	: 39 200 t
Max. Service speed	: 15.8 knots
Class:	BV, CSR, BC-A

Ship compliant with IACS CSR for Bulk Carriers

FE models and load cases

Two types of FE models were developed:

- Model A1→ macroelement model (using orthotropic element for stiffened panel) → to be used in concept design phase (CDP)
- Model A2→ FE model (without orthotropic element) → to be used in preliminary design phase (PDP) for the final scantling optimization and standardization. These types of models were sent in BV for the final approval together with the classification drawings made by the shipyard.

In total five different 3-hold FE models were built as full-asymmetric models based on CSR-BC requirements (mesh, size, aspect ratio, etc.):

- Model A1a- (Hold 2-**3**-4) - *macroelement model - Hold No.***3** was analyzed/optimized hold - CDP
- Model A1b- (Hold 3-**4**-5) - *macroelement model - Hold No.***4** was analyzed/optimized hold - CDP
- Model A2a- (Hold 2-**3**-4) - *FE model - Hold No.***3** was analyzed/optimized hold - PDP
- Model A2b- (Hold 3-**4**-5) - *FE model - Hold No.***4** was analyzed/optimized hold - PDP
- Model A2c- (Hold 1-**2**-3) - *FE model - Hold No.***2** was analyzed/optimized hold - PDP

A2 type of FE models provides boundary conditions for further detail stress and fatigue analysis that can be required at the critical locations. The middle holds, of each 3-hold model were analyzed. First and third holds of the each 3-hold model were excluded from safety evaluation, as requested by CSR-BC, due to influence of the boundary conditions, see Fig.2.

The same CSR-BC prescribed loading conditions were applied for both models (A1 or A2) of the same hold combination. All masses were given corresponding accelerations based on the acceleration vector components calculated from CSR-BC. Global hull girder loads, dynamic external and internal pressures were calculated according to distributions requested by CSR-BC rules and implemented on each FE model using in-house developed module *CRS- BC Loads*.

Each load case comprised three components: a) structural mass, b) deadweight items and c) buoyancy loading and dynamic sea pressures, all factored to suit the needs of pressure and acceleration data supplied from CSR-BC rule requirements. Balancing procedure requested by CSR-BC was followed to achieve specified target values (hull girder moments and shear forces) at specified locations in all load cases for all models. Equivalent moments at starting “cut” section and at last section were calculated following the IACS procedure (Ch.7, Sec 2, 2.5) and implemented to satisfy the requested target moment. In-house module *CRS-BC-Balance* was developed for the automatic generation of all requested target values. From 14 selected loading conditions 32 loading cases were generated following CSR-BC (Ch.4 App.2) and analyzed. The brief description of load cases is summarized in Table 1. The still water bending moments from T&S book and those calculated from the CSR-BC were compared and bigger were combined with IACS rule wave bending moments to achieve appropriate total bending moments and total shear force in every hold. On the basis of the chosen load conditions 32 MAESTRO load cases are formed (LC1 to LC32), see Table 1. The total target bending moments for these load cases were calculated according to CSR-BC rules. For load cases LC1 to LC28 the target value was total vertical bending moment (still water + dynamic) at the middle of the mid-hold. For the last four load cases (LC28 to LC32) the target values were the shear force and the reduced total vertical bending moment at transverse bulkhead (Fr.111 and Fr.147). For all load cases the realization of target values was controlled by the in-house developed module *CRS-BC Balance*. See graphical validation for LC24, on Fig. 4.

Table 1: Selected loading conditions and global target bending moments and shear forces for Hold No.3

LC	Name	MVT [kNm]	MHT [kNm]	QVT [kN]
1	LC1_FullLoad (Tab3No1P1 Sagg)	-1373767	0	0
2	LC2_FullLoad (Tab3No2P1 Sagg)	-1373767	0	0
3	LC3_SlackLoad (Tab3No3P1 Sagg)	-839122	0	0
4	LC4_DeepestBallast (Tab3No4aR1 Hogg)	1285110	337851	0
5	LC5_DeepestBallast (Tab3No4aR1 Sagg)	-1069290	337851	0
6	LC6_DeepestBallast (Tab3No4aP1 Sagg)	-1543678	0	0
7	LC7_DeepestBallast (Tab3No4bR1 Hogg)	1285110	337851	0
8	LC8_DeepestBallast (Tab3No4bR1 Sagg)	-1069290	337851	0
9	LC9_DeepestBallast (Tab3No4bP1 Sagg)	-1543678	0	0
10	LC10_MultiPort2 (Tab3No5F2 Hogg)	2578546	0	0
11	LC11_MultiPort2 (Tab3No5P1 Sagg)	-1670661	0	0
12	LC12_MultiPort3 (Tab3No6P1 Sagg)	-1446895	0	0
13	LC13_MultiPort3 (Tab3No7P1 Sagg)	-1446895	0	0
14	LC14_MultiPort4 (Tab3No8F2 Hogg)	2578546	0	0
15	LC15_MultiPort4 (Tab3No8R1 Hogg)	1285110	334754	0
16	LC16_MultiPort4 (Tab3No8R1 Sagg)	-1069290	334754	0
17	LC17_MultiPort4 (Tab3No8P1 Sagg)	-1558778	0	0
18	LC18_MultiPort4 (Tab3No9F2 Hogg)	2578546	0	0
19	LC19_MultiPort4 (Tab3No9R1 Hogg)	1285110	334754	0
20	LC20_MultiPort4 (Tab3No9R1 Sagg)	-1069290	334754	0
21	LC21_MultiPort4 (Tab3No9P1 Sagg)	-1558778	0	0
22	LC22_AlternateLoad (Tab3No10F2 Hogg)	2578546	0	0
23	LC23_AlternateLoad (Tab3No10P1 Sagg)	-839122	0	0
24	LC24_HeavyBallast (Tab3No13H1 Sagg)	-2467826	0	0
25	LC25_HeavyBallast (Tab3No13R1 Sagg)	0	338046	0
26	LC26_HeavyBallast (Tab3No13R1 Sagg)	-1069290	338046	0
27	LC27_HeavyBallast (Tab3No14R1 Sagg)	0	338046	0
28	LC28_HeavyBallast (Tab3No14R1 Sagg)	-1069290	338046	0
29	LC29_AlternateLoad (Tab4No10SFHogg)	1868821	0	-65899
30	LC30_AlternateLoad (Tab4No10SF Hogg)	1861761	0	61562
31	LC31_HeavyBallast (Tab4No13SF Sagg)	-1764480	0	-65899
32	LC32_HeavyBallast (Tab4No13SF Sagg)	-1756847	0	61562

MVT-total vertical bending moment, MHT-total vertical bending moment, QVT-total vertical shear force

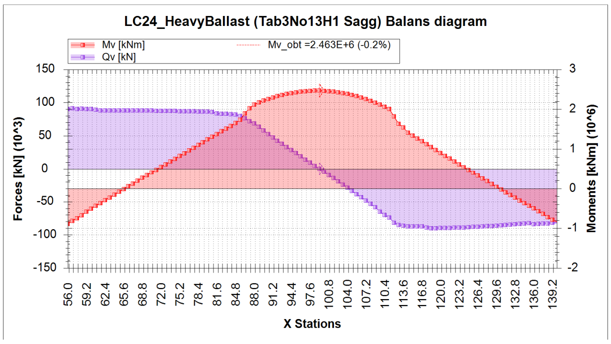

Fig. 4: Check of balancing procedure and realization of specified target values for LC 24

Buckling criteria and allowable stresses

Structural adequacy was checked using the library of the failure criteria through the in-house developed module *CRS-BC Local Adequacy*. Library of criteria were specified by CSR-BC (Ch.6, Sec.3). For the direct (FE) calculation level, buckling of the elementary plate panels is given on an uni-axial level (*BEPPxx, BEPPyy, BEPPxy*) and bi-axial (with shear) level (*BEPP*):

$$\left(\frac{|\sigma_x|S}{\kappa_x R_{eH}}\right)^{e1}+\left(\frac{|\sigma_y|S}{\kappa_y R_{eH}}\right)^{e2}-B\left(\frac{\sigma_x\sigma_y S^2}{R_{eH}^2}\right)+\left(\frac{|\tau|S\sqrt{3}}{\kappa_\tau R_{eH}}\right)^{e3}\leq 1.0 \tag{1}$$

For the yielding strength assessment (via FE) the equivalent stress criteria is defined (CSR-BC Ch7, Sec.2, 3.2) and abbreviation used in adequacy calculation is ESCA for this criteria. According to CSR-BC (Ch. 7 Sec. 3, 3.2.3) yield criteria *ESCA* depends on the type of element used. For the CDP level where FE model A1 were used, allowable stresses is defined as $Q_L = 205 / k$;(k is material factor), while for the PDP where FE model A1 were used allowable stresses is defined $Q_L = 235 / k$.
According to CSR-BC (Ch. 7 Sec. 3, 3.2.3) the safety factor for buckling and ultimate strength assessment of the plates is to be taken as $\gamma = 1$.
For the purpose of the presentation of results the strength ratio R is defined as follows:

$$R(X) = Q(X) / Q_L(X) \tag{2}$$

Where X is vector of current values of structural parameters including scantlings, Q(X) is load effect and $Q_L(X)$ is its limit value for particular failure mode. **Failure criterion** is given by:

$$\gamma\, R(X) < 1 \text{ (safe design)} \tag{3}$$

In normalized form, using 'adequacy parameter' g(R,γ), failure criterion reads:

$$g\,(R,\gamma) > 0 \tag{4}$$

where $g(R,\gamma) = (1-\gamma R) / (1+\gamma R)$ and $-1<g<1$

Design with g (R, γ) > 0 means safe design
Based on calculated stiffened panel adequacy values two global deterministic safety measures are calculated for usage in optimization process. The first is the cumulative sum of the all adequacy criteria that are less than 0.05 (abbreviation used for this measure in optimization diagrams is GMean):

$$g_{<0.05}=\sum_{i=1}^{n_p}\sum_{j=1}^{n_c} g_{ij}\Big|_{<0.05} = \text{GMean}; \tag{5}$$

The second is average value of the lowest (worst) 5% of adequacy criteria (abbreviation used for this measure in optimization diagrams is GMin):

$$g_{\min 5\%}=\frac{\sum_{i=1}^{n_{5\%}} g_{ij}\Big|_{5\%}}{n_{5\%}} = \text{Gmin}; \tag{6}$$

In following Sections results of Hold 3 for both design phases (CDF and PDP) where given in more details, while for other evaluated Holds (2 and 4) only the final results have been presented.

CDP-Prototype analysis of Hold 3-model A1a

Based on initial drawings and initial scantlings (calculated following prescribed CSR-BC rules) the model A1a was developed, loaded and analyzed.
It was found that initial structure within the Hold 3, with given scantlings based on prescribed rule calculation, does not comply with the CSR-BC criteria for several structural parts, mainly due to the bi-axial (with shear) buckling. Increased possibility of biaxial buckling of bottom plating as standard example (where adequacy parameter g<0) is presented in Fig.5.

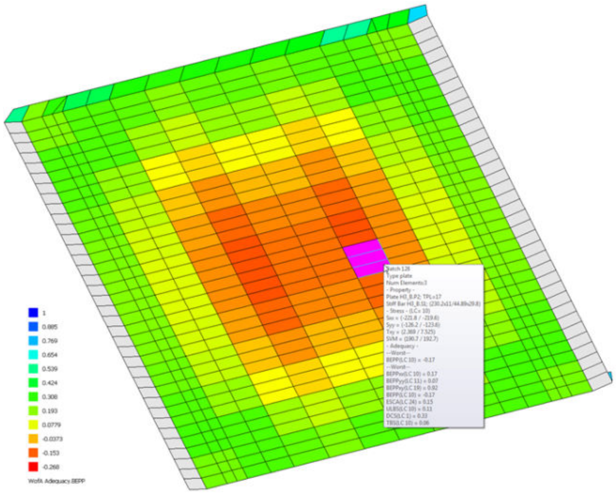

Fig. 5: Worst normalized safety factor BEPP achieved in the bottom plating

Based on the findings of this analysis some topological/geometrical changes were introduced prior to scantling optimization process. Those changes are shortly summarized below and implemented into the FE model A1a, which serves as an updated structural model for optimization:

- Height of web frames in wing tank has been increased (750mm→800mm and 800mm →900mm) due to deficiencies of bending stiffness;
- Intercostal anti-buckling stiffener in wing sloping plate near the transverse bulkhead has been inserted due to biaxial buckling problems;
- Strong bracket on the middle of wing web frame spacing has been inserted connected longitudinal hatch coaming, deck and wing sloping plate;

The Table 2 summarizes the main result of the adequacy analysis of the 3-hold FE model A1a for the structural parts with the insufficient structural safety (areas that do not comply with the CSR-BC requirements).

Table 2: Adequacy analysis of prototype structure for Hold No.3

ITEM	Part	Load case	TYPE* g-value	Comments on Prototype
1	Bottom plating (middle part)	LC 10	BEPP -0.17	Increased probability of -axial buckling
2	Floors	LC10,23.	BEPP -0.268	Increased probability of ıckling
3	Double Bottom Long. Girders	LC10,23	BEPP -0.13 ESCA -0.09	Increased probability of buckling and yield (high shear stresses)
4	Hopper Tank (sloping plate next to TBHD	LC 23	BEPP -0.17 ESCA -0.03	Increased probability of buckling and yield (high shear stresses)
5	Hopper Tank Web Frame	LC 23	BEPP -0.24	Increased probability of buckling High shear stresses
6	Side shell Plating	LC 22,32	BEPP -0.03 ESCA -0.01	Increased probability of buckling and yield (high σ_x and τ stresses)
7	Wing Tank (sloping plate next to TBHD	LC 1	BEPPyy -0.29 BEPP -0.43	Increased probability of buckling
8	Wing Tank Web Frame	LC 27, 28	BEPP -0.25 ESCA -0.09	Increased probability of buckling and yielding
9	Plating Deck Around openings	LC 22	ESCA 0.00	Increased probability yielding
		LC 11	BEPP -0.46 ESCA -0.14	Increased probability yielding

*BEPP, ESCA- mnemonics for the failure criteria defined in before

CDP-Structural optimization of Hold 3-model A1a

Objective, variables and constraints
As stated before, the objective of the optimization was to reduce structural weight while fulfilling strength requirements defined by the IACS CSR BC. Design variables were the scantlings of structural members, mainly plates and stiffeners. Due to the relative coarse mesh of the orthotropic stiffened panels, many details have been excluded from the model (e.g. manholes in double bottom floors and girders). A total of 101 design variables was used in this optimization problem. Minimal and maximal nominal scantlings were prescribed by the client, based on the CSR BC minimal scantlings requirements, local strength requirements (e.g. coils on inner bottom), Uljanik Shipyard technological preferences and ship-owner requests and preferences. The adequacy criteria have been checked for all 32 considered load cases. This resulted with the total of 6058 structural adequacy constraints defined in the optimization problem.

Optimization problem solution
Optimization was performed by the in-house decision making tool DEMAK, with integrated MAESTRO XML Solver, using Sequential Linear Programming (SLP) algorithm with dual formulation inbuilt in DEMAK (Zanic et al. 2013, Prebeg et al. 2014).
Solution sequence for the model of Model A1a – HOLD 3 is presented in Fig.6. Each block is an optimization problem for structures defined in Hold 3 – H3_B (Hold 3 Bottom), H3_F (Hold 3 Flors), etc.
Optimization problem (All in one-*AiO*) is used for the full FE analysis and adequacy evaluation of the instantaneous state of the model after each cycle. The main purpose of this is to calculate the real state of model

outputs after all substructure optimization problems have changed variables in respective cycle.

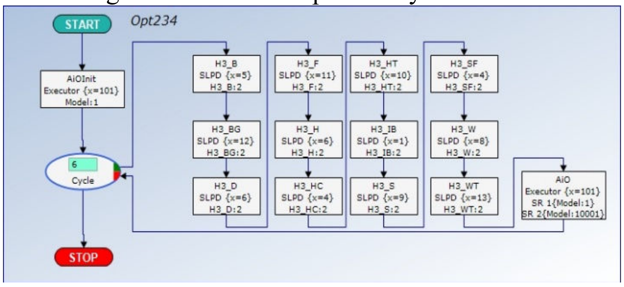

Fig. 6: Model A1a – Hold 3 - Optimization problem solution sequence

The history of optimization process convergence is shown in Fig.7. Due to the inadequacy of the initial model, the optimization has resulted with an increase of the structural mass, while satisfying structural adequacy. The structural mass of the control structure have increased from 978t to 993t (1.5% or 15 tonns) while increasing the safety measure $g_{min5\%}$ from -0.04 to 0.01.

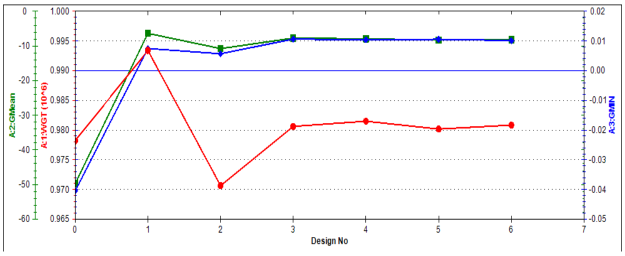

Fig. 7: Model A1a – Hold 3 - The history of optimization process convergence

Web frame spacing parametric study

The initial ordinary frame spacing of evaluated structure was 800mm, web frame spacing of the double bottom and hopper tank structure was 3·800=2400mm, while web frame spacing of the deck and wing tank structure was 5·800=4000mm, and was proposed by shipyard (A1a-800). Those parameters were fixed during optimization process and the results presented above where with those topological parameters.

To investigate the possible benefits of different frame spacing, another topological solution (A1a-735) with the following parameters was developed as A1 macro-element FE model and fully optimized:

- Ordinary frame spacing=735mm
- Web frame spacing of double bottom=3·735=2205mm
- Web frame spacing of deck structure=6·735=4410mm
- Two less double bottom girders due to the increased number of floors

The complete process, as described above, was repeated with the new model A1a-735. Results show low sensitivity of the proposed solution compared to the initial design (A1a-800). After the complete optimization process, the difference in the structural mass of Hold 3 is smaller by about 20 tons. The shipowner and shipyard design teams decided to keep the initial frame spacing of 800mm due to the several topological benefits regarding the hatch cover/hatch coaming shape and more standardization possibilities.

CDP-Structural optimization of Hold 4-model A1b

A similar process in conceptual design phases (CDP) that includes prototype analysis and structural optimization process was performed for Hold no.4. Results follow the trend identified for Hold 3 and can be summarized thus:

- Initial structure in Hold 4 with given scantlings based on prescribed rule calculation, does not satisfy the CSR-BC criteria for several structural parts mainly due to the bi-axial buckling criteria.
- The structural mass of the control structure was slightly increased from 927.5t to 928.3t (less than 0.1% or 1 tonns), while increasing safety measure $g_{min5\%}$ from -0.07 to 0.01.

PDP-Structural optimization of Hold 3-model A1a

This section shortly presented results of structural optimization based on A2a model, relevant for evaluation of Hold No.3. Compared to model A1a used in CDP, model A2a for PDP has more detailed scantling property breakdown, based on detailed yard technological requirements specified in document *1-102-301: Basic breakdown of the ship in groups and sections*. This document specifies, in detail, the standardization strategy, the steel plate's position and dimensions (breadth and length), stiffeners grouping, etc. All of these requirements were implemented in a new FE model (A2a). Due to these requirements a higher number of scantling properties was generated compared to model A1a. The starting point for this phase (PDP) was the structural scantlings defined through optimization process in CDP phase (using A1a and A1b models). Those structural scantlings were implemented in the model marked as A2a$_{\text{Prototype}}$. Also due to fact that A2 models are developed with the finer FE mesh then A1 models, a lot of details that were skipped in CDP now were taken into account for the final scantling determination.

It was found that the initial structure in Hold 3 (marked as A2a$_{\text{Prototype}}$), with given scantlings based on prescribed rule calculation and optimal scantlings from CDP does not completely comply with the CSR-BC criteria for several structural parts, mainly due to the bi-axial (with shear) buckling, but in general has adequate strength and only "fine tuning" is need to get minimal weight design with all adequacy criteria satisfied. Several topological/geometrical changes were implemented prior to scantling optimization process to obtain more rational design. Those changes are summarized bellow and implemented in the FE model A2a, which serves as an updated structural model for the final scantling optimization:

- Several manholes on double bottom longitudinal girders should be closed close to connection to transverse bulkhead (TBHD).
- Intercostal anti-buckling stiffeners are suggested on (hopper sloping plate near TBHD, hopper tank web frame, wing tank sloping plate, wing tank web

frame, deck plating between hatches, etc.).

Objective, variables and constraints

The same principles were implemented as stated for the CDP phase. The main difference is in an increased number of the design variables and local structural adequacy constraints that need to be evaluated due to the increased number of elements in the model. Ultimate hull girder strength has been controlled throughout the whole optimization process by calculation of the ultimate bending moment in hogging and sagging condition for all evaluated design variables. The in-house module *CRS-BC HG Ult* was used (Kitarovic and Zanic 2014, Andric et al., 2014). This requirement mainly affected scantlings of deck and wing tank structures in sagging condition, especially for damage case condition. It can be seen in Fig.8 (column marked as "%"), that for the final solution usage factor related to the hull girder ultimate strength reaches slightly above 99%.

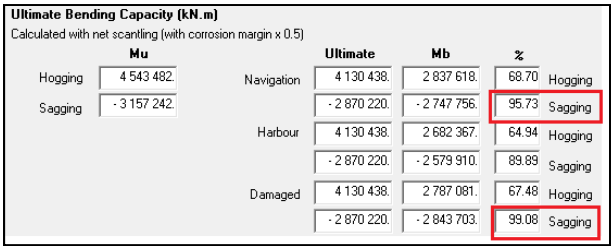

Fig.8: Hull girder ultimate strength of midship section

As in CDP, optimization was performed using the in-house decision making tool DEMAK, with integrated MAESTRO XML Solver, using Sequential Linear Programming (SLP) algorithm with dual formulation. Solution sequence for the model of Model A2a – HOLD 3 is presented in Fig.9. Each block is an optimization problem for structures defined in Hold 3.

Due to the inadequacy of initial model, the optimization resulted in a small increase of the structural mass, while satisfying structural adequacy. The structural mass of the control structure increased from 649t to 658t (1.3% or 9 tonns), while increasing safety measure $g_{min5\%}$ from 0.022 to 0.029.

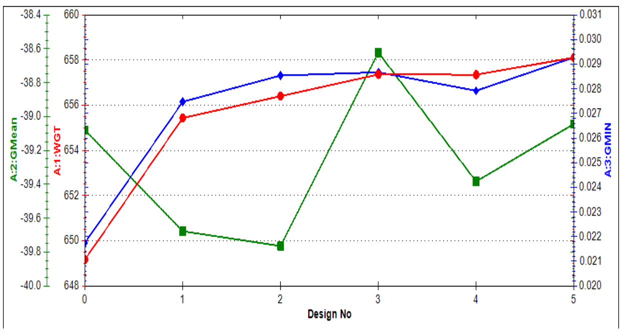

Fig.9: Model A2a – Hold 3 - The history of optimization process convergence in PDP

The increase of several plate thicknesses due to the biaxial buckling requirement was used in order to reduce the mass of longitudinal stiffeners (approx. 9 tonns in Hold 3):

HOLD 3	Profile type	
	Prototype	Final Proposal
Bottom longitudinals No.14-17	HP 240*12 AH32	HP 240*11 AH32
Inner bottom longitudinals No.1-12	HP 300*13 AH36	HP 300*12 AH36
Hopper tank longitudinals No.1-3	HP 300*13 AH36	HP 300*12 AH36
Side shell longitudinals No.23-26	HP 340*14 AH36	HP 300*11 AH36
Wing tank longitudinals No.1-8	HP 300*13 AH36	HP 300*11 AH36

At the end, after standardization process has been performed, the total structural mass of Hold 3 was increased from 1219t to 1223t (0.83% or 4 tonns).

Compliance with the rule prescribed requirements (on global and local level) of all structural scantlings of the preferred design solution was finally checked with BV design tool MARS.

PDP-Structural optimization of Hold 4

Similar process in preliminary design phases (PDP) that includes prototype analysis and structural optimization process was performed for Hold no.4. The starting point for this phase (PDP) was structural scantlings defined through different design phases and using different structural models:

- initial scantlings of Hold 4 were defined through optimization process in CDP phase (A1b model).
- scantlings of Hold 3 were defined through optimization process in PDP phase(using A2a model).
- scantlings of Hold 5 were calculated following prescribed CRS_BC calculation (MARS).

Results follow the trend identified for Hold 3. The structural mass of control structure was decreased from 369.7t to 366t (1 % or 6 tonns), while increasing safety measure $g_{min5\%}$ from 0.029 to 0.06, see Fig.10.

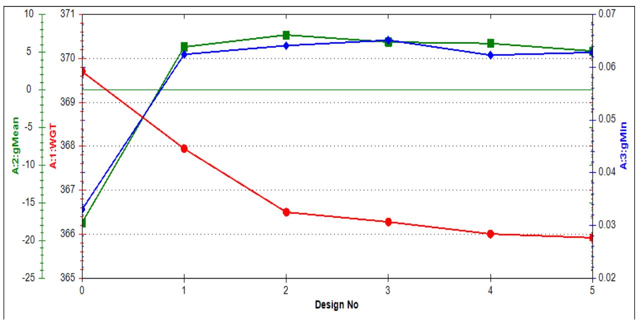

Fig.10: Model A2b – Hold 4 - The history of optimization process convergence in PDP

At the end, for all structural elements in Hold 4 the total structural mass was reduced from 1076t to 1074t (0.21% or 2 tonns).

PDP-Structural optimization of Hold 2

A similar process in preliminary design phases (PDP) that includes prototype analysis and structural optimization process was performed for Hold no.2, as was done before for Hold no.3 and 4. The starting point was structural scantlings defined using different structural models:

- scantlings of Hold 3 were defined through optimization process in PDP phase (using A2a model).
- initial scantlings of Hold 2 were defined following

prescribed CRS-BC calculation (MARS) and partially by results influenced using A2a model in PDP.
- scantlings of Hold 1 were defined following prescribed CRS-BC calculation (MARS).

The structural mass of control structure was slightly increased from 373.5t to 385.5t (3.3% or 12 tonns), while increasing safety measure $g_{min5\%}$ from -0.01 to 0.055, but the total structural mass in Hold 2 was reduced from 971.5t to 970t (0.14% or 1.5 tonns) due to several topological modifications.

Conclusions

This paper briefly presents results obtained after completing structural design and optimization of Holds 2, 3 and 4 of handymax bulk carrier, for all relevant load cases required by CSR-BC direct calculation. Due to the fact that prototype structure (starting from the rule minimum requirements and prescribed 2D calculation) was unsatisfactory, structural optimization performed through this study enabled only a minimum increase of the mass (compared to unsatisfactory prototype). Approximately, the total mass of all structural scantlings in optimized Holds 2, 3 and 4 was unchanged compared to the prototype structure, but with all structural problems solved and with an increase in overall safety. Structural mass was removed from the areas of increased safety to areas that do not satisfy the CRS-BC criteria. Developed tools, design environment and methodology provide the shipyard and the ship-owner with the possibility to generate rational structural design and fully control structural scantlings.

Optimization algorithms and other synthesis tools are mature enough to be efficiently used in ship structural design process, but what is needed is the possibility to use and easily link already existing rule-based analysis tools (such as rule defined modules for loads, feasibility criteria, etc.) to FE solver and optimization tools. Open source code of the mentioned analytical modules (already developed, tested and validated by class societies) or at least a library with prescribed API that would be available to structural designer could be a strong wind ahead to use the presented approach in standard design work following the basic paradigm: lower ship production cost for the shipyard and more profitable and durable ship for the ship-owner with the acceptable level of safety defined by the rules.

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