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TOPOLOGY OPTIMIZATION OF AN OILTANKER BULKHEAD SUBJECTED TO HYDROSTATIC LOADS

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***Abstract*:**

In the field of Naval Architecture, the conventional approach to design any vessel is to follow the classification societies' rules to ensure adequate strength and structural integrity. Nowadays, owners' demands and purposes of vessels are changing dramatically. To ensure these demands, sometimes it is necessary to design new types of structures. But the classification society's rules alone are not enough to prepare these advanced designs automatically. Moreover, Naval Architects are always eager to minimize the lightweight of a vessel as this is directly related to cost and carrying capacity. Topology optimization has become a powerful tool for designing structures. The concept of topology optimization has been utilized by the automotive and aerospace industry for almost thirty years where problems associated with solutions meant to satisfy maximum stiffness and structural integrity with minimum weight which are of utmost importance. However, in the field of marine and offshore structures, the use of topology optimization is infrequent. As structural optimization aims to design structures under certain constraints to achieve better strength and lower cost, the introduction of this technique in ship structure can be lucrative. In this paper, structural topology optimization is used in the field of ship design. An Oil Tanker Bulkhead has been selected for this study. SIMULIA Abaqus software is used in this regard. The study gives a very interesting and optimized structure.

Keywords: Topology, optimization, structures, bulkhead, class rules.

NOMENCLATURE

c	compliance	x_{min}	vector of minimum relative densities
U	global displacement vector	N	number of elements
F	global load vector	p	penalization power
K	global stiffness matrix	V_o	volume of design domain
u_e	element displacement vector	V_x	volume of material
k_e	element stiffness matrix	f	prescribed volume fraction
x	vector of design variable		

1. Introduction

Achieving a safe design is the primary target of any engineer. Naval architects design ship structures based on their experience and existing ships. This design must comply with the applicable rules as well as minimum requirements of the concerned classification societies. Over the years the classification societies have been providing the necessary standards to ensure the adequacy of strength against all demands that can be envisaged during service life of the ship. With the advancement of Numerical methods and availability of computing facility at affordable costs, use of such methods provides more reliable and direct assessment. Finite Element Analysis (FEA) is a universally known structural analysis tool in use today to check such structural concerns (Kar et.al., 2008, Parunov et.al., 2010 and Islam et.al, 2017) which can be used alongside class rules for better structures.

It is expected that a designed object is economical i.e., optimal also. A design is said to be optimal if the value of the objective function for the design is as low or high as possible, depending on the objective. To design this kind

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of optimal object, the use of optimization algorithms for efficient products is rapidly increasing due to continuously increasing computational power. Generally, the optimization algorithm is used in the development of aeronautic applications, other areas which demand high performance and cost savings. Nowadays, this includes, but is not limited to, the automobile, oil and electronics industries (Johnsen, 2013).

2. Optimization Methods

Structural optimization can be classified as size optimization, shape optimization and topology optimization. Size optimization seeks to change only the dimensions of the structural members. Shape optimization scales the cross-section of structural members, but in addition, can modify the position of members to support the load more efficiently. Both methods depend, however, on an initial structural configuration, not being able to add or remove members. Unlike those two, topology optimization is used to update the initial configuration. It gives a structure where it is superior in some domains. The efficiency of the structure is increased by increasing the stiffness and reducing the material (Casas et.al., 2016).

Topology optimization is a material distribution procedure for synthesizing structures without any preconceived shape. This freedom provides topology optimization with the ability to find innovative, high-performance structural layouts, which has attracted the interest of designers of many engineering fields. Lucien Schmit in the 1960s —recognized the potential of combining optimization methods with finite-element analysis for structural design and Bendsøe and Kikuchi (1988) presented a seminal paper in this topic (Liu and Tovar, 2013).

A very effective topology optimization method using SIMP approach (Solid Isotropic Material with Penalization) was proposed by Bendsøe (1989). According to Sigmund (2001), A topology optimization problem, to minimize compliance, based on the power-law approach can be written as

$$\begin{aligned} &\min_{x} && : c(x) = U^T K U = \sum_{e=1}^{N} (x_e)^p u_e^T k_e u_e \\ &Subjected\, to && : \frac{V_x}{V_0} = f \\ & && : KU = F \\ & && : 0 < x_{\min} \le x \le 1 \end{aligned} \tag{1}$$

Jin Ju et.al. (2014) used multi-objective optimization methods inspired by Pareto Front to reduce the design tank weight and outer surface area of a container ship simultaneously. Additionally, an enhanced Level Set Method (LSM) which employs implicit algorithm is applied to the topological design of typical bracket plate which is used extensively in ship structures. They did not mention the type of finite element used for modeling the structures.

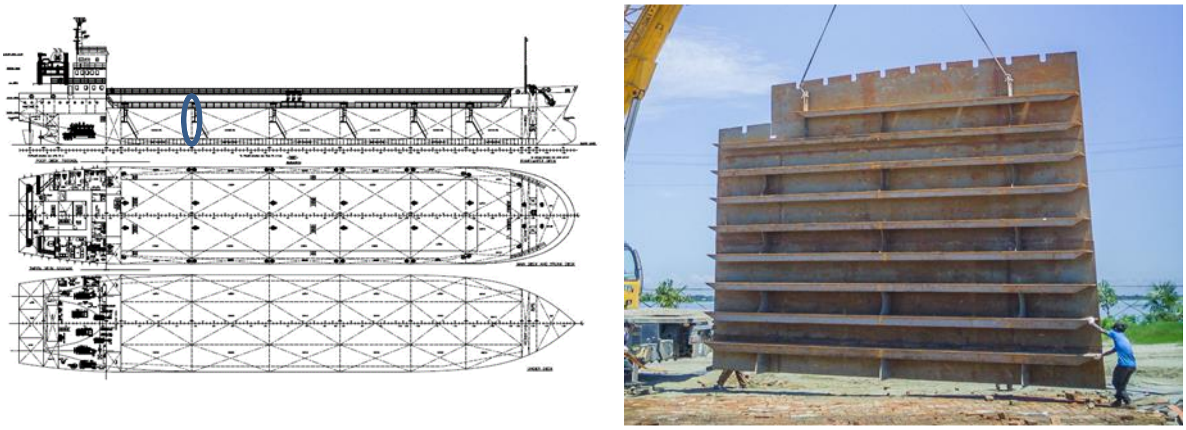
Vuijk (2020) optimized the midsection of a Trailing Suction Hopper Dredger (TSHD) in his Master’s thesis. The optimization was performed in two steps. In the first step, shape optimization was performed for the longitudinal stiffener arrangement using Simulated Annealing algorithm. It was followed by a topology optimization for the transverse web frame by modified Bi-directional Evolutionary Structural Optimization (MBESO) method. Shell and plate elements are used for modeling structures. As limitation of the study, Vuijik stated that the optimization could not directly be implemented in the final design since there was a discontinuity between the model and the real-life situation.

From the literature survey it is found that the application of topology optimization in ship structures are not frequent. This study shows a direct application of the method to a specific structure by a renowned software.

In this research, the optimization method which is based on finite element analysis has been applied to optimize a transverse bulkhead of an oil tanker. For modeling the bulkhead, shell element with reduced integration has been used (Getting started with Abaqus, 2013). The bulkhead with some simplifications, and increased stiffener thicknesses as discussed in section 4, is analyzed. The objectives are to check the performance of shell elements for optimization process and to check the features of the optimized bulkhead. The load bearing performance of continuous vertical stiffeners is an important requirement of this study. As there is no way to reduce thickness of plates, as modeled by shell elements, how the structures are optimized is a matter of interest. The possible use of additive manufacturing (Ziółkowski and Dyl, 2020) to produce such items in near future is also a matter of interest.

3. The Ship and The Bulkhead

In this research, topology optimization is applied to optimize a transverse bulkhead of an oil tanker. A transverse bulkhead is an important structure for the strength of a ship because it supports the deck and side shells and transfers stress to the floor. The dimensions of the structural members of the bulkhead are calculated using class rules.



(a) (b)

Fig. 1: (a) Position of bulkhead in the oil tanker; (b) Figure of half of the bulkhead under construction.

Fig. 1(a) shows a general arrangement of a typical oil tanker and Fig. 1(b) shows half portion of the bulkhead to be fitted. Fig. 2 shows the bulkhead which is designed according to the class rules. The principal particulars of the Oil Tanker are the length overall 93.5 m, breadth 17m, depth 6.5 m, draft 4.6 m and deadweight 4980 tonnes. The thickness of plates at upper portion is 9 mm and at lower portion it is 12 mm. Vertical stiffeners are of 9 mm thickness. Fig. 2 shows the position and size of stiffeners (Islam et.al, 2017).

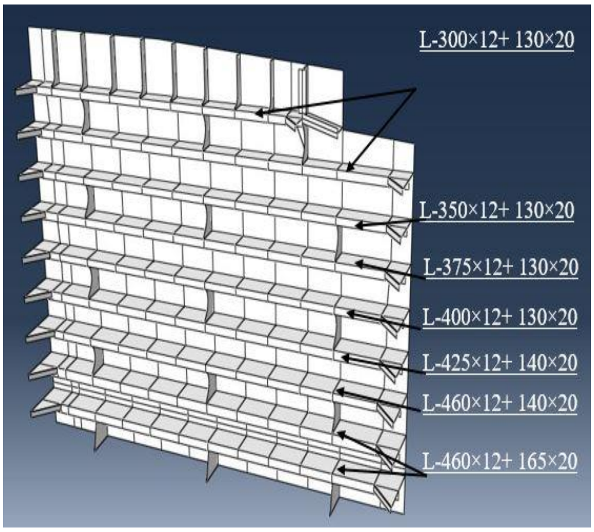


Fig. 2: 3D model of the original bulkhead

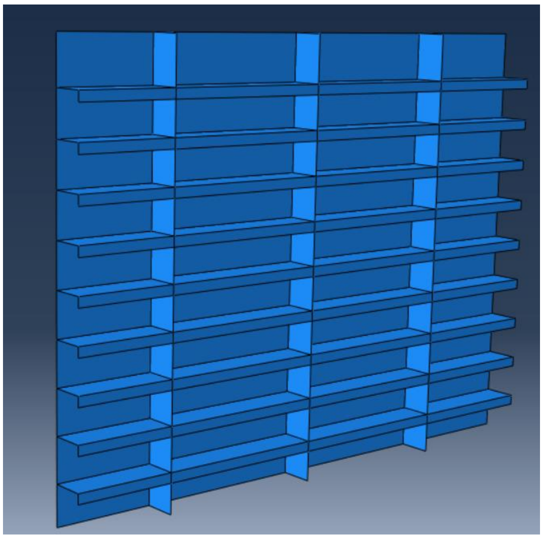


Fig. 3: Bulkhead with arbitrary sized structural members

4. Finite Element Model

To prepare a model for topology optimization, some simplification is made which is shown in Fig. 3. From assembling point of view, the bulkhead was difficult to transport and welded to its position due to absence of vertical stiffeners. To avoid this difficulty, a change is made where three flat vertical stiffeners are provided to investigate their effectiveness in strength. All the brackets are eliminated to make the model simpler. All the horizontal stiffeners are given a size of 500 x 150 x 20 mm. The nonexistent continuous vertical stiffeners are given a size of 500 x 20 mm. All the four sides of this bulkhead will be welded to tank floor, longitudinal bulkhead, double hull and deck. Clamped boundary condition is used (Hughes et.al., 2010). The worst loading condition, when bulkhead is subjected to hydrostatic pressure of one side, is considered. The volume of the half of the bulkhead is found as 1.77 m^3. The liquid is considered as water and maximum hydrostatic load at the bottom of the bulkhead is taken as 0.064 MPa. Shell element with reduced integration S4R (Abaqus Analysis Users Guide, 2013) is used to model the bulkhead.

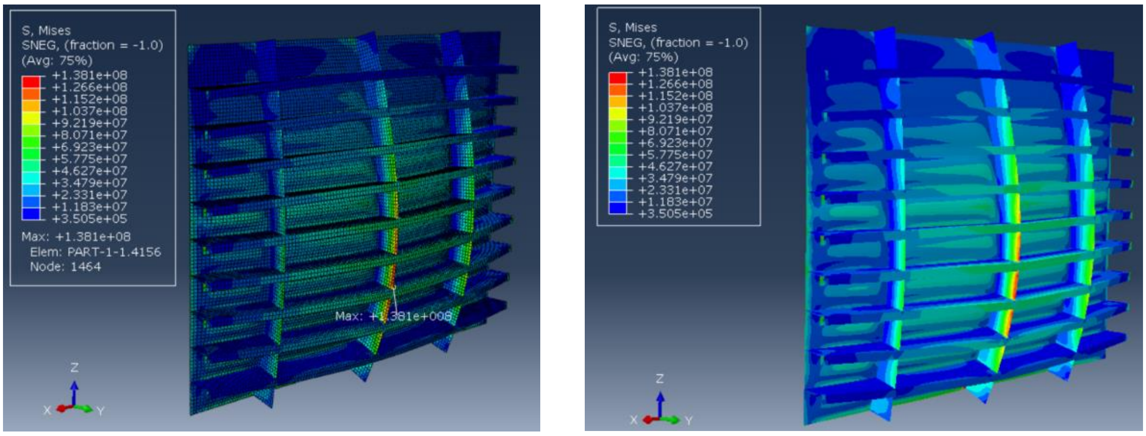
Results and Discussions

First static analyses are performed. Convergence of static analysis is shown in Table 1. During the analysis it is very important to check for position of center of pressure and the location of maximum stress. Those should match. It seems that after converging (seed 0.08, node 17738 and element 17676), the result is diverging. Further subdivision does not converge the result and does not give correct location of maximum stress.

Table 1: Convergence table of static analysis of the bulkhead

Model No.	Seeds	Node	Element	Maximum VM Stress (MPa)	% Change
1.	0.09	15816	15767	130.1	-
2.	0.08	17738	17676	130.4	0.23
3.	0.07	22968	22895	134.4	3.37
4.	**0.065**	**27175**	**27100**	**138.1**	**2.75**

The model containing 27175 node and 27100 element is chosen for topology optimization for conservative design. The result of finite element analysis of the model shows a safe stress limit (Fig. 4). The location of maximum stress is also shown in Fig. 4(a).



(a) (b)

Fig. 4: Von Misses stress distribution (a) With mesh (b) Without mesh

The maximum Von Misses stress is generated as 138.1 MPa, which is well within acceptable limit. SIMULIA Abaqus Topology Optimization Module (ATOM) supports several types of elements. S4R element is one of those and this is chosen for this study.

In the topology optimization process, two single term design responses, strain energy and volume are chosen. Strain energy was taken as objective function to be minimized and a volume fraction of 0.7, meaning 30% of volume reduction is chosen first. Both load and boundary condition regions were freezed. Maximum 50 cycle for optimization was selected and every cycle data was chosen to be saved. It took 37 minutes and 29 design cycles to finish the optimization process. Fig. 5 shows convergences of strain energy and volume fraction with iteration numbers.

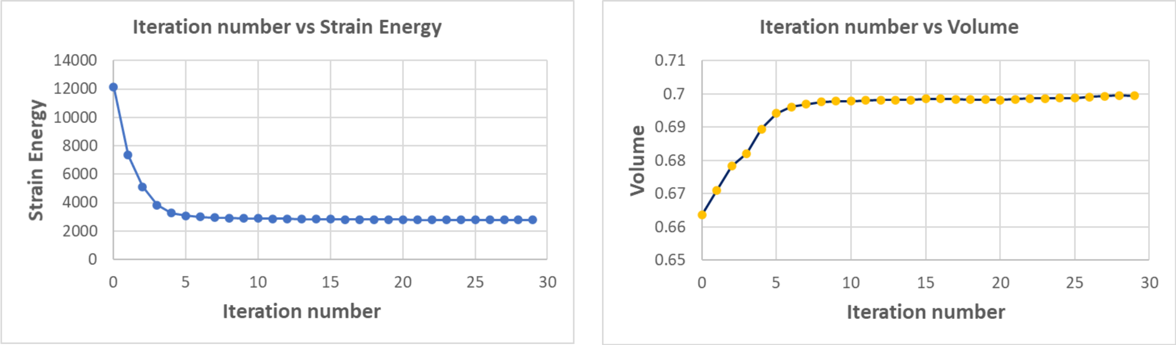
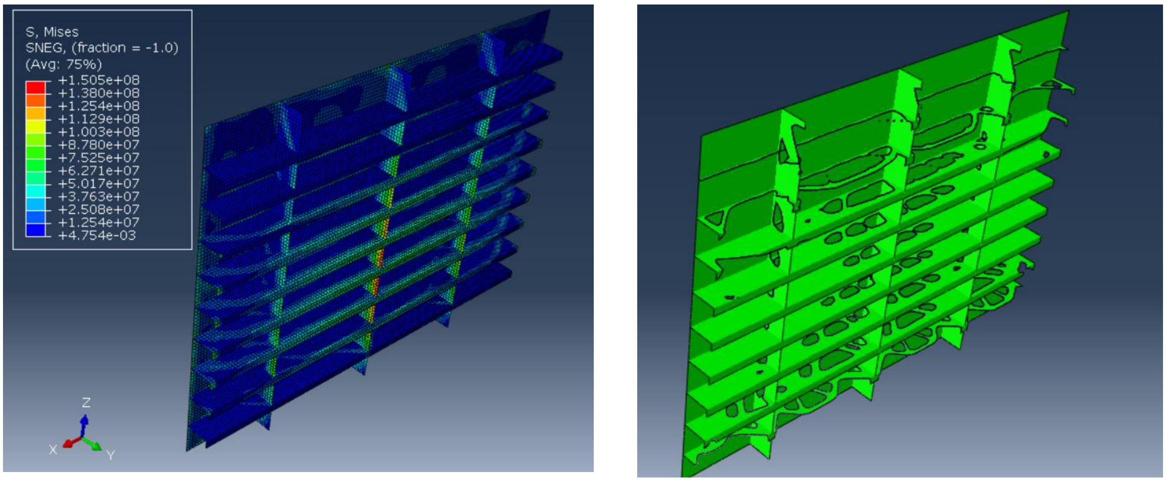


Fig. 5: Convergence of optimization process for 30% volume reduction

Fig. 6 shows Von Misses stress distribution for 30% volume optimization on meshed structure. The maximum developed stress is 150.5 MPa which is well below the yield stress of mild steel. Fig. 6(a) shows stress contour over the meshed structure and Fig. 6(b) shows the final optimized BHD (bulkhead) without mesh and stress contours.

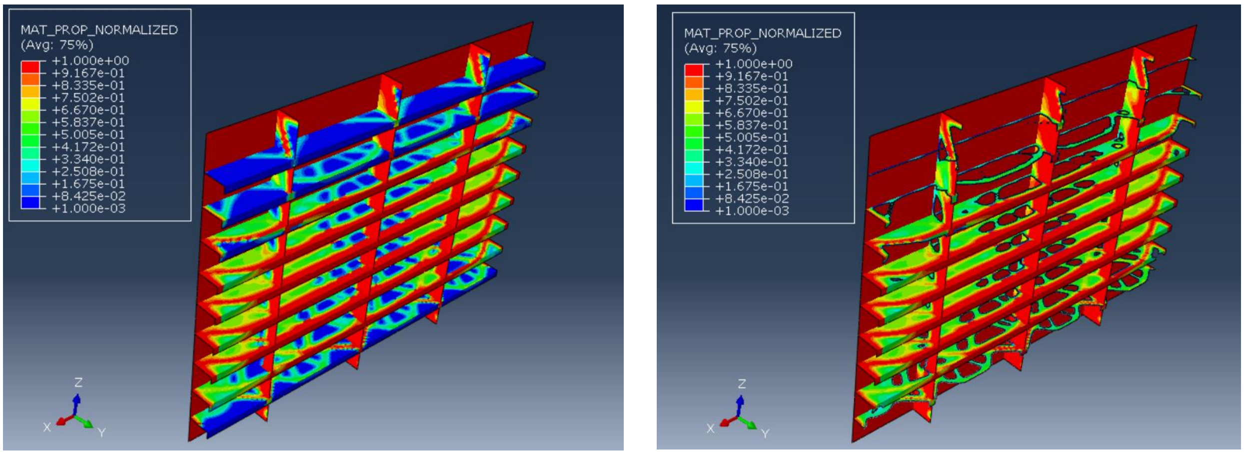


(a) Stress contour over the whole bulkhead (b) The bulkhead after optimization

Fig. 6: BHD for 30% volume optimization

Fig. 7 shows normalized material property over the bulkhead. The maximum value is 1 and the minimum value is close to zero as optimization theory states. Fig. 7 (a) shows the full structure and Fig. 7 (b) shows only the remaining portion of the structure. As the loading area is frozen, the plate of BHD is shown completely red-colored, that is the normalized material property of value 1.

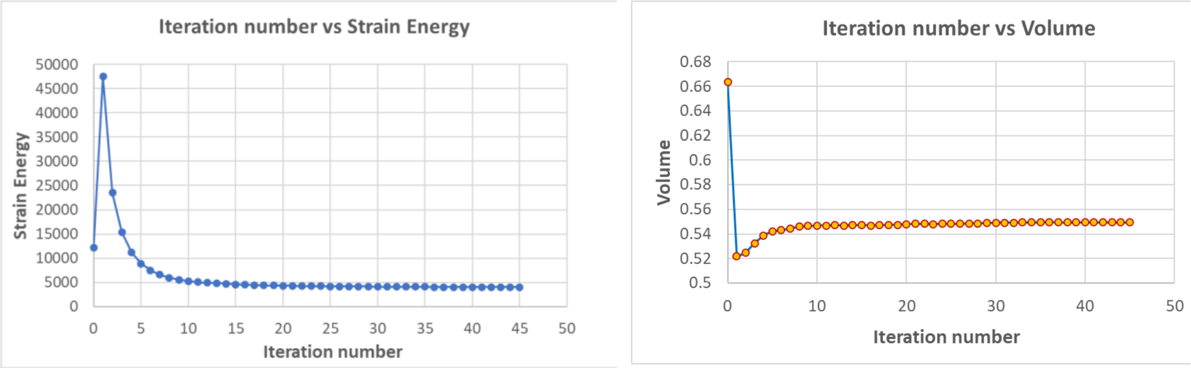
The stress contour on the 45% volume optimized BHD assures more level of optimization. The 45% volume optimization is achieved at 45 iterations, and it took about an hour. The maximum stress is 203.1 MPa. Fig. 8 shows the convergence of the optimization process.



(a) Normalized material property of full structure

(b) Normalized material property of final structure after removal of materials

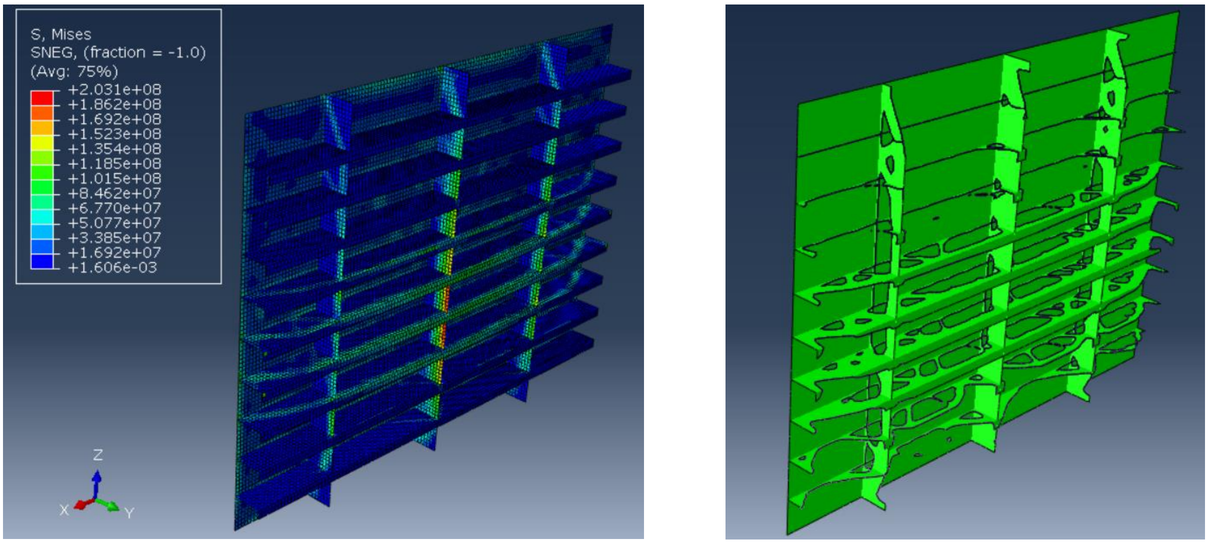
Fig. 7: BHD for 30% volume optimization with normalized material property



(a)

(b)

Fig. 8: Convergence of optimization process for 45% volume reduction



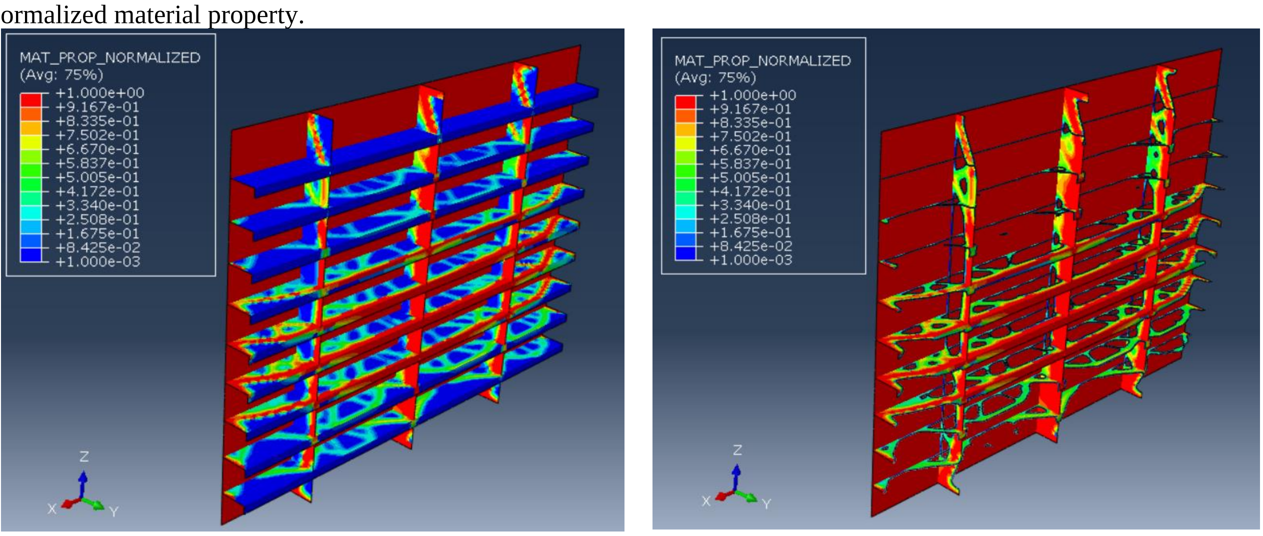
(a)Stress contour over the whole bulkhead

(b) The bulkhead after optimization without mesh

Fig. 9: BHD after 45% volume optimization

Fig. 9 (a) shows Von Misses stress distribution for 45% volume optimization on full meshed bulkhead. Fig. 9 (b) shows optimized final bulkhead without mesh.

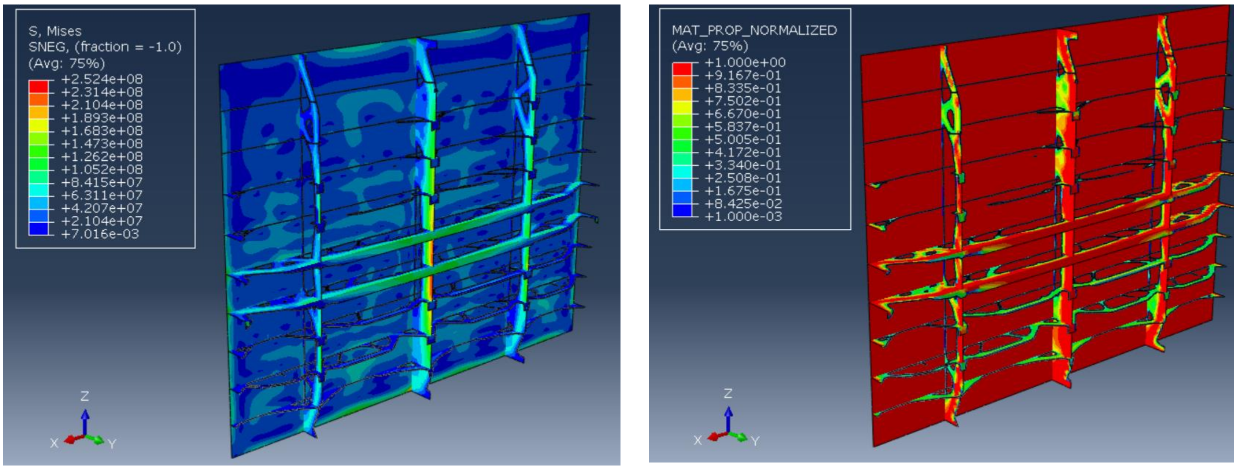
Fig. 10 (a) shows the full structure and Fig. 10 (b) shows only the remaining portion of the structure with normalized material property.



(a) Normalized material property of full structure (b) Normalized material property of final structure

Fig. 10: BHD for 45% volume optimization with normalized material property

From Fig. 9 and 10, it is seen that the first three horizontal stiffeners are almost eliminated. Bottom two stiffeners are also reduced a lot. The vertical stiffeners, specially the middle one, is taking a considering amount of the loading. The other stiffeners are taking loads but with reduced area. The analyses have given a very good idea about how an effective design solution is achievable automatically by the topology optimization.



(a) Stress contour over the whole bulkhead (b) Normalized material property of final structure

Fig. 11: BHD for 50% volume optimization with normalized material property

The output file of the optimization procedure by SIMULIA Abaqus can then be used for CNC cutting. In addition to this, STL file is possible to generate for the optimized bulkhead which is expected to be used for 3D printing in near future.

The final optimization reduces 45% volume from 1.77 m^3 (13.9 tonne) to 0.9735 (7.65 tonne) from the starting configuration. This reduces material (6.25 tonne) cost of about USD 7800, a significant amount, only from half of the single bulkhead of a small tanker.

A 50% volume reduction causes stress value (252 MPa) going beyond yield stress and is shown in Fig. 11. Further analysis is thus felt unnecessary.

5. Conclusion

Nowadays, the application of structural topology optimization is increasing significantly, mainly in the field of aeronautical, electrical, and mechanical engineering. This study has implemented the optimization technique in the field of shipbuilding. The study successfully optimized a bulkhead of an oil tanker. In the context of this study, the following conclusions can be made.

- The optimization method used in this study is coupled with the finite element method. It is an iterative process. Each possible result can be opened and can be seen for the converging improvements.
- From the result, it is seen that the method has minimized 45% weight of the bulkhead from the initial provided design. The lighter structure ensures increased payload, decreased engine power, reduced fuel consumption, and thus increased profit. This is a huge achievement in terms of economy as well as efficiency of a ship. The savings in terms of monetary value is provided in Section 5 of this paper.
- The obtained lighter structure has been achieved without compromising the required strength.
- As thickness cannot be reduced in the case of shell elements, we see the reduction of material has come in terms of voids in the stiffeners. The smaller voids can be ignored for conservative design. The larger ones can be achieved by CNC cutting with necessary smoothing and rounding.
- The continuous vertical stiffeners are found to be very effective. The highest stress has developed in the middle one. The other vertical stiffeners are also found effective but with a reduced area.
- The procedure encourages more complicated ship structures to be optimized.
- At present conventional design solutions with CNC plate cutting machines are possible. But futuristic design solutions may be expected by 3D printing in near future.

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