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FINITE ELEMENT ASSESSMENT OF THE DOUBLE BOTTOM STRUCTURE UNDER STATIC AND DYNAMIC SHIP LOADS

PROCENA KONSTRUKCIJE SA DUPLIM DNOM METODOM KONAČNIH ELEMENATA PRI STATIČKIM I DINAMIČKIM OPTEREĆENJIMA BRODA

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Keywords

- finite element analysis (FEA)
- dynamic loads
- double bottom
- concentrated load

Ključne reči

- metoda konačnih elemenata (MKE)
- dinamička opterećenja
- dvodno
- koncentrisano opterećenje

Abstract

This paper presents a finite element strength assessment of a ship double bottom structure. A detailed three-dimensional finite element model is developed to describe the structural arrangement and complexity of the double bottom, including plating and longitudinal and transverse stiffening. Static loads represent both uniform and concentrated loads from various cargo types acting on the inner bottom of the cargo hold. Dynamic loads are represented through equivalent load components derived from gravitational forces and inertia effects associated with vessel motions, enabling the evaluation of dynamic loading effects within a quasi-static analysis framework. Structural response is assessed using stress-based criteria in accordance with classification society requirements. Results demonstrate that dynamic ship loads can notably alter stress patterns and increase stresses in critical regions of the double bottom compared to purely static loading. Results show that whether the cargo carried acts as a uniform load or a concentrated load, the double bottom structure should accommodate these changes in loading for ships operating with different types of cargo. The study highlights the importance of explicitly accounting for dynamic loading effects in double bottom strength verification and confirms the effectiveness of finite element analysis as a tool for achieving a more reliable assessment of ship structural strength beyond simplified rule-based approaches.

Izvod

U ovom radu je prikazana procena čvrstoće konstrukcije sa duplim dnom primenom metode konačnih elemenata. Razvijen je trodimenzionalni model koji opisuje raspored i složenost konstrukcije, uključujući oplatu, uzdužna i poprečna ukrućenja. Statička opterećenja obuhvataju ravnomerno raspodeljena i koncentrisana opterećenja tereta koji deluju na unutrašnje dno teretnog prostora. Dinamička opterećenja su predstavljena ekvivalentnim komponentama opterećenja izvedenim iz gravitacionih sila i inercijalnih efekata povezanih sa brodskim kretanjima, čime je omogućena analiza dinamičkih efekata u okviru kvazistatičkog pristupa. Strukturni odziv je analiziran kriterijumima zasnovanih na naponima, u skladu sa zahtevima klasifikacionih društava. Rezultati pokazuju da dinamička brodska opterećenja mogu značajno promeniti raspodelu napona i povećati nivoe napona u kritičnim regionima konstrukcije dvodna. Takođe, rezultati ukazuju na to da konstrukcija dvodna treba da bude prilagođena promenama opterećenja, zavisno od toga da li se teret javlja u vidu ravnomerno raspodeljenog ili koncentrisanog opterećenja kod brodova koji prevoze različite vrste tereta. Rad ističe značaj eksplicitnog uvažavanja dinamičkih efekata opterećenja u proveri čvrstoće konstrukcije dvodna i potvrđuje efikasnost metode konačnih elemenata kao alata za pouzdaniju procenu čvrstoće brodskih konstrukcija u odnosu na pojednostavljene proračunske pristupe zasnovane na pravilima.

INTRODUCTION

From the early beginnings of shipbuilding practice rules and regulations for the classification of ships specify standardised formulas and calculation procedures to evaluate the structural integrity of conventional ship structures. Mostly, for conventional ships and their operations, those are empirical and well-known formulas for the design of structural elements /1-3/. In some cases, classification societies require direct calculation methods to verify the strength of novel design features, or more commonly, for existing ships that are being overhauled with alternative structural arrangements. In situations involving a change in the ship's purpose, modifications to specific deck or cargo-hold areas, or other non-standard configurations, classification societies may request a finite element analysis (FEA) to assess the ship's structural integrity. In such cases, the FEA should be performed in accordance with existing recommendations and guidelines, /1-4/.

The present work comprises FEA-based approach to examine the structural response of the double-bottom structure and the additional under-deck reinforcements in way of the 20-foot high-cube containers located in cargo holds no. 2 and no.4 of a multi-purpose vessel. Originally, the double-bottom structure of these cargo holds is designed to carry bulk cargo. However, after several years of service, the need arose to accommodate container loads.

Modern multi-purpose vessels increasingly face operational demands that require flexible cargo capabilities beyond their original design intent. Traditionally, multi-purpose vessels designed for bulk cargo assume a near-uniform load distribution across cargo holds. However, the transportation of container cargo imposes fundamentally different load patterns, concentrated point loads applied over hatch and tank top areas which can significantly alter the stress state of the double bottom and underdeck reinforcement structure.

The practice and literature support regulatory evolution is labelled at the start of this section /1-3/. Study of double bottom floor, with the combined effects of geometric discontinuities (such as openings and cutouts) under diverse in-plane loads are taken into consideration as the perforated plates located in the double bottom floor of a 3000 m^3 wellboat are investigated for their linear and elastic buckling behaviour /5/. Likewise, conversion case studies provide empirical evidence of how local and global structural modifications need to follow classification FEA guidance to maintain class status after alternative loading is introduced /6-7/. Together, rules and publications form a coherent regulatory-technical narrative. When researchers and designers propose modifications to cargo holds such as adapting bulk-carrier holds for concentrated loads, their analyses must align with the Lloyd's Register (LR) and International Association of Classification Societies (IACS) direct calculation framework and demonstrate equivalent or improved structural performance under the new service conditions.

From a wider technical perspective, conversion case studies demonstrate the importance of local strengthening, redistribution of stiffening and stress, and consideration of dynamic load amplification caused by ship motions, /8/. Moreover, several studies have investigated geometric alternatives for double bottom floors in ship structures using detailed FEA to assess variations in strength and stiffness. The results show that optimised geometries can significantly improve structural performance without major increase in steel weight /9/. In addition, such conversions affect the overall hull-girder strength by altering the position of the neutral axis, modifying the strength of individual structural members, and consequently influencing the vessel's ultimate strength, as demonstrated by the authors in their earlier studies, /10-12/.

In this context, the present study employs a novel approach by applying a structured FEA methodology to quantify the structural response of the existing double bottom structure under concentrated container loads and dynamic loads induced by vessel motions. The aim is to identify critical regions where conventional scantlings are insufficient and to design targeted reinforcements that restore compliance with classification rules while minimising both weight and production impact. The outcomes offer practical guidance for owners and designers seeking to extend the operational capability of multi-purpose vessels to include container cargo, without compromising safety or class compliance.

THE VESSEL

The vessel has five cargo holds and a deadweight capacity of 34037 t. The main particulars of the vessel are as follows: length overall 182.87 m, breadth 28.39 m, height 15.3 m, and design draught 10 m. Container storage plan is given in Fig. 1. In the as-built design, the cargo holds are intended for bulk cargo, while containers are carried on deck, i.e., on the hatch covers. Over the years, cargo holds no. 1, 3, and 5 are converted to accommodate 40-foot high-cube containers (rectangles indicated in orange in Fig. 1). However, the analysis presented in this paper focuses on the remaining cargo holds (no. 2 and no. 4), allowing the vessel to operate more flexibly and to carry, in addition to bulk and 40-foot containers, 20-foot high-cube containers as well (rectangles indicated in blue in Fig. 1).

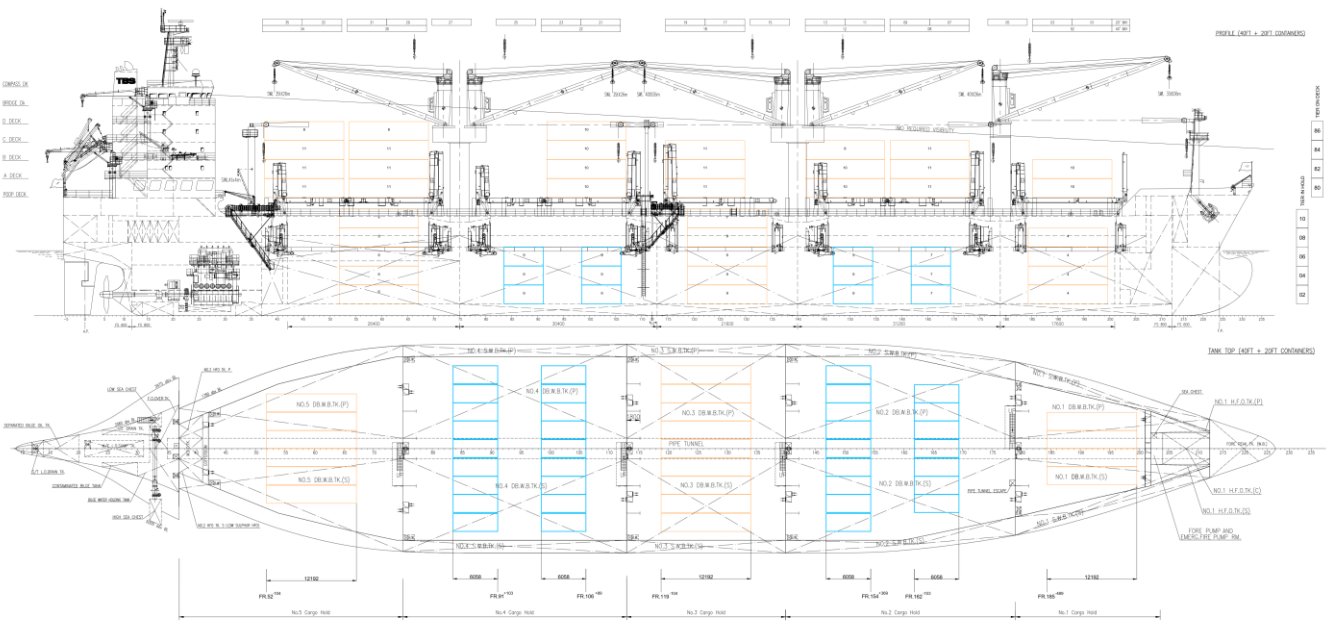

Figure 1. Vessel's container storage plan (up: profile view; down; tank top view).

Cargo hold's double bottom structure is made of mild steel (grade A) and high-tensile steel (grade AH32). The modulus of elasticity is 207 GPa, Poisson's ratio is 0.3, and the density of the steel is 7.85 t/m^3, while the yield stress is 235 MPa for mild steel and 315 MPa for high-tensile steel. The elements made of mild steel are the inner bottom plate, the floors (transverse girders) and their adjacent flat bars, as well as the flat bars of longitudinal girders, while all other elements of the double bottom are made of high-tensile steel. The vessel is longitudinally stiffened, with web-frame spacing of 1200/1600 mm and an average longitudinal stiffener spacing of 737 mm. Throughout the entire double bottom area, the cargo-hold structure is stiffened by eight longitudinal girders. The overall dimensions of modelled double bottom of cargo holds (length×breadth×height) are as follows: 26.4×24.9×1.78 m for the cargo hold no. 4 (see Fig. 1).

METHODOLOGY

Finite element analysis

The rules and regulations of classification societies, as well as common practice and guidance, recommend the use of thin-plate theory for small deformations as applicable to ship structures such as shell plating, girders, web frames, and similar elements /1-3/. Therefore, shell elements are used to represent the plating, web frames, girders, longitudinal stiffeners, and additional local stiffeners in way of the containers. On the other hand, beam elements are used for the representation of secondary stiffeners and flanges of primary members. The beam's deflections are assumed to be small compared to their length, allowing for linear analysis. In addition, the material behaviour (stress-strain relationship) is modelled as linear-elastic. The von Mises stress criterion is used to evaluate the results, combining the effects of normal and shear stresses into a single equivalent value. The acceptance criteria for the analysis are defined as 70 % of yield stress of the respected materials, 164.5 MPa (for grade A), and 220.5 MPa (for AH32).

To minimise computational time, each cargo hold (no. 2 and no. 4) is split into two parts. For the same reason and given the symmetry of the double bottom cargo holds, only one side (the port side) is modelled. Both cargo holds are modelled up to the longitudinal bulkheads and to the inner bottom, located 1780 mm above the baseline. This approach is adopted because the applied loads and resulting stresses are localised around container fittings; therefore, extending the model further would not provide additional value to the analysis. Four different models are created: two separate models for each cargo hold. Fixed boundary conditions are applied at the fore and aft edges (transverse girders) of all model parts, while translations along the sides (longitudinal girders) are constrained to zero. The entire model is meshed with an average element size of 100 mm, which is sufficient to obtain a representative distribution of stress. The double bottom of cargo hold no. 2 contains 181943 finite elements and 210973 nodes, while double bottom of cargo hold no. 4 includes 171950 finite elements and 198686 nodes. However, Fig. 2 shows the geometric model of the double bottom of cargo hold no. 4, which is used as input file for the FEA software. The right-hand side of Fig. 2 presents the FE model of the same cargo hold, corresponding to a single container column (as mentioned earlier, it is divided into two FE models).

Loads

The applied loads considered in this study include acceleration due to ship motions, the weight of containers, and gravity. The combined effect of gravity and ship-motion-induced acceleration is examined to understand the structural response under various loading conditions. The weight of the container stacks is represented by concentrated masses located at their centres of gravity. Each container weighs 37.5 t, and weight of each stack is 112.5 t (three container rows). The transmission of loads from the containers' centres of gravity to the inner bottom of the cargo holds, as well as the interpolation of loads to the surrounding structure, is accounted for in the analysis. Including these loads ensures that the design remains robust under the range of environmental conditions encountered in service. The accelerations are calculated according to CSR for Bulk Carriers and Oil Tankers, see Eqs.(1)-(3), /3/.

$$a_{x-env} = \sqrt{a_{sway}^2 + (g\sin\theta + a_{roll-x})^2}\ , \tag{1}$$

$$a_{y-env} = 0.7\sqrt{a_{surge}^2 + \left[\frac{L}{325}(g\sin\varphi + a_{pitch-y})\right]^2}\ , \tag{2}$$

$$a_{z-env} = \sqrt{a_{heave}^2 + \left[\left(0.3+\frac{L}{325}\right)a_{pitch-z}\right]^2 + (1.2a_{roll-z})^2}\ . \tag{3}$$

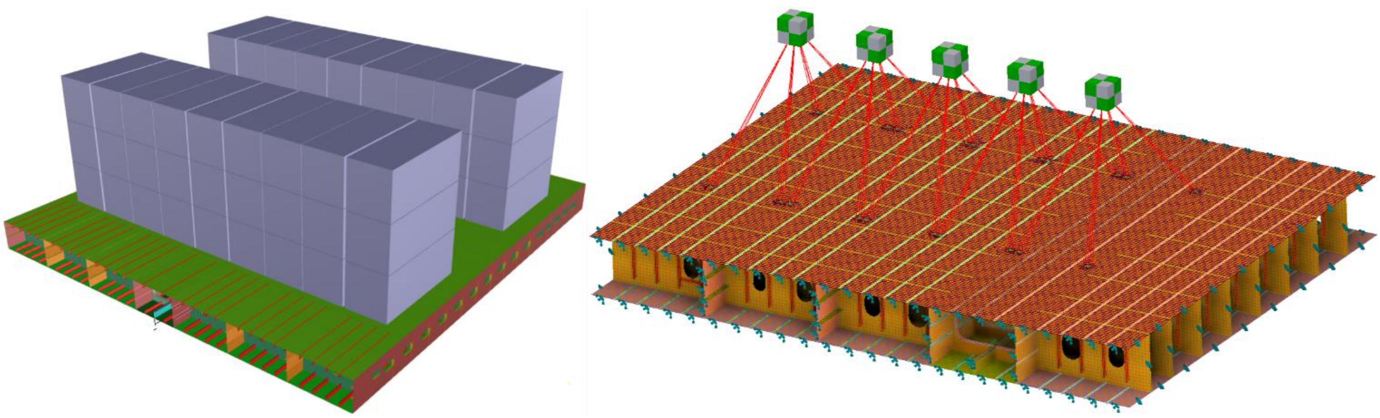

Figure 2. 3D models of cargo hold no. 4: a) geometric model with container arrangement; b) FE model with containers as concentrated masses.

Loading cases

The accelerations acting on the structure are derived from the envelope accelerations and are calculated according to Eq.(1), with the coefficients in the equation depending on the vessel's particulars and loading conditions. A summary of the calculated accelerations for each cargo hold is presented in Table 1.

Table 1. Accelerations considered for each cargo hold.

Acceleration (m/s^2)	Cargo hold no. 2	Cargo hold no. 4
a_{X-env}	4.507	4.507
a_{Y-env}	1.100	1.100
a_{Z-env}	5.113	4.230

These accelerations are applied to the entire model in addition to the gravitation acceleration. Based on the above described loads, the load cases are summarised in Table 2.

Table 2. Description of examined load cases.

Load case	Description
LC-x-01	transverse acceleration
LC-y-01	forward acceleration
LC-z-01	downwards acceleration

RESULTS AND DISCUSSION

As mentioned in previous sections, the two cargo holds are divided into four computational models. Each model includes three load cases corresponding to prescribed accelerations (i.e., ship motions), resulting in a total of twelve finite element simulations. Based on the stress distribution observed across the inner bottom plating and the underlying stiffening structure, significant stress concentrations are identified in the vicinity of the load application points, corresponding to container support locations. This behaviour is both expected and conceptually anticipated prior to numerical analysis. The double bottom structure in these regions is not originally designed to withstand such localised stress concentrations; therefore, structural optimisation and reinforcement of the affected areas are required.

The most critical stresses occur in load case 3 (LC-z-01), where vertical load components combine gravitational acceleration due to ship heave superimposed with the static weight of the containers, leading to the highest resultant stresses in the inner bottom plating and supporting floors. From the optimisation standpoint, the FE models identified 80 points of interest corresponding to the container footing locations, which are considered for structural modification (note that only one side of the cargo holds is modelled due to their symmetry about the centreline), see /13/.

For this reason and owing to the extensive amount of data generated by the large-scale model encompassing the entire cargo-hold region of the vessel, a representative example of the double bottom structural optimisation within cargo hold no. 4 under load case 3 is selected and is presented as a reference case for further discussion.

Figure 3 provides an overview of the structural response of the double bottom structure. Illustrations labelled a) and b) show critical stress regions within the double bottom where von Mises stress values exceed 164.5 MPa, corresponding to the allowable limit for mild steel. In contrast, the illustrations labelled c) and d) depict regions where the stress values exceed the critical level of 220.5 MPa, characteristic of high-tensile steel members.

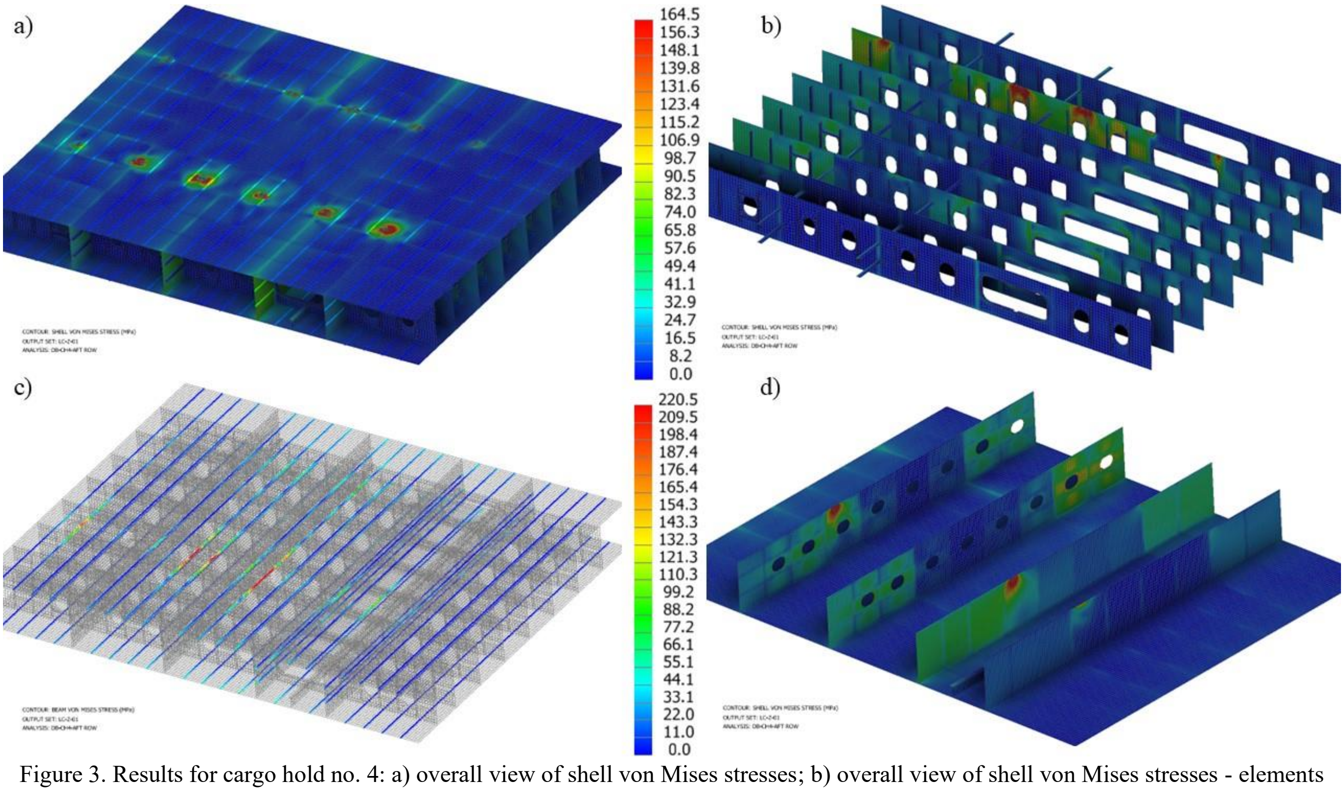

Figure 3. Results for cargo hold no. 4: a) overall view of shell von Mises stresses; b) overall view of shell von Mises stresses - elements made of mild steel (excluding inner bottom plate); c) overall view of beam von Mises stresses; d) overall view of shell von Mises stresses - elements made of high-tensile steel.

In Fig. 4, the maximum deformations can be observed, slightly above 6 mm, at locations where the container corner castings are supported by the inner bottom structure. According to the IACS Shipbuilding and Repair Quality Standard - No.47 /14/, the allowable deformation between two longitudinal stiffeners should not exceed 3-4 mm. Within certain portions of cargo holds, where the container arrangement and spacing permits, it is possible to position the container supports directly above the primary transverse (floors), effectively reducing local stress concentrations. However, in areas where such alignment is not feasible, structural optimisation of the double bottom arrangement is required to mitigate stress concentrations and achieve a more uniform stress distribution.

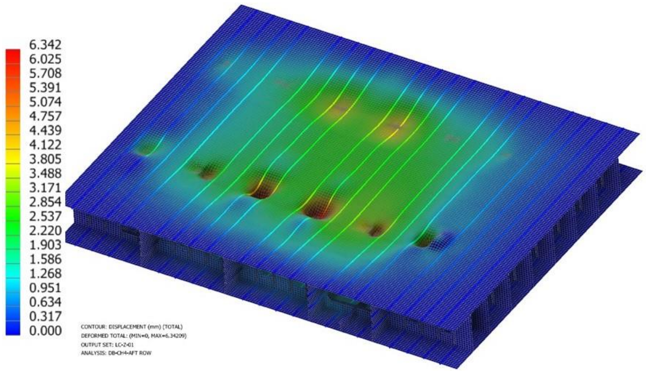

Figure 4. Deformation.

In the context of structural optimisation, it is necessary to increase the thickness of the inner bottom plating at the locations where container footsteps are supported. Subsequently, additional stiffening elements are introduced along the load-application lines corresponding to container weights, in order to transfer the induced loads through these stiffeners and their associated bracket connections to the primary transverse and longitudinal girders. In areas where no primary longitudinal girder is available nearby, secondary stiffeners are added and integrated into the double bottom framework using additional reinforcing profiles, thereby creating alternative and continuous load paths. This arrangement enables the inner bottom longitudinals to effectively receive and redistribute the transferred loads from the newly installed stiffening system, ensuring that the modified structure remains within the allowable stress limits prescribed by the classification society rules. The optimisations measures are subsequently verified through FEA, confirming that the revised configuration achieves a more uniform stress distribution and eliminates previously identified overstressed regions.

In Fig. 5, the optimised double bottom structure is shown, where newly introduced components such as insert plates, stiffeners, brackets, and reinforcing profiles, are highlighted in magenta colour. Validation of the optimised results, confirming the effectiveness of the stiffener arrangement illustrated in Fig. 5, is presented in Figs. 6-7.

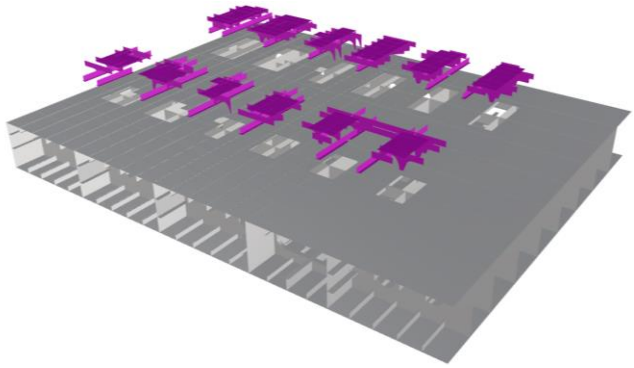

Figure 5. Optimised double bottom of cargo hold no. 4.

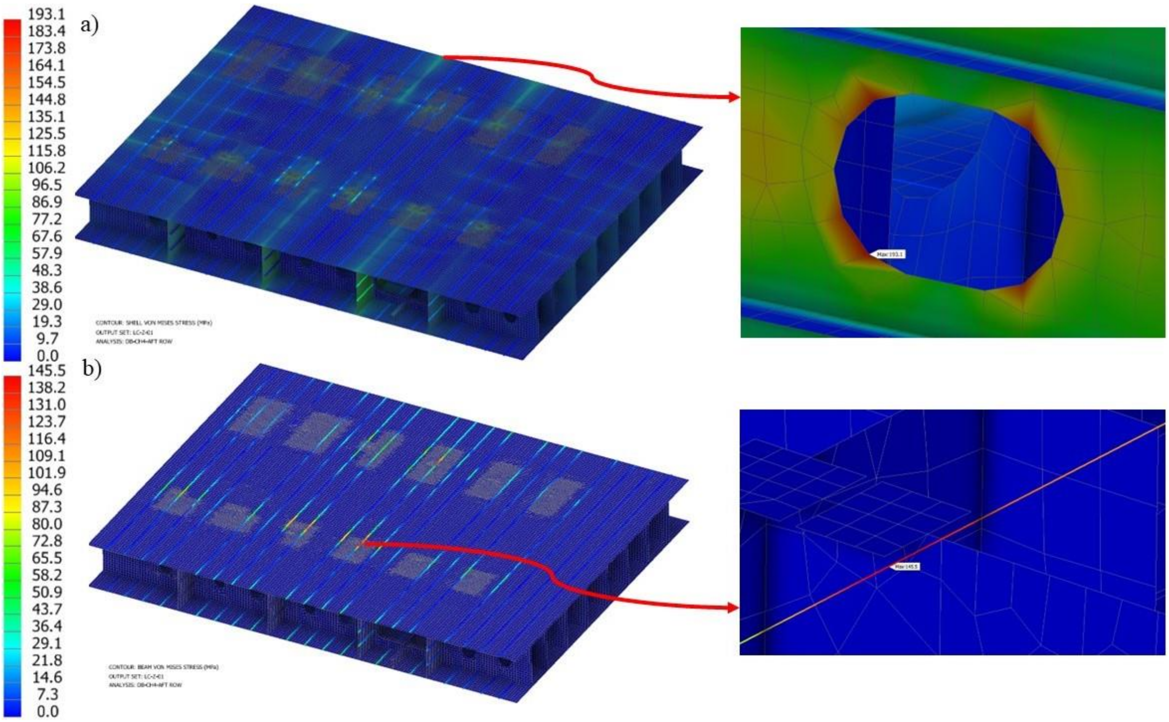

Figure 6. Von Mises stress distribution after optimisation: a) shell elements; b) beam elements.

As evident from the analysis, following the optimisation, the maximal shell von Mises stress within the inner bottom plating is reduced to 193 MPa (stress concentration observed in the cutout of the longitudinal girder), remaining safely below the allowable limit of 220.5 MPa for high-tensile steel. For the beam elements, the maximal stress value reaches 146 MPa, which also lies within the permissible range. Figure 6 provides an overall view of the stress distribution, showing that the remaining stress concentrations are now below the critical threshold, thereby confirming the structural adequacy of the modified design.

Following optimisation, the stress distribution becomes more uniform, with no pronounced concentrations resulting from applied loads. As illustrated in Fig. 7, the maximal deformation of the structure is reduced to approximately 3.8 mm, indicating a significant improvement in overall stiffness and structural response of the double bottom structure.

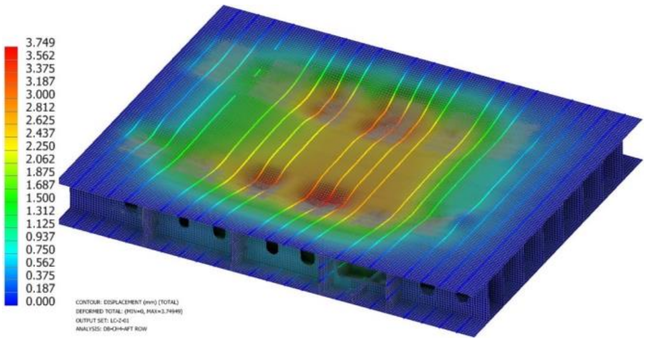

Figure 7. Deformation (after optimisation).

CONCLUSION

This study presents the structural analysis and optimisation of the double bottom structure within the cargo holds of a multi-purpose vessel, examined in the context of a change in cargo type and the operational purpose of the holds. The analysis demonstrates that a different cargo configuration characterised by non-uniformly distributed and concentrated loads can significantly influence and alter the original structural concept of a vessel whose design loads are uniformly distributed across the cargo holds. Although calculations are performed for cargo holds no. 2 and no. 4, due to the large number of optimisation variables and loading cases modelled across four simulations in the FE software, the paper focuses on a representative example: the optimisation of the double bottom structure in cargo hold no. 4. Since the objective is to provide a qualitative assessment of how structural optimisation affects stress-concentration redistribution, the remaining optimisation cases show no significant deviation from the typical configuration presented in this study.

The optimisation reveals that the existing double bottom structure could not safely withstand container-induced loading without reinforcement. By combining local increases in plate thickness with the addition of secondary stiffeners and improved load paths through brackets and reinforcing profiles, the modified structure reduces the maximum von Mises stress to acceptable level of 193 MPa and limits deformation from 6.3 to 3.8 mm, keeping all components within classification limits.

The results emphasise the importance of early-stage numerical verification when adapting ships for new cargo types and provide a practical reference for future retrofitting of multi-purpose vessels to ensure compliance, safety, and operational flexibility.

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