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FEM Structural Analysis and CAD Hull Modelling for a Bulk Carrier - a Case Study

A. Pintilie, M.G. Manea, O. Cristea, P. Burlacu, D. Mărăşescu & C.P. Clinci
Mircea cel Bătrân Naval Academy, Constanța, Romania

ABSTRACT: Due to the frequent damage encountered in the hull of bulk carriers in operation, it is necessary to analyse the possibilities to increse the performances by structural and dimensional modeling of the central area of the hull of the vessel under the effect of combined general stresses (and specific local stresses. The present paper analyzes the response of the central section of the bulk carrier of 165000 tdw for three representative cases of total stress, re-evaluated by simulation with the help of finite element analysis software. Following the interpretation of the results obtained by the finite element analysis, the authors propose some solutions to increase the structural strength of the central area of the bulk carrier of 165000 tdw. The present study shows that the structure of the cylindrical area of the hull of the analyzed ship, remodeled by finite element, ensures the compromise between the operational requirements and the design requirements imposed by the norms The structural characteristics of the central section of the ship were analyzed, the practical validation being provided by the finding that the bending moments do not exceed the permissible values imposed by the class society. Work was done on three separate cases of ship loading and corrections were made for 12 sections of the hull. The use of high-strength steel has led to a weight reduction of 22%.

1 INTRODUCTION

The requirements for increasing the safety of bulk carriers were presented in 1993 by the International Association of Classification Societies (IACS) and the International Maritime Organization (IMO). The need to acknowledge a premier role in the constructive-elastic optimization of bulk carriers was claimed by the large number of registered damages, including losses of ships from this functional-constructive category [43]. Justifiably, the authors of this paper are interested in limiting the number of ship losses by improving their constructive structure, respectively the control over the (general and local) elastic behaviour for the ship's hull in the mentioned category. The constructive restructuring of the bulk carrier's hull appeared because of the factors involved in damage losses [32].

The simple comment on the above-mentioned factors highlights the actual priorities regarding the constructive structuring of the bulk carrier's hull. Of course, two distinct situations arise: for the existing bulk carriers already in operation, the necessary structural corrections can only be partially assimilated; for the bulk carriers to be designed and built, the structure must be reanalyzed and rationally designed.

Table 1. Factors involved in damage losses ships

Cause	Previous research	Authors solution
corrosion of materials	- corrosion is the most frequent form of degradation (measurements on the walls of the fuel tank onboard a 25-year-old bulk carrier demonstrate a reduction in thickness at a rate of 1.55 %/year [16]); - a linear model [17] was used to describe the percentage of plate wear and tear as a function of the built-in thickness of a longitudinal girder; - a progressive collapse analysis of a bulk carrier was carried out in [5] considering the existence of cracking damage at different locations of the hull girder - bottom, double bottom, side and deck.	limit the effects either by using resistant materials or by intensifying protection measures
grounding and collisions of ships	- Alie and Adiputra propose a solution for the situation in which the cross-section remains plain, and the vertical bending moment is applied to the cross section [1]; - Sun et.al. [34] predicted the residual ultimate strength of a ship hull after a shoal grounding accident, by a method based on the plastic-elastic deformation mechanism (the improved Smith's method); - time-variant reliability analysis is performed by Campanile, Piscopo and Scamardella, for a damaged single side bulk carrier, to investigate the incidence of the applied collision damage models on hull girder annual failure probabilities in sagging and hogging conditions [8]; - [6] paid attention to the subject of the multi-agent anti-collision system thus increasing safety at sea	reevaluating whit FEM to ship hull girder strength due to grounding and collisions of ships
goods with high density	- the authors of [12] modelled with the Finite Element Method (FEM) the overall deformation and rigidity under various operational scenarios because the cargo loading conditions can vary significantly and affect the local static deflection due to the compartments	FEM analysis of ship loading cases
fatigue	- for a new type of steel developed for the first time in Japan, the paper [20] certified the fact that the fatigue strength of Heat-Affected Zone (HAZ), where fatigue crack generally initiates, is higher than that in conventional steel. They considered the mechanism of suppression of fatigue crack initiation with FEM analysis and fatigue test, and concluded that the newly developed steel could effectively extend fatigue fracture life of the welded structure from the viewpoint of material	redesign the structure elements of transition from a framework system to another
wide cutouts for the deck's	- Yao and his colleagues [39] propose a method to evaluate the collapse strength of a hatch cover subjected to lateral load, using the FEM analysis	stiffening of these decks is required
the presence of corrugated walls which	- due to the attachment system to the main deck, it has reduced strength to the pressure of loads or flood water from the cargo holds; - the results obtained in [10] show that the ultimate capacity of the corrugated bulkhead is significantly larger than that of the traditional T-shaped stiffened plane bulkhead under the same weight of materials	redesign the fixing system of corrugated walls to the main deck
the cargo effects on the double-bottom	- these are locally under strong strain; - in [19] the authors highlight that the accurate estimation of cargo load is important for designing a ship's double bottom structures, being necessary to consider the dry bulk cargo load due to the ship acceleration in real conditions of navigation	redesigning in terms of control the oversizing

2 LITERATURE REVIEW

The design characteristics of bulk carriers have been the focus of naval classification societies that over time have been concerned with setting up design and construction criteria that allow appropriate responses to the general and local strains upon the hull while in operation.

2.1 *Design requirements of classification societies*

2.1.1 *American Bureau of Shipping requirements*

Since 1991 the American Bureau of Shipping (ABS) has become interested in investigating the response of the bulk carrier hull structure to stress, to understand the causes of the structural weaknesses which may contribute to ship losses. They proposed a new complete, flexible, and integrated strength criteria for the design of bulk carrier hull structures, which involve loading, strength for minimum scantling requirements, and strength assessment procedures [18].

The American Bureau of Shipping (ABS) indicates that most structural deficiencies in bulk carriers are generated by irrational cargo loading in holds and/or asymmetric ballasting of trim tanks, necessitating frequent visits by the ship classification societies so that flaws be detected before they produce major damage to the material [40]. According to the ABS Rules, the following aspects must be considered:

– checking the degree of participation of the efforts in the general and local demands of the ship's hull, idealized as a complex beam (the sectional efforts resulting from the calculation must be amplified in order to be sure of taking over the additional loads due to the cuts in the decks);
– anticipating the loading variant of the goods in the cargo holds (uniform or alternating,
– the latter producing bending moments and shear forces which can cause damage to the structure when combined);
– the participation of dynamic efforts to the hull stress, with effects on the safety of the structure (avoided in current design practice by accepting some covering safety coefficients);
– appreciation of the effects of excessive corrosion phenomena in various structural areas of the hull (a fact that sometimes requires the reconsideration of the materials currently in use).

2.1.2 *Bureau Veritas requirements*

In 1995, Bureau Veritas imposed VeriSTAR, a set of recommendations regarding ship design, which considers that fatigue and corrosion are the main causes of damage observed on ship structures [7].

2.1.3 *IACS requirements*

For safety reasons, in 2010, a consolidated version (more complex and time consuming for the design process) of the Common Structural Rules (CSR) for oil tankers and bulk carriers was established by the IACS. To strengthen the IACS CSR design rules, the following studies were carried out:

– preoccupied by the problem of time, Na and Karr developed a new structural analysis tool for the optimum design of ship structure named Efficient

Stiffness Method (ESM) trough what reduce the analysis computing time compared with FEM method [26];
- to follow the structural design according to IACS CSR requirements, an original approach has been presented, proposed by Andric et.al. [3], which uses an in-house structural design support system, named OCTOPUS-CSR for the preliminary design of a bulk carrier;
- others, like Kitarovic, Andric and Piric consider the rules of IACS CSR to analyze the ultimate strength of a bulk carrier hull girder at its amidships section, using the nonlinear finite element method analysis, the results being compared and discussed on both local and global level, for sagging and hogging cases [22];
- to evaluate the Ultimate Limit State (ULS) performance of a bulk carrier structure designed by the IACS CSR method, and to certify the quality of the design, at first, it was necessary to compare this method with the similar class / type bulk carrier structure designed by the IACS pre-CSR method [29].

The conclusion is that the constructive structure must be established beforehand so that it can be found in elastic and resistant forms of the ship's hull supported by quality materials and efficient manufacturing technologies, respectively in shortening the ship's manufacturing cycle. Right from the design phase, the multiple, diverse and complex demands to which the ship's hull is subjected must be known and anticipated preventively and systematically controlled during operation.

2.2 *FEM studies of the ship's structural strength*

The elastic-plastic behaviour of the ship is influenced by certain factors, namely: the geometric and material properties; the characteristics of the loads upon the decks; the initial imperfections of the material; up to the limit conditions; local damage due to corrosion, cracks and stress concentrators. The Finite Element Method (FEM) is an advanced method for numerically solving problems arising in marine engineering and naval architecture such as structural analysis. Therefore, various researchers have used this method both for the ship as a whole and for the analysis of areas considered critical to the ship's structure. Yang et.al. [38] analysed (using 3D FEM to design the dry structure model and 3D methods in the frequency and time domain to predict the wave loads) the vertical and horizontal bending moment together with the torsional moment caused by the wave loads for a very large bulk carrier. The hydro elastic responses of ships traveling on waves were studied and a comparison was conducted between the numerical prediction results and experimental data measured from the sea-keeping basin. Pei, Iijima, Yao et.al. [30] were interested in examining the influence of the local bending of the double bottom on the ultimate hull girder strength for a bulk carrier in alternate heavy loading conditions. For that reason, they used a nonlinear FEM analysis which found that bending deformation was produced not only in the double bottom but also in the bilge hopper tank, and the ultimate hull girder strength was reduced by roughly 20% due to this local bending. Two years later, the same authors concentrated their efforts to simulate progressive collapse behaviour of a single hull kamsarmax type bulk carrier [31]. Progressive collapse behaviour obtained through Idealized Structural Unit Method (ISUM) analysis (compared with MARC as a Finite Element Analysis solver) proved their applicability to structure system by offering high accuracy and sufficient efficiency. Alie and coauthors [2] studied the ultimate strength of ship's hull considering the cross section and beam finite element under longitudinal bending (only one-frame space of the ship was taken into consideration in the calculation and the cross section of the bulk carrier's hull was divided into element-composed plate and stiffened plate). Knowing that bulk carriers have been designed with a small safety margin, Frystock and Spencer present analyses of the strength in flooded conditions, performed for different loading conditions: alternate and uniform loading distribution of heavy cargo [14]. The paper [9] focuses on time-variant longitudinal strength of bulk carriers under corrosion wastage, the hull girder section modulus and ultimate bending moment capacity being determined. The [33] paper studies the progressive collapse of the hull girder subjected to pure bending in hogging conditions for a bulk carrier, using the nonlinear finite element analysis. The author's conclusion is that the tripping or flexural-torsional buckling of the bottom longitudinal stiffeners after the plate buckling under extreme hogging condition can be clearly captured by the nonlinear finite element analysis.

Having in mind that for bulk carriers, the longitudinal bending moments induce both longitudinal and transverse stresses in the hull section, Ohta conducted some studies to verify that the upper deck was bent outward or inward horizontally by using FEM for stress calculations and found that the transverse stresses was higher than the longitudinal stresses at the hatch corners, depending on the ballast loading condition [28]. Nakai and his colleagues [27] observed the pitting corrosion on hold frames and a series of tensile tests concluded that the tensile strength decreased gradually, and the total elongation decreased drastically with the increase in the thickness loss due to pitting corrosion. A series of tests were performed which revealed that compressive buckling strength of pitted members was smaller than or equal to that of members with uniform thickness loss in terms of average thickness loss. The authors provided an elastoplastic analysis by FEM to simulate the compressive buckling test to validate the proposed method of modelling. The buckling / plastic collapse behaviour of stiffened panels under longitudinal thrust was investigated by Tanaka et.al. [35] using FEM analysis; the results were compared with several existing methods such as CSR for bulk carriers and PULS (concluding that PULSE method gives a good estimation).

2.3 *Advanced bulk carriers hull design studies*

It is a very well-known fact that the loads upon the ship's hull in operation can manifest themselves statically or dynamically. From the static point of view, the advanced design of a ship structure involves [24]: the physical-mathematical modelling of the hull structure, starting from the initial imperfections of the materials (initial deformations and welding residual stresses); the identification of the working characteristics of the decks (mode of support and predominant stresses); the determination of the expressions that describe the strength of the decks subjected to combined static loads; the determination of critical stresses in the case of static loads. Most of the damage to the hull of bulk carriers is failures in the plastic area due to the bending of the deck and bottom panels, and sometimes of the side panels. This is the reason why the accuracy of determining the bending stresses and critical stresses in the mentioned decks becomes a basic requirement for the structure safety. From the dynamic point of view, the advanced design of naval structures involves [31]: physical-mathematical modelling of the ship's hull structure, starting from the initial imperfections of the materials; determining the effects of hindered rotations and torsional stiffness for backing supports to the naval decks; determining the breaking strength for any potential combination of loads; determination of critical stresses in the case of dynamic loads.

Regarding the design of bulk carriers, the specialized literature is very rich, with several articles of very good quality that have been published, and have made important contributions, and it is practically impossible to mention them all. For rational dimensioning of this paper, only a few have been retained, and are presented in the table below.

Table 2 Bulk carrier hull design studies

Author(s)	Research direction
Liao et. al. [23]	were concerned with the application of Controlled Robust Optimization (CRO) methods in solving conceptual design problems of bulk carriers and the paper demonstrates the feasibility of the mentioned approach to find robust solutions for optimizing ship design for long-term ocean voyages, designer being able to handle optimization problems with multiple uncertain parameters
Mohamed et. al. [25]	the main objective is to design a bulk carrier to minimize the construction cost, and to maximize the annual transported cargo. To reach the objective, the authors have used a method based on Multi-Attribute Decision Making (MADM), which proves certain advantage related to construction and voyage cost (compared to other methods) but remains deficient regarding the annual transported cargo
Aksu et. al. [4]	highlighted that the basic design parameters of bulk carriers could be optimized using the Parameter Space Investigation method
Zheng et. al. [36]	studied the data (obtained through an optimization algorithm) which can be used to find the optimal solution in hull form design and proposes a set of knowledge extraction methods suitable for multi-objective ship optimization. Design aspects of some components of interest of the bulk carrier hull were also targeted
Do et.al. [11]	uses the finite-element (FE) modelling for flat and curved plates of a ship to assess their safety in conditions of axial compression, based on the Ultimate Limit State (ULS) design and analysis concept
Kitamura et al. [21]	Finite Element Method (FEM), with a numerical example as confirmation, was used for structural optimization of a ship's bottom in this paper, for shape optimization being considered: the height and width of the double bottom, the height of the bilge hopper tank, and the 2 widths of the lower stool
Feng et al. [13]	the paper studied, through building finite element model of a bulk carrier's hold section, the design loads, boundary conditions and several load cases

The general objective of the research shown in this paper is to optimize the construction of the cylindrical area of the 165,000 tdw bulk carrier through structural and dimensional modelling, under the conditions of the manifested combined stresses resulting from the general combined longitudinal-vertical bending stress, with transverse-vertical bending and longitudinal torsion.

3 THEORETICAL CONSIDERATIONS

The stress that is common to all categories of ships comes from the longitudinal-vertical bending; however, for ships with considerable width, such as the 165,000 tdw bulk carrier which is the subject of the present research study, the transverse-vertical bending and the torsion are significant [24]. In principle, the stress is the state that determines the general stress upon the ship's hull which is represented by the shear forces, bending moments as well as torsion moments resulting from the vertical loads (the effect of horizontal loads can be neglected). Depending on the effort's distribution along the transverse section of the ship's elastic hull, the following stress cases are of interest [24]: the pure bending (when the cutting forces are zero), in the simple variants (with the vector section moment located on the main inertia axis) or oblique (with the section moment vector having non-zero components in accordance with both main inertia axes); the shear bending (when the shear forces are non-zero), also in the simple and oblique variants; the shear and torsion bending (when the loads vary both along the length and across the width of the ship, and the shear forces along the two directions are non-zero). In this paper, the symbols σ_iifor the normal stresses and σ_ijfor the tangential stresses are accepted, where i and j represent the orthogonal directions.

Figure 1 shows the ship's hull, idealized by a box-type beam having thin walls, sectioned by a normal plane to its axis and to which the Oxyz axis system was attached.

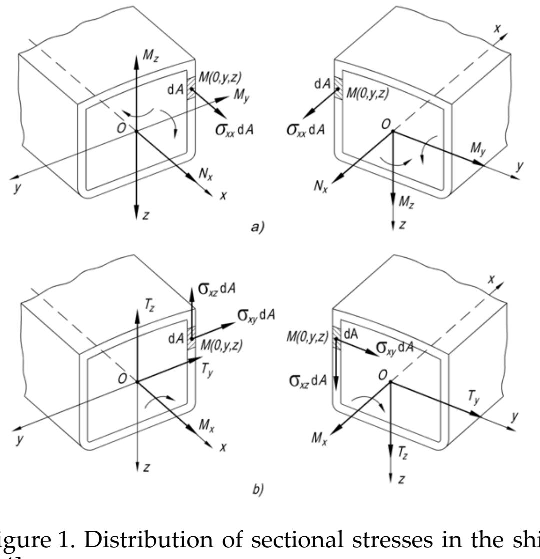

Figure 1. Distribution of sectional stresses in the ship's hull [24]

Additionally, the elementary connection forces determined by the normal stress σ_{xx} are represented, respectively the components of the tangential stress σ_{xy} and σ_{xz} corresponding to the shear bending stress and torsion. They belong to the set of stress components acting on the elementary rectangular trihedron, reduced at point P, symbolized by the square matrix

$$\left[T_{\sigma}\right]=\begin{bmatrix}\sigma_{xx} & \sigma_{yx} & \sigma_{zx}\\ \sigma_{xy} & \sigma_{yy} & \sigma_{zy}\\ \sigma_{xz} & \sigma_{yz} & \sigma_{zz}\end{bmatrix}, \tag{1}$$

called the tension tensor, to which corresponds the set of specific deformation components expressed by the square matrix

$$\left[T_{\varepsilon}\right]=\begin{bmatrix}\varepsilon_{xx} & \frac{1}{2}\gamma_{yx} & \frac{1}{2}\gamma_{zx}\\ \frac{1}{2}\gamma_{xy} & \varepsilon_{yy} & \frac{1}{2}\gamma_{zy}\\ \frac{1}{2}\gamma_{xz} & \frac{1}{2}\gamma_{yz} & \varepsilon_{zz}\end{bmatrix}, \tag{2}$$

called the tensor of specific deformations.

From the analysis of Figure 1a) one can notice that the following sectional stresses are obtained upon reducing the normal elementary stresses:

– the normal force or the axial force having the expression

$$N_x=\int_A \sigma_{xx}dA \quad [\text{kN}]; \tag{3}$$

– the bending moments having the expressions

$$M_z=\int_A \sigma_{xx}ydA \;\text{ and }\; M_y=\int_A \sigma_{xx}zdA \quad [\text{kNm}] \tag{4}$$

From the analysis of Figure 1b) one can notice that the following sectional forces are obtained upon reducing the elementary tangential forces:

$$T_y=\int_A \sigma_{xy}dA \;\text{ and }\; T_z=\int_A \sigma_{xz}dA \quad [\text{kN}]; \tag{5}$$

– the torsion or twisting moment having the expression:

$$M_x=\int_A\left(\sigma_{xz}y-\sigma_{xy}z\right)dA[\text{kNm}] \tag{6}$$

The complexity of the stresses results from the fact that the interaction process, which is carried out on both waveless and wavy seas, can be deterministic or random. The general ways of approaching this interaction process are known [32]; however, the present paper suggests highlighting the situations that determined the stress condition in the cylindrical area within the hull under study, finally causing certain structural elements in the field of plastic distortions to cave in.

4 MATERIAL AND METHODS

The bulk carrier (BK) is a ship for dry goods, specially designed for the transport of cargo with different specific weights, stowed directly in cargo holds, without prior packaging [24]. The reference ship (courtesy of [42]) falls under the category of universal bulk carriers equipped with bilge tanks and anti-roll tanks, adapted for the transport of goods with different densities (grains, coal, coke, phosphates, iron ore, etc.). It features the following constructive characteristics: it has a single, continuous deck along the entire hull length, no longitudinal deck sheer and connected to the shell plating through the curvature; the engine room and the superstructure located aft, except the forecastle, which is located forward; has nine self-trimming cargo holds; it is equipped with side ballast tanks, the upper ones located under the main deck, and the lower ones in the bilge area; the prismatic shape of the ballast tanks gives the cargo holds their orthogonal shape (thereby allowing the use of the entire deadweight space for the transport of goods while ensuring, at the same time, the stability and trim for safe exploitation); the general hull framing system is combined (longitudinal for the deck, bottom, double bottom and ballast tanks in the cargo holds area; transversal for the sides, in the cargo holds, the after end and forwards end, the engine room); the double bottom of the odd-numbered cargo holds is properly reinforced for the transport of heavy cargo and for supporting the loading and unloading operations with the help of grabs.

Main dimensions and displacement characteristics are as follows:

– $L_{OA} = 303.34\ [m]$; $L_{CWL} = 292.00\ [m]$;
– $B_{max} = 46.00\ [m]$; $B_x = 46.00\ [m]$; $T = 18.00\ [m]$; $D = 24.40\ [m]$;
– $\Delta = 1984184.77\ [kN]$;$M_{dw} = 165000\ [tdw]$.

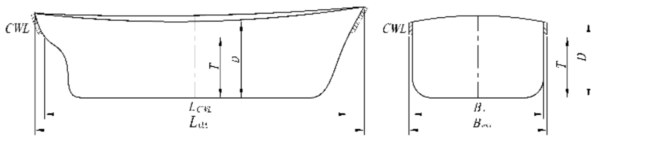

Figure 2. Main dimension of ship

For the hull construction, the following types of steel were used: ordinary naval steel A (yield strength 235 N/mm^2), for the shell plating and hull framing; high-strength naval steel A32, D32, E32 (yield strength 315 N/mm^2) was used for the deck, in the central area of the ship; special naval steel B, D and E was used for the hull elements indicated by the rules of the classification society. The central section under investigation is in the cargo holds area, between ribs C53 and C292, so as to include in its structure all the constructive units (including the ones in the transversal bulkhead). The functional and dimensional diversification, respectively the increase in the requirements regarding the technical-economic performances of the current ships, have a limiting role in the application of classical calculation models, while in some situations they are even inadequate. Therefore, there is the need to perfect the modelling in the context of the facilities offered by the progressive evolution of the computerized calculation technique. Modern naval design is dominated by computerized systems based on the development of complex computer programs. As of 1990, ABS has been using computer technology to carry out dynamic technical projects and implement optimal assessment methods for establishing the structural requirements of bulk carriers and oil tankers. Known as "SafeHull", the current trend in register rules differs from the conventional one in that the requirements are established based on the first principle of classical mechanics, where the action criterion is explicitly defined, and the structural responses are assessed against different types of potential damage. Therefore, the newly developed criterion, together with the software developed for its application, allow the designer to perform the initial minimum sampling and assess the structure responses based on the finite element analysis. Naval competitiveness is based on three reference coordinates, which ultimately express the essential requirements, namely quality, cost, delivery date. These requirements are currently calling for the exploitation of the fast-processing capacity and the interaction type facilitated by personal computers. Computer Aided Design (CAD), Computer Aided Manufacturing (CAM) and, in general, the Computer Aided "X" (CAX) concept [15], are current use technologies. But for their use, the previously stated desiderata would remain utopian. Understanding the CAX concept requires examining the various activities and functions that must be performed in the hull design/manufacture process. Generically referred to as the "ship manufacturing cycle", the process comprises two main activities: design and manufacture. During these stages, a wide range of software tools have been used: graphic programming tools (the role of CAD systems is to create graphic representations of engineering systems designed by computer programming, computer-aided drawing and geometric modelling are necessary); analysis tools (CAE systems have the role of facilitating the analysis of the geometry made by CAD techniques, allowing the designer to simulate and study the product behaviour so that the project can be optimized). The sequential programming method, also accepted by the authors of this paper, uses as operational environment the Femap finite element analysis program (a finite element analysis model and post-processing system that facilitates fast and useful engineering analysis), made by Enterprise Software Products Inc. [37]. The finite element analysis model offered by the Femap program can use two distinct database variants: internal, which introduces the model geometry step by step; and external, made with another program product. For this specific paper, its authors propose an external program for generating and optimizing the ship's shapes, through the AutoLisp programming environment, specific to the AutoCad program product. In general, the creation of the finite element analysis model involves the following stages: establishing the reference system; identification of structure nodes; the choice of materials, respectively their properties; setting up boundary conditions by introducing the types of restrictions (constrains, articulations, supports, etc.); establishing loads (forces, pressures, tensions, efforts, etc.). Finally, having established all the analysis elements, the post-processing is carried out, and the model response to the imposed stress is obtained. Regarding the model made with the help of Femap for the 165000 tdw bulk carrier – as the reference vessel for the applicative part of this research – the following were taken into consideration:

– the central module was identified from the ship's hull, including three cargo holds: cargo hold no. 6 (extended on the range limited by the real ribs C.134-C.160); cargo hold no. 5 (extended on the range limited by the real ribs C.160-C.186), and cargo hold no. 4 (extended on the range limited by the real ribs C.187-C.211);
– the model was initiated with the transversal framework rib in the amidship section for which the boundary conditions were established to one single board (due to symmetry) and the loading of the half framework rib with loads (Figure 3).

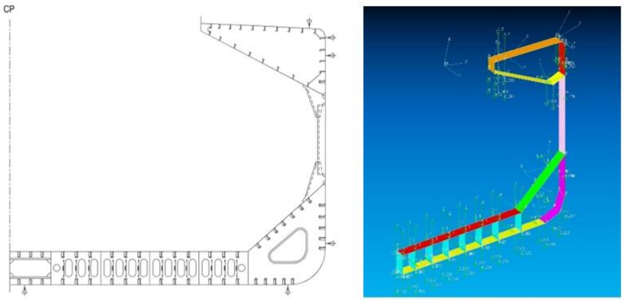

Figure 3. 3D-Model of transversal framework rib for the reference ship (left side) and the loading of the half framework rib with loads (right side)

5 CASE STUDY ANALISYS

Checking up the model involved the determination of the longitudinal strength of the ship beam in the weakened cross-sections, for 3 representative loading cases. The initial state of the ship is characterized by the values of moments and admissible shear forces calculated according to (courtesy of [42]) and centralized in Table 3.

Table 3. Admissible shear forces and bending moments in the initial ship beam on calm sea

Section	$(T_{sc})_a$ [kN]			$(M_{yc})_a$ [kNm]		
	Underway	In the roadstead	In harbour	Underway	In the roadstead	In harbour
C59	46116.54	55339.84	62257.32	2570788	2396443	3244829
C84	48222.13	57866.55	65099.87	3709843	5211920	6338093
C109	55426.41	66508.09	74821.60	4723755	6597066	7689772
C134	56361.28	67633.53	76087.72	4015747	5731620	6688897
C160	70193.98	84232.77	94761.87	4015747	5731620	6688897
C186	70193.98	84232.77	94761.87	4015747	5731620	6688897
C211	53353.50	64002.46	72002.77	4015747	6056162	7064225
C236	40772.68	48927.21	55043.12	4128988	5411829	5667267
C267	37224.04	44668.85	50252.45	3405939	3688044	4863149
C303	45953.19	55143.82	62036.80	3258593	3047126	4309644

Construction-wise, the ship's hull under study ensures the compromise between operational stresses and structural requirements. Therefore, the safety limits between the structural components cannot be uniform. The optimal content of the present paper requires the analysis to be limited only to the structural changes made in the planks of the watertight transversal bulkheads, and respectively to the change of the material and the thickness of the plank covering for the shell plating.

5.1 *Remodeling the planks of watertight transversal bulkheads*

The optimization by modelling the plank in the watertight transversal bulkhead envisaged two aspects: increasing the rigidity of the upper part of the plank, by introducing a support structure into the model, and respectively reducing the weight of the bulkhead plank by changing the geometry of the corrugation system and, implicitly, reducing the number of corrugations. To reduce the weight of the plank in the watertight transversal bulkhead, the type of corrugation has been modified, (see Figure 4.

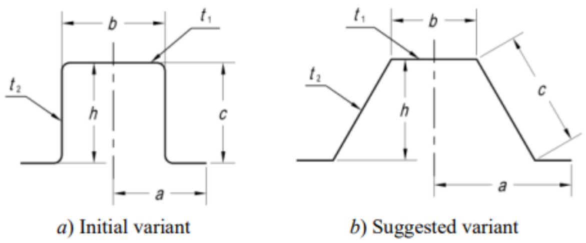

Figure 4. Structural remodelling of side panel corrugations

For the proposed variant, keeping the same thicknesses, the normal stress in the wall floor exceeds the admissible value, correction being made by increasing the wall thickness from t=13 mm to 14 mm, the normal stress in the deck becoming σ_{yy}=218.52N/mm^2, falling within the admissible limits.

To stiffen the wall deck at the top, the constructive solution from Figure 5 is adopted.

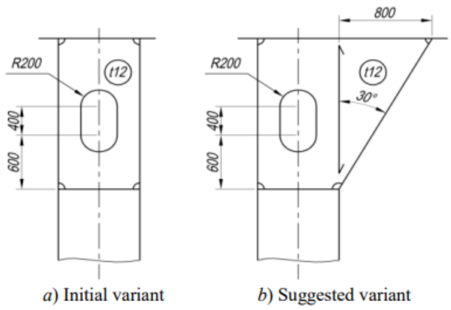

Figure 5. Structural remodelling of the upper support of the side panel

5.2 *Remodeling the side panels*

Remodelling the side panels is based on the analysis of the behaviour of the ship's cylindrical area analyzed in three representative flooding situations: unloaded and unflooded cargo holds; loaded and successively flooded cargo holds; unloaded and flooded cargo holds. To establish the thickness values for the shell plating in the three flooding cases, based on the principle of effects superposition, only the maximum effective and admissible absolute values of the shear forces in calm water are kept on the same diagram. The authors' proposal was represented by two types of steel: ordinary naval steel, with σ_c = 235 N/mm^2; high strength naval steel, with σ_c = 315 N/mm^2.

The analysis of the diagrams resulting from the effects of superposition of the shear forces and the admissible values recommends the variant in Figure 6 as acceptable (to ensure the compromise between the ship safety and the technological implications), corresponding to the worst situation (the case of unloaded and flooded cargo holds). In the areas where the admissible values of the shear forces are exceeded, a shell plating covering made of steel is proposed: thickness 19.0 mm, quality A32, between C83 and C86; thickness 16.5 mm, quality A32, between C238 and C241; thickness 19.0 mm, quality A32, between C270 and C280.

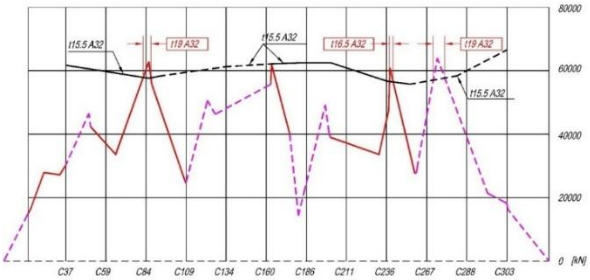

Figure 6. Diagram resulting from the effect of superposition of the shear forces and admissible values, for the case of unloaded and flooded cargo holds

Following the change in the quality of the materials, the thickness of the component elements and the changes in the structure, the values of moments and admissible shear forces in the weakened sections will have the values in Table 4, calculated according to [42] requires.

Table 4. Shear forces and admissible bending moments - remodeled ship beam, in calm water

Section	$(T_{sc})_a$ [kN]			$(M_{yc})_a$ [kNm]		
	Underway	In the roadstead	In harbor	Underway	In the roadstead	In harbor
C59	70800	70800	86900	3189140	3497730	3960620
C84	60880	70490	84910	5017010	5636760	6397130
C109	73770	83380	97800	5765000	6612730	7884320
C134	78050	85430	96500	4499550	5600730	7251600
C160	78070	85440	98940	3901630	5122040	6952640
C186	78710	85950	96820	4434020	5547950	7218830
C211	70940	79760	92990	5511090	6416150	7761460
C236	52940	63100	78360	4980000	5622400	6574010
C267	52890	63050	78310	3591000	3971370	4541930
C303	59690	64040	70560	2964170	3190590	3430170

The local stress on the ship's hull in the cargo holds area depends on the usual loading options in operation. Each load variant (Table 5) of the cargo holds was associated with a stress model (which responds to the type of cargo, environmental conditions, dynamic responses and representative stress rates), finally resulting in the design proposal.

Table 5. Representative load situations

Situation	Loading situation	Draft
1	Ship having ballast in cargo hold	$T_1 = 0.45T$
2	Ship having high-density ore in cargo hold	$T_2 = T$
3	Ship having heavy ore in cargo hold	$T_3 = 0.67T$

Particular features for loading situation 1 (see Figure 7): if the tanks in the double bottom, bilge and below deck are intended for ballast, then they are considered full; the adjacent watertight compartment has empty cargo holds and associated tanks; the external load exerted by the sea water on the structure is determined by the rules of the naval classification registers, for draft T1, excluding the dynamic pressure exerted by the wave; the internal load exerted by the ballast (sea water) on the structure is also determined by the Rules of the Naval Classification Registers, considering only the static pressure.

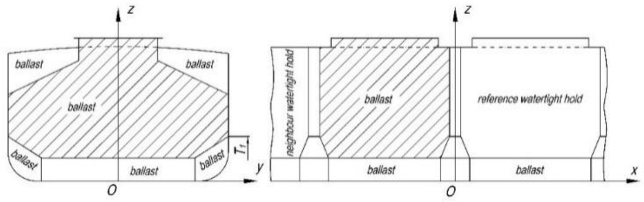

Figure 7 Loading situation 1

Particular features for loading situation 2 (Figure 8): the cargo partially takes up the volume of the cargo holds, the bilge and under-deck tanks are empty, and the double-bottom tanks are full of fuel; the adjacent watertight compartment has empty stores as well as empty associated tanks; both the external and internal loads on the structure was determined according to the specific Rules of the classification register.

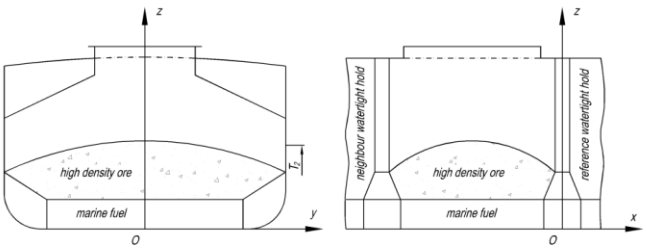

Figure 8. Loading situation 2

Particular features for loading situation 3 (see Figure 9): in the analysed watertight compartment, the bilge, under-deck and double-bottom tanks are empty; the adjacent watertight compartment has empty stores as well as the associated tanks; the external load exerted by the sea water on the structure is determined by the Rules of the naval classification register for the specified draft, excluding the dynamic pressure caused by the wave; the internal load, exerted by the load on the structure, is determined with the specific rules of the naval classification register.

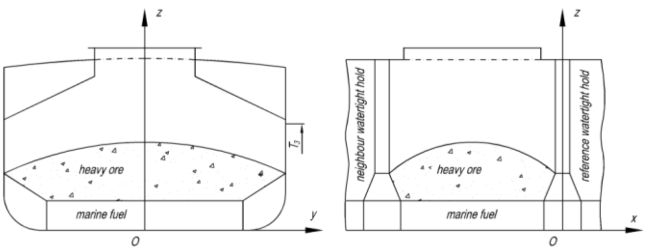

Figure 9. Loading situation 3

The effective values of shear forces and bending moments, for the load cases analyzed, were determined in 12 verification sections and the obtained results were centralized in Tables 6 –8. Also, the stress states on the framework rib are illustrated in Figures 10 - 12.

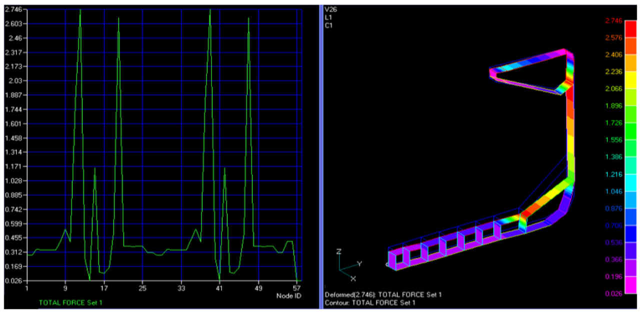

Figure 10. Stress state on framework rib for Loading situation 1

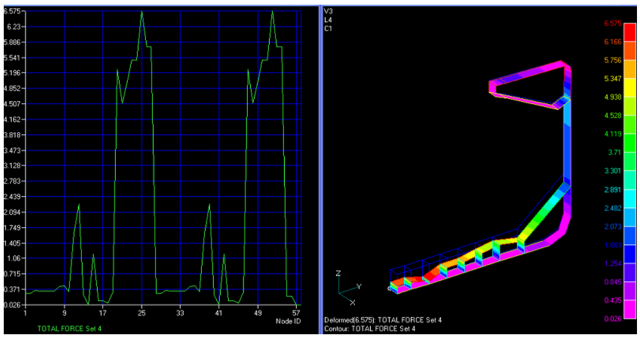

Figure 11. Stress state on framework rib for Loading Situation 2

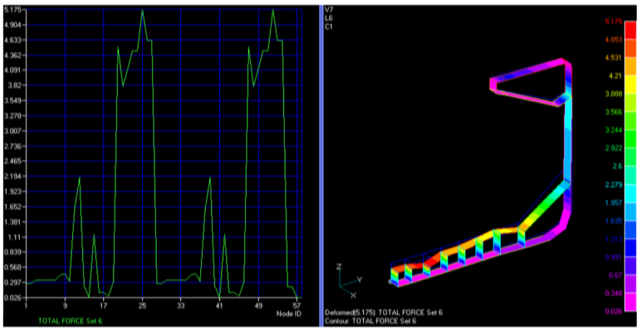

Figure 12. Stress state on framework rib for Loading Situation 3

Table 6. The effective shear forces in the calculation sections for loading case 1

Section	M_{yc} [kNm]			T_{zc} [kN]			Remarks
	Det.value [kNm]	Adm. value [kNm]	Ratio [%]	Det.value [kN]	Adm.value [kN]	Ratio [%]	
C59	1528040	3189140	47.9	64220	70800	90.7	accepted
C84	2801880	5017010	55.8	43800	60880	71.9	accepted
C109	3584100	5765000	62.2	21750	73770	29.5	accepted
C134	3903570	4499550	86.8	3540	78050	4.5	accepted
C147	3911930	4153490	94.2	-5000	78050	6.4	accepted
C160	3781040	3901630	96.9	-13480	78070	17.3	accepted
C173	3599800	4167830	86.4	-19210	78390	24.5	accepted
C186	3308610	4434020	74.6	-24410	78710	31.0	accepted
C211	2644480	5511090	48.0	-32000	70940	45.1	accepted
C236	1858460	4980000	37.3	-35190	52940	66.5	accepted
C267	1020050	3591000	28.4	-34050	52890	64.4	accepted

C303	296390	2964170	10.0	-26360	59690	44.2	accepted
Maximum bending moment: $(M_{yc})_{max}$ = 3930030 [kNm[(90.2%), corresponding to C134 + 5.12 [m]							

Table 7. The effective shear forces in the calculation sections for loading case 2

Section	M_{yc} [kNm]			T_{zc} [kN]			Remarks
	Det.value [kNm]	Adm. value [kNm]	Ratio [%]	Det.value [kN]	Adm.value [kN]	Ratio [%]	
C59	-774010	3189140	24.3	-47540	70800	67.2	accepted
C84	-353930	5017010	7.1	81430	60880	133.8	unacceptable
C109	-491010	5765000	8.5	-95080	73770	128.9	unacceptable
C134	-660890	4499550	14.7	99630	78050	127.6	unacceptable
C147	-3030	4153490	0.1	62100	78050	8.0	accepted
C160	-513990	3901630	13.2	-87500	78070	112.1	unacceptable
C173	-1045680	4167830	25.1	23900	78390	3.0	accepted
C186	-422750	4434020	9.5	101980	78710	129.6	unacceptable
C211	-98360	5511090	1.8	-74490	70940	105.0	unacceptable
C236	-71030	4980000	1.4	94600	52940	178.7	unacceptable
C267	71340	3591000	2.0	-80910	52890	153.0	unacceptable
C303	-380190	2964170	12.8	41800	59690	70.0	accepted
Maximum bending moment: $(M_{yc})_{max}$ = -1266290 [kNm] (24.6%), corresponding to C109 + 11.60 [m]							

Table 8. The effective shear forces in the calculation sections for Loading Situation 3

Section	M_{yc} [kNm]			T_{zc} [kN]			Remarks
	Det.value [kNm]	Adm. value [kNm]	Ratio [%]	Det.value [kN]	Adm.value [kN]	Ratio [%]	
C59	-263960	3189140	8.3	-68970	70800	97.4	accepted
C84	-266900	5017010	5.3	67030	60880	110.1	unacceptable
C109	-671970	5765000	11.7	-103510	73770	140.3	unacceptable
C134	-981390	4499550	21.8	96020	78050	123.0	unacceptable
C147	-354460	4153490	8.5	4640	78050	5.9	accepted
C160	-872850	3901630	22.4	-87330	78070	111.9	unacceptable
C173	-1392350	4167830	33.4	3990	78390	5.1	accepted
C186	-741480	4434020	16.7	104700	78710	133.0	unacceptable
C211	-333160	5511090	6.0	-70500	70940	99.4	accepted
C236	-205160	4980000	4.1	98700	52940	186.4	unacceptable
C267	27820	3591000	0.8	-77870	52890	147.2	unacceptable
C303	-369380	2964170	12.5	42740	59690	71.6	accepted
Maximum bending moment: $(M_{yc})_{max}$ = -1530070 [kNm] (30.0%), corresponding to C109 + 12.32 [m]							

6 RESULTS AND DISCUSSIONS

The analysis of the obtained data revealed that the admissible shear forces were exceeded in several verification sections (for two of the three load cases analysed). In this situation, the effective shear forces in all the verification sections are reduced, and the obtained values are compared with the admissible values.

The results are summarized in Tables 9 and 10. As can be seen from the tables below, following the reduction of shear forces in the calculation sections, the effective values fall within the admissible values so that the longitudinal strength of the ship beam is verified. Furthermore, considering the total loads reassessed, the central section of the 165 000 tdw bulk carrier is remodelled in accordance with the requirements of [44] and considering the recommendations of [41], for the GL 100 A5 class.

The response of the central section, subjected to the 3 representative load cases, together with the diagrams of bending moments and shear forces on the structure nodes, can be visualized in Figures 13-15.

Table 9. Values of reduced shear forces $(T_{zc})_{red}$ for loading case 2

Section	Determined value T_{zc}[kN]	Reduction factor	Reducedvalue $(T_{zc})_{red}$ [kN]	$(T_{zc})_a$ [kN]	Ratio [%]
C59	-47540	0.2845	-47540	70800	67.2
C84	81430	0.2825	44740	60880	73.5
C109	-95080	0.3130	-45210	73770	61.3
C134	99630	0.2825	46770	78050	59.9
C147	62100	-	6210	78050	8.0
C160	-87500	0.3130	-34640	78070	44.4
C173	23900	-	2390	78390	3.0
C186	101980	0.2825	52130	78710	66.2
C211	-74490	0.3130	-24640	70940	34.7

C236	94600	0.2915	43430	52940	82.0
C267	-80910	0.2290	-52810	52890	99.9
C303	41800	-	41800	59690	70.0

Table 10. Values of reduced shear forces $(T_{zc})_{red}$ for loading case 3

Section	Determined value T_{zc}[kN]	Reduction factor	Reducedvalue $(T_{zc})_{red}$ [kN]	$(T_{zc})_a$ [kN]	Ratio [%]
C59	-68970	0.2845	-68970	70800	97.4
C84	67030	0.2825	28340	60880	46.5
C109	-103510	0.3130	-55330	73770	75.0
C134	96020	0.2825	44220	78050	56.7
C147	4640	-	4640	78050	5.9
C160	-87330	0.3130	-35530	78070	45.5
C173	3990	-	3990	78390	5.1
C186	104700	0.2825	55210	78710	70.1
C211	-70500	0.3130	-21010	70940	29.6
C236	98700	0.2915	47230	52940	89.2
C267	-77870	0.2290	-50250	52890	95.0
C303	42740	-	42740	59690	71.6

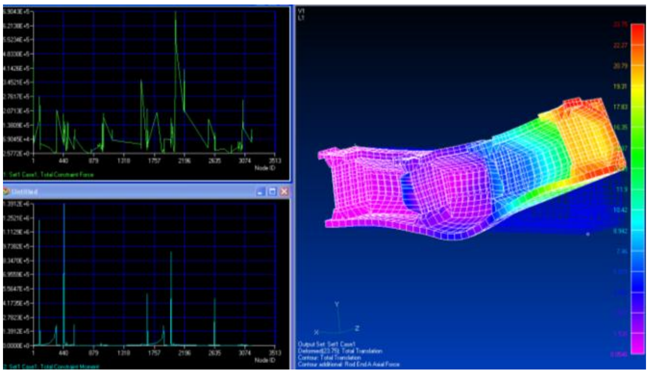

Figure 13. Response of the central section subjected reassessed total loads for situation 1

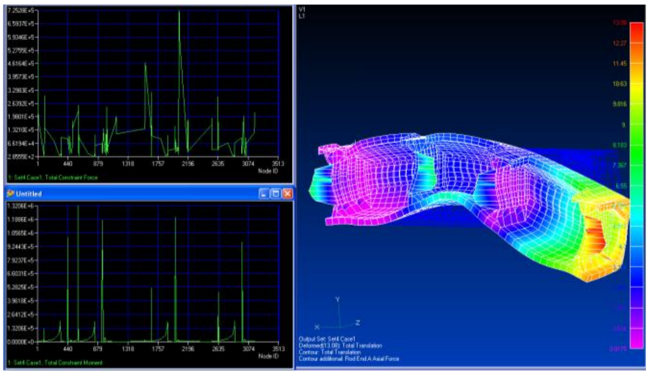

Figure 14. Response of the central section subjected reassessed total loads for situation 2

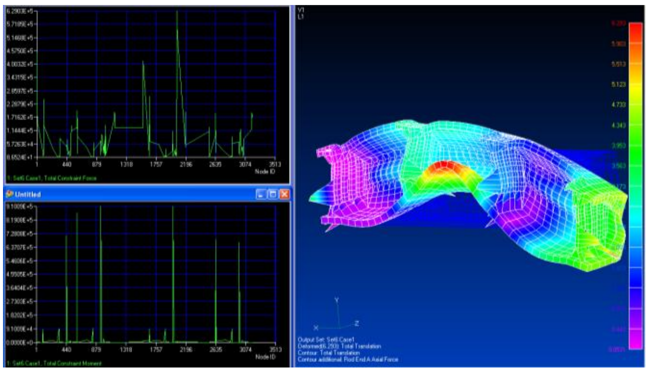

Figure 15. Response of the central section subjected reassessed total loads for situation 3

7 CONCLUSIONS

This paper analyses the response of the central section of the 165 000 tdw bulk carrier to the total loads reassessed by simulation using FEMAP finite element analysis software. The structural-constructive characteristics for the initial and final variants of the central section subjected to remodelling are highlighted and compared. Thus, structurally and constructively, the authors made qualitative and dimensional changes to the planks that make up the watertight transversal bulkheads and the bulkheads in the central area of the ship’s hull. The practical validation of the research results was based on the verification of compliance with the registry rules and the application of corrections for 12 calculation sections of the ship’s hull, selecting three representative load cases. It was found that the bending moments do not exceed the admissible values, while critical situations are recorded for the shear forces for four of the selected load cases. Consequently, the effective cutting forces were subjected to reduction, to be within the admissible values. Through these corrections, the safety of the longitudinal strength of the ship's hull becomes certain. The structure of the cylindrical hull area of the 165,000 tdw bulk carrier, remodelled in accordance with the rules of the registry and verified by finite element analysis programs, ensures that the compromise between operational demands and structural requirements is met. Also, in addition to the fact that the structure meets the safety criteria, by using high-strength steel, its weight has been reduced by 22%.

As stated at the beginning of this paper, the general objective was to optimize, through structural and dimensional modelling, the construction of the central area belonging to the hull of bulk carriers, under the effect of combined general stresses of longitudinal-vertical bending, transverse-vertical bending, and longitudinal torsion, complemented with specific local stresses.

The fulfilment of the stated general objective required a step-by-step process and the solution of the following problems:

– theoretical, consisting in the identification, processing and adequacy of the physical-mathematical support, based on the analytical support of the dominant ship exploitation situations;

– practical-experimental, consisting of: creating programs for the calculation and computer simulation of elastic behavior; verification and experimental or practical-statistical correction of the results, in order to validate the research.

The authors remain convinced that the application of numerical methods, based on the power of the computerized calculation technique, offers the possibility of almost complete ship modelling and estimation. Major marine classification societies give due importance to online vessel assessment and assistance systems that respond to this concept. Thus, detailed numerical ship models (in terms of volume and structure) are built, fully supported by the calculation technique. Limit states are evaluated taking into account the actual operation of the structure, including the effect of corrosion, loading and damage situations, as well as changes in the technical state (generated by: accidents; flooding of compartments; loss of cargo or reserves, as a result of failure or collision; changes in the condition of materials, as a result of major fires on board, etc.). Thus, the ship can be assisted and followed in its evolution throughout its operation, anticipating possible safety risks.

REFERENCES

[1] Alie, M.Z.M. and Adiputra, R., Investigation of ship hull girder strength with grounding damage, MAKARA Journal of Technology, vol.22, no.2, pp.88-93,2018, https://doi.org/10.7454/mst.v22i2.3355.

[2] Alie, M.Z.M. et.al., Study on ultimate strength of ship's hull considering cross section and beam finite element, 5th International Seminar on Ocean and Coastal Engineering, Environmental and Natural Disaster management (ISOCEN2017), vol.177, 2018., https://doi.org/10.1051/matecconf/201817701030.

[3] Andric, J., Prebeg, P., Andrisic, J. and Zanic, V., Structural optimisation of a bulk carrier according to IACS CSR-BC, Ships and Offshore Structures, vol.15, no.2, pp,123-137, 2019, https://doi.org/10.1080/17445302.2019.1589976.

[4] Aksu, C. and Yaman, R., Multi-criteria analysis of capsize bulk carrier design optimization model, Journal of ETA Maritime Science, vol.11, pp.168-185, 2023, DOI: 10.4274/jems.2023.77045.

[5] Babazadehand, A., Khedmati, M.R., Progressive collapse analysis of a bulkcarrier hull girder under longitudinal vertical bending moment considering cracking damage, Ocean Engineering, vol.242, 2021, https://doi.org/10.1016/j.oceaneng.2021.110140.

[6] Banachowicz A., Wołejsza P., The Analysis of Possibilities How the Collision Between m/v 'Gdynia' and m/v 'Fu Shan Hai' Could Have Been Avoided., TransNav, the International Journal on Marine Navigation and Safety of Sea Transportation, Vol. 2, No. 4, pp. 377-381, 2008

[7] Beghin, D., Fatigue strength of knuckle joints - a key parameter in ship design, Transactions on the Built Environment vol.24, 1997, WIT Press, www.witpress.com, ISSN 1743-350, Doi:10.2495/MTECH970041.

[8] Campanile, A., Piscopo V. and Scamardella, A., Conditional reliability of bulk carriers damaged by ship collisions, Marine Structures, vol.58, pp.321-341, 2018, https://doi.org/10.1016/j.marstruc.2017.12.003.

[9] Campanile, A., Piscopo V. and Scamardella, A., Statistical properties of bulk carrier longitudinal strength, Marine Structures, vol.39, pp.438-462, 2014, https://doi.org/10.1016/j.marstruc.2014.10.007.

[10] Cui, J.J. and Wang, Y., An experimental and numerical investigation on ultimate strength of corrugated bulkheads and plane bulkheads subjected to lateral pressure, Ocean Engineering, 295, 2024, https://doi.org/10.1016/j.oceaneng.2024.116895.

[11] Do, K.K., Imjun, B., Poh, B.Y. and Sung-Chul, S., A useful guide of effective mesh-size decision in predicting the ultimate strength of flat and curved plates in compression, Journal of Ocean Engineering and Science, 8(4), 401-417, 2023, https://doi.org/10.1016/j.joes.2022.02.014.

[12] Eto, H., Sato, C. et.al., Effect of coal loading conditions on elastic behavior of large-scale floating trans-shipment station (LFTS), 36th ASME International Conference on Ocean, Offshore and Arctic Engineering, vol.6, 2017, https://doi.org/10.1115/OMAE2017-61897.

[13] Feng, L., Zhen, C.B., Feng R. andDong, S., Research on the direct strength calculation of a 70000 dwt bulk carrier, International Conference on Advances in Energy, Environment and Chemical Engineering, vol.23, pp.55-58,2015,Doi: 10.2991/aeece-15.2015.11.

[14] Frystock, K. and Spencer, J., Bulk carrier safety, Marine Technology SNAME News, vol.133, pp.309-318, 1996, https://doi.org/10.5957/mt1.1996.33.4.309.

[15] Giesecke, F., Mitchell, A. et.al., Technical Drawing with Engineering Graphics, 15th Edition, Peachpit Press, Berkeley, CA, USA, 2016, ISBN: 978-0134306414.

[16] Ivosevic S., and Kovac, N., An analysis of hull structure plating failures due to corrosion, Transactions on Maritime Science - TOMS, vol.12, no.2, 2023, , https://doi.org/10.7225/toms.v12.n02.w04.

[17] Ivosevic, S., Kovak, N., Momcilovic N. andVukelic, G., Evaluation of the corrosion depth of double bottom longitudinal girder on aging buk carriers, Journal of Marine Science and. Engineering, vol.10, no.10, 2022, https:// doi.org/10.3390/jmse10101425.

[18] Jankowski, J., Bogdaniuk M. and Dobrosielski, T., Buoyancy and strength of existing bulk carriers in flooded conditions, Transactions on the Built Environment vol.24, 1997, WIT Press, www.witpress.com, ISSN 1743-350, Doi:10.2495/MTECH970041.

[19] Jones, N., Uran, T.O. and Tekin, S.A., The dynamic plastic behavior of fully clamped rectangular plates, International Journal of Solid and Structures, vol.6,no.12, 1970, https://doi.org/10.1016/0020-7683(70)90060-0.

[20] Katsumoto, H., Konda, N. et.al., Development of structural steel with high resistance to fatigue crack initiation and growth, Part 3, 24th International Conference on Offshore Mechanics and Arctic Engineering, vol.3, pp.143-151, 2005,https://doi.org/10.1115/OMAE2005-67298.

[21] Kitamura, M., Hamada, K., Takezawa A., and. Uedera, T., Shape optimization system of bottom structure of ship incorporating individual mesh subdivision and multi-point constraint, International Journal of Offshore and Polar Engineering, vol.21, pp.209-215,2011, WOS:000294699900007.

[22] Kitarovic, S., Andric J. and Piric, K. Hull girder progressive collapse analysis using IACS prescribed and NLFEM derived load - end shortening curves, Brodogradnja, vol.67, pp. 115-128, 2016, https://doi.org/10.21278/brod67208.

[23] Liao, Q.M., Wan, Y. et.al., Controllable robust optimization of ship concept design for quantifying uncertainty of marine water quality forecast, Desalination and Water Treatment, vol.314, pp.295-303, 2023, https://doi.org/10.5004/dwt.2023.30022.

[24] Maier, V., General loads in modern naval architecture, Technical Publishing House, Bucharest, Romania, 1997, ISBN: 973-31-1048-5.

[25] Mohamed, B.H., Belkadi, M., Aounallah, M. and Adjlout, L. Multi-objectivedesignoptimization of bulkcarriers, Journal of Naval Architecture & Marine Engineering, vol.20, pp.77-88, 2023, WOS:001134663300004.
[26] Na, S.S. and Karr, D.G., An efficient stiffness method for the optimum design of ship structures based on common structural rules, Ships and Offshore Structures, vol.8, pp.29-44, 2013, https://doi.org/10.1080/17445302.2012.669213.
[27] Nakai, T., Matsushita, H., Yamamoto N. and Arai, H., Effect of pitting corrosion on local strength of hold frames of bilk carriers (1st report), Marine Structures, vol.17, pp.403-432, 2004, https://doi.org/10.1016/j.marstruc.2004.10.00.
[28] Ohta, T., Stress distribution of a box girder with hatch openings, 10th International Offshore and Polar Engineering Conference (ISOPE-2000), vol.4, pp.458-463, 2000, WOS:000089401900071.
[29] Paik, J.K., Kim, J.Y. and Kim, M.S. Ultimate limit state performance of 170k bulk carrier structures: pre-CSR versus CSR, Marine TechnologySNAME News, 46, 174-182, 2009, https://doi.org/10.5957/mtsn.2009.46.3.174.
[30] Pei, Z.Y., Iijima, K. et.al., Collapse behaviour of a bulk carrier under alternate heavy loading conditions, International Journal of Offshore and Polar Engineering, vol.23, no.3, pp.224-231, 2013, WOS:000324224800010.
[31] Pei, Z.Y., Iijuma, K., et.al., Simulation on progressive collapse behavior of whole ship model under extreme waves using idealized structural unit method, Marine Structures, vol.40, pp.104-133, 2015, https://doi.org/10.1016/j.marstruc.2014.11.002.
[32] Pintilie, A., Contributions to optimizing the structural design of bulk carrier hulls, PhD thesis, Technical University of Cluj-Napoca, Romania, 2009.
[33] Shu, Z. and Moan, T., Assesment of the hull girder ultimate strength of a bulk carrier using nonlinear finite element analysis, 2nd International Conference on Marine Structures, 2009 and chapter in Analysis and Design of Marine Structures, 1st Edition, Imprint CRC Press, Taylor & Francis eBook, https://doi.org/10.1201/9780203874981.
[34] Sun, B., Hu, Z., Wang, J. and Yu, Z., An analytical method to assess the damage and predict the residual strength of a ship in a shoal grounding acciden tscenario, Journal of Ocean Engineering andScience, vol.1, no.2, pp.167-179, 2016, https://doi.org/10.1016/j.joes.2016.03.007.
[35] Tanaka, S., Yanagihara, D. et.al., Evaluation of ultimate strength of stiffened panels under longitudinal thrust, Marine Structures, 36, 21-50, 2013, https://doi.org/10.1016/j.marstruc.2013.11.002.
[36] Zheng, Q., Chang, H.C. et.al., Design knowledge extraction framework and its application in multi-objective ship optimization, Ocean Engineering, vol.280, 2023, https://doi.org/10.1016/j.oceaneng.2023.114782.
[37] Zienkiewicz, O.C., Taylor, R.L. and Zhu, J.L., The Finite Element Method: Its Basis and Fundamentals, Butterworth-Heinemann imprint of Elsevier, Seventh edition, 2013, ISBN: 978-1-85617-633-0.
[38] Yang, P., Zhan, W et.al., Uncertainty analysis of hydro elastic responses and wave loads for different structural modelling and potential methods, Ocean Engineering, vol.222, 2021, https://doi.org/10.1016/j.oceaneng.2020.108529.
[39] Yao, T., Magaino, A., Koiwa T. and Sato, S., Collapse strength of hatch cover of bulk carrier subjected to lateral pressure load, Marine Structures, vol.16, no.8, pp.687-709, 2003, https://doi.org/10.1016/j.marstruc.2004.01.001.
[40] American Bureau of Shipping (ABS), Common Structural Rules for Bulk Carriers. Status and Guidance, Common Structural Rules for Bulk Carriers (eagle.org).
[41] IACS Unified Requirements, Interpretations and Recommendations, International Association of Classification Societies, https://iacs.org.uk/publications/unified-requirements, (frequently accessed 2020-2024).
[42] ICEPRONAV Engineering SRL, Romania, part of ICE Marine Design, ICE: Europe's largest independent ship design group (icedesign.info).
[43] International Maritime Organization, 2009. Guidelines on the Enhanced Program of Inspections During Surveys of Bulk Carriers and Oil Tankers: Resolution A.744(18), as Amended 2008 Edition, Published byInter-Governmental Maritime, https://puc.overheid.nl/nsi/doc/PUC_2338_14/2/, (frequentlyaccessed 2020-2024).
[44] Rules &Guidelines, Germanicher Lloyd, https://www.dnv.com/rules-standards/gl-rules-guidelines, (frequently accessed 2020-2024).