Research on Topology optimization Method for Tanker Structures in Cargo Tank Region

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Abstract

In this paper, the differences between the cargo tank structure topology optimization and structural members' scantling optimization are researched, such as the design variables, restriction conditions, load-cases, and morbidity load-case due to the significant differences between the strain energy of different load-cases. To carry out topology optimization of the cargo tank structure on the ordinary computer and to achieve clear topological configuration, it is necessary to study on the appropriate optimization objects, the property of elements, the topology methods and optimization software, the restriction conditions, the percentage of volume constriction and the weightiness factor of load-cases. The modeling methods of topology optimization fundament structures and analysis methods of topology optimization are recommended for the application on the actual engineering cases. For example, in the topology optimization of a VLCC with one centerline longitudinal bulkhead, the SIMP method (Solid Isotropic Microstructures with Penalization) and BESO method (Bi-directional Evolutionary Structural Optimization Method) are applied to achieve clear topological configurations of Primary Support Members (PSM) in cargo tanks.

1 Introduction

In the recent years, the theory and method of topology optimization are developing quickly, and application on the car production and spaceflight design step up day and day. But in the design of ship structures, the topology optimizations are rarely used. As the key technique of modern structures, innovative design, the topology optimizations are the expansion of traditional scantling optimizations and shape optimizations. Aim at the objects to develop new green, lower-energy, environment safeguard and economic ships, the topology optimizations are necessary means. At the present time, the actual topology optimization cases of cargo tank structures are absent. The main reasons are the disassociation between the theory research and engineering cases, and there are no methods to abstract the real structures from the topological configurations of cargo tank structures. The main technique difficulties are numerous and complicated, such as more design variables, more restriction conditions, more load-cases, and morbidity load-cases due to the significant differences between the strain energy of different load-cases. So these complications induce optimization calculation times that are nearly endless, the topological configurations are not clear, and it is difficult for abstraction of viable structure forms.

In this paper, the above techniques are solved in general. Using a VLCC with one centerline longitudinal bulkhead as an example, the SIMP method (Solid Isotropic Microstructures with Penalization) and BESO method (Bi-directional Evolutionary Structural Optimization Method) are applied to achieve clear topological configurations of Primary Support Members (PSM) in cargo tanks based on the load-case conditions and boundary conditions from New Common Structural Rules (CSR).

2 Mathematics and engineering modeling of cargo tank structures

2.1 Basic principle of topology optimization and selection of optimization methods

The classical criterion for optimized design of ship structure is to: Minimize the total steel weight of structures which fulfill all the strength requirements . The most common strength requirement is the fourth strength theory. Distortional strain energy is the main state variable of material. The distortional strain energy is to be described as follow:

$$e_{il}^{f} \le \frac{(1+\mu)\overline{\sigma_i}^2 V_i}{3E} \qquad (2.1)$$

Where, e_{il}^{f} Distortional strain energy of elements; μ Poisson's ratio; $\overline{\sigma_i}$ minimum yield strength of material; V_i volume; E Young's modulus. When the material is determinate, if the total element volume is to be minimized, every element stress should be maximized and be close to the minimum yield strength of material. All the element stresses should be homogeneous, and the topology optimization is necessary. The topology optimization means that the optimal structure for most and optimal transfer route of loads in the appointed area.

Two familiar topology optimization methods are introduced briefly, such as SIMP method (Solid Isotropic Microstructures with Penalization) and BESO method (Bi-directional Evolutionary Structural Optimization Method). SIMP method's resolution stability is well and had been extensively used in the software Hyperworks/Optistruct. BESO method's theory is easy to understand and program with codes. The two methods can be verified and supplement each other.

2.2 Mathematics foundation of topology optimization

2.2.1 Mathematics foundation of SIMP method

SIMP method allows the density of a material to cover the complete range of values from 0 (void) over intermediate values (composite) to 1 (solid) and this kind of composite material model is called SIMP model. For the SIMP model, the elasticity tensor E_{ijkl} and the volume of a structure are given by

$$E_{ijkl}(\rho) = \rho^p E_{ijkl}^0, \quad p > 1, \quad Volume = \int_{\Omega} \rho(x) dx \qquad (2.2)$$

Where $\rho(x), x \in \Omega, 0 \le \rho \le 1$ is a density function of the material and E_{ijkl}^0 the elasticity tensor of a given solid isotropic reference material. The density function $\rho(x)$ enters the stiffness relation in a power $p > 1$ which has the effect of penalizing intermediate densities $0 \le \rho \le 1$, shown that the use of the SIMP model will force the topology design toward limiting values $\rho = 0$ (void) and $\rho = 1$ (solid).

Restricting to 2D plane elasticity, assume that SIMP model is composed of two materials. One's density is 0(void) and another density is ρ .Then the bulk modulus k and shear modulus μ in elasticity tensor E_{ijkl} of this artificial material should satisfy the so-called Hashin-Shtrikman bounds

$$0 \le k \le \frac{\rho k^0 \mu^0}{(1-\rho)k^0 + \mu^0}, \quad 0 \le \mu \le \frac{\rho k^0 \mu^0}{(1-\rho)(k^0 + 2\mu^0) + k^0} \qquad (2.3)$$

Where, k^0 and μ^0 represents the bulk modulus and shear modulus of material with density ρ .

And the Young's modulus should satisfy

$$0 \le E \le E^* = \frac{\rho E^0}{3-2\rho}, \quad 0 \le \rho \le 1 \tag{2.4}$$

Isotropic materials have the relationship

$$k^0 = \frac{E^0}{2(1-\upsilon)}, \quad \mu^0 = \frac{E^0}{2(1+\upsilon)} \tag{2.5}$$

Substituting (2.5) into (2.3), we have

$$0 \le \frac{\rho^p E^0}{2(1-\upsilon)} \le \frac{\rho E^0}{4-2(1+\upsilon)\rho}, \quad 0 \le \frac{\rho^p E^0}{2(1+\upsilon)} \le \frac{\rho E^0}{2(1-\rho)(3-\upsilon)+2(1+\upsilon)} \tag{2.6}$$

From (2.6), the penalization power p should satisfy

$$p \ge p^*(\upsilon) = \max\left\{\frac{2}{1-\upsilon}, \frac{4}{1+\upsilon}\right\} \tag{2.7}$$

For a Poisson's ratio υ equal to 1/3, both for 2D and 3D problems a penalization power $p > 3$ in (2.7) ensures that the Hashin-Shtrikman bounds can be satisfied, so that the SIMP model can be realized as its stiffness varying with ρ and FEM singularity problem is avoided. Thus the SIMP model yield relatively nice results and this simplicity of the penalization power p facilitates the implementation of topology design in commercial finite element codes.

2.2.2 Mathematics foundation of BESO method

BESO is an evolutionary topology optimization method whose theory is relatively simple and direct. This method is based on evolutionary strategy and introduces the inclusion ratio (IR), rejection ratio (RR) and evolutionary volume ratio (ER) which are used to confirm the number of elements to be added and removed. And then by ranking the sensitivity number of the elements (normally strain energy or von mises stress), removing and adding the certain elements. Simply speaking, utilizing a suitable scheme, to add more elements where the sensitivity numbers are high and to remove more elements where sensitivity numbers are low.

The principal procedure of BESO is as follows:

1) Discretize the design domain using a finite element mesh and assign initial property values (0 or 1) for the elements to construct an initial design.

2) Perform finite element analysis and then calculate the elemental sensitivity number.

3) According to Equation 2.8 average the sensitivity number applying the filter scheme to minimize the effect of "Checkerboard and Mesh-dependency Problems"

4) Average the sensitivity number with its history information using Equation 2.9 and then save the resulted sensitivity number for next iteration.

5) Determine the target volume for the next iteration using Equation 2.10.

6) Determine the IR and RR based on V_{k+1}, and then get and. Add the elements whose $\alpha_i > \alpha_{add}^{th}$ and remove the elements whose $\alpha_i < \alpha_{del}^{th}$

7) Repeat steps 2–6 until the constraint volume $V^* = MaxRate \times V_0$ is achieved and the convergence criterion for total sensitivity number C is satisfied (Equation 2.11).

$$\alpha_i = \frac{\sum_{j=1}^{K} \varpi(r_{ij})\alpha_j^n}{\sum_{j=1}^{K} \varpi(r_{ij})} \tag{2.8}$$

Where, K is the total number of nodes surrounding the target element within the circle of radius r_{min},.

$$\alpha_i = \frac{\alpha_i^k + \alpha_i^{k-1}}{2} \tag{2.9}$$

Where, i is the element's ID and k is the current round number of the optimization.

$$V_{k+1} = V_k (1 \pm ER) \tag{2.10}$$

$$error = \frac{\left| \sum_{i=1}^{N} C_{k-i+1} - \sum_{i=1}^{N} C_{k-N-i+1} \right|}{\sum_{i=1}^{N} C_{k-i+1}} \le \tau \tag{2.11}$$

Where, τ is allowable convergence tolerance and N is an integer number. Normally, N is selected to imply that the change in the mean compliance C over the last N iterations is acceptably small.

One advantage of BESO is that it could take account of the effect of the distribution of sensitivity number at design field and non-design field. In this way the optimized shape around the field of boundary could be smoother. Nevertheless, since the convergence criterion of BESO is volume fraction, it is hard for it to take account of displacement, buckling and other structural design factors. Besides, the efficiency of BESO is relatively lower than that of SIMP and the optimized results relies greatly on the initial shape.

The initial shape of the design field plays a great role in determining the final volume fraction and iteration efficiency. If at the very beginning, removing some redundant design field based on preliminary structural judgment, the optimization efficiency and result could be much better. For different optimized object, it is hard to simply determine a suitable volume fraction. This value needs to be determined by repetitive tests and experience.

Although there are some negative aspects of BESO, it is still a good method to get an ideal optimized result only if a suitable design field and volume fraction has been selected.

2.3 Selection of optimization objects and elements of FE analysis in oil tanker structures optimization

2.3.1 Select of research object for topology optimization

As topology optimization is an iterative process, the calculation data would be enormous and the calculation process would be time-consuming. And for a general large and medium size oil tanker, the results of cargo hold analysis should meet the requirements of HCSR rules, thus it would consume a lot of time completing rule computation once. For those reasons, time-consuming problem for the iterative process can't be completely solved even when the evolutionary algorithms are applied to solve the combination explosion problem. In order to complete the topology optimization calculation on general microcomputers, a series of non-essential structures are ignored in this paper. And the research object is selected by the basic principles of topology optimization, engineering practice experiences and engineering constraint conditions, thus topology optimal structure with good manufacturability can be obtained from a selected model with reasonable calculation amount.

According to basic theory of mechanics, when tensile stress or compressive stress is applied to finite elements, stress and size of the finite element can be homogenized simultaneously, and the topology optimal structure tends to minimize shear stress in itself, which can change the structure from shear bearing form into tensile or compressive bearing form. But when lateral loads are applied to planar structures, large shear stress appears inevitably, and the shear stress can't be totally transformed into tensile or compressive stress, which may lead to uneven distribution of stresses in structure.

For the reason mentioned above, the planar bulkheads of deep tank don't conform to the mechanism of topology optimization. Therefore, on the premise of enough hold capacity, the area of planar bulkheads of deep tank should be minimized or the planar bulkheads should be changed into curved bulkheads, while the number of bulkheads of deep tank should meet the requirements of IMO rules. In fact, changing planar bulkheads into curved bulkheads will be rejected firmly by the shipyard, because it will increase large amount of work.

In the topology optimization of oil tank cargo hold structure process, the number of deep tank bulkheads should be as least as possible on the basis of topology optimization theory, and two measures can be taken to achieve that goal, such as deleting one of the two longitudinal bulkheads in VLCC, or reducing transverse bulkheads in some oil tankers on the premise of satisfaction of rules. But on the other hand, the knuckle line of cargo hold, the height of inner bottom, and the width of double hull depend more on requirements of general arrangement, cargo hold capacity, and calculation of oil spill. Structural optimization design is one of the constraints, but it is not the most crucial one. The final decision is made by the general designer. Structural designers can submit an optimal project obtained with theory of classical mechanics or calculated with three dimensional beam system to the general designer, who will consider different situations to decide to adopt the project or not. Therefore, the longitudinal strength bulkheads of oil tanker were not selected as topology optimization object in this paper. Sometimes the general arrangement plan may have disadvantages for structural lightweight design, and in these situations topology optimization has more significant effect. Structural designers should make the best use of advanced design technology, and minimize the adverse impact of different constraints.

Considering the requirements of simplification process, the space between web frames or longitudinals should not be selected as topology optimization object either. Otherwise, there will be too many kinds of longitudinals and plates, which will increase the cost of management and manufacture greatly. Within one single cargo hold, the optimal space of equally spaced longitudinals or web frames is convenient to obtain with theory calculations, so it is not necessary to optimize the space value. The design and arrangement of longitudinal strength structures can be completed with rule computation software, and it's not selected as optimization object either.

Above all, primary supporting members in cargo holds, including all the transverse webs and horizontal stringers were selected as topology optimization objects in this paper.

2.3.2 Topology optimization elements of FE analysis

It’s different from the 3D solid elements’ topology optimization，the elements of three cargo hold FE analysis and topology optimization are 2D shell elements and 1D beam elements. The ship structures are be simulated use shell and beam elements in general. Though they are 3D structure in miniature, the macrostructures are 2D type. In traditional FEA, the web plate of primary support members are simulated use shell elements, the flange plates of primary support members (ab. PSM) and buckling stiffeners on PSM’s web plate are simulated use beam/rod elements. The elements of topology optimization are also to be like that, otherwise the topology optimization calculation times will be too long to endure.

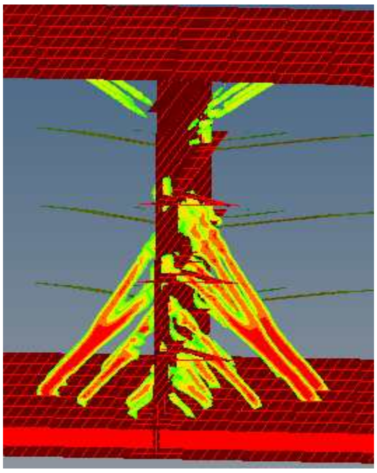
The authors also tries to add some rod elements in the shell elements’ edges to simulate the flange plates of PSM and buckling stiffeners in the topology analysis process. But the result are unsuccessful——most of shell elements are deleted and rod elements are reserved, also the topological configuration is unviable for shipyard workman.

In any case, the flange plates of PSM and buckling stiffeners are to be simulated as additional thickness on the shell elements in some equivalent manners, such as equivalent section areas. The thicknesses of topology basic structures are to be the PSM’s web plate thickness multiply by magnified factor. The factor should be different for different ship types and structure areas.

2.4 Selection of topological field in topology optimization

The topology basic structures in topological field should be defined firstly, and include the entire possible topological configuration. According to the preamble, all the transverse webs and horizontal girders in cargo hold are to be taken as the topology objects. And because the longitudinal members are not taken as the topology objects, the stress restrictions on them will not be take into account to reduce the calculation time. In this case, The PSM to support them may be lost somewhere in optimization procedure because they may not be on the main load transfer route which is in accordance with the mechanism of topology optimization. *See figure 1*. The vertical girder is lost after the topology optimization, but this result can’t be accepted by designer in practice.

Consequently, the vertical girders, deck webs and horizontal girders with minimum depth will be kept inevitably, and they will inflect the distribution of the entire cargo hold structures’ distortional strain energy. So we need try to take the vertical girders, deck webs and horizontal girders with certain depths as the unalterable elements. What’s more, these depths should be calculated based on HCSR and iterated improvement several times until that will not affect the topological configurations. The other areas except the unalterable elements should be taken as topological field and fulfilled with shell elements as following *figure 2*.



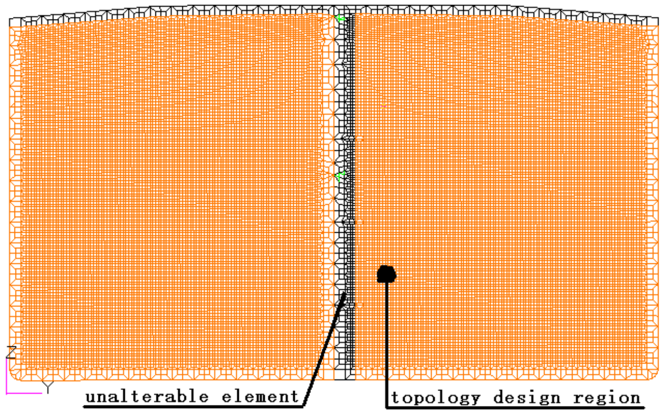


Fig.1 Topological configuration when no topological field restriction

Fig. 2 Topological fields in transverse webs

For the general tanker structures, the topological fields distribute discretely on the 6~8 transverse webs and 2~3 horizontal girders. The topological configurations of them are to be related together according to certain rules or not? In the start of topology optimization, to research every inch, all the topological fields should be unattached to each other. But to reduce the workmanship of shipyards, it also be permitted for the conjunction of different design regions according to certain rules. As shown in *figure 3*, symmetrical to the centerline of cargo hold in long direction, the two similar transverse webs are assembled together with same topological configuration. The topological configurations of horizontal girders can also be assembled together or divided into two topological fields.

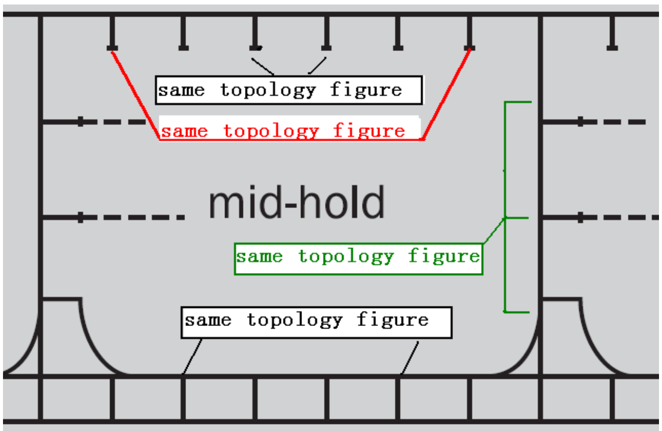


Fig. 3 Assemble relations between different topological fields

2.5 Optimization models of oil tanker cargo structures' topology optimization

2.5.1 Optimization models of SIMP method

The general formulation to solve a ship structure optimization problem means to find a combination of the vectors of design variables $\mathbf{X}=[x_1,x_2,\cdots,x_N]^T$ defining the structure which optimizes the objective function. An essential task of the ship structure optimization is to reduce the hull structure weight, consequently the minimum weight is assumed as an objective function. The design variables should also meet the complex set of constraints imposed on their values. Therefore the mathematical formulation of the optimization problems reads:

$$\begin{cases} Find \quad \mathbf{X}=[x_1,x_2,\cdots,x_N]^T \\ minimize \quad f(\mathbf{X})=W(\mathbf{X}) \\ subject \quad \mathbf{K}(\mathbf{X})\mathbf{U}(\mathbf{X})=\mathbf{F} \\ \qquad\qquad \boldsymbol{\sigma}(\mathbf{X})\text{-}[\boldsymbol{\sigma}]\le\mathbf{0} \\ \qquad\qquad \dfrac{V(\mathbf{X})}{V_0}\le f \\ \qquad\qquad 0<x_{\min}\le x_e\le x_{\max}\le 1 \end{cases} \tag{2-12}$$

With the SIMP method, the material density is used as the design value, and varies between $x_{\min}$ and $x_{\max}$. X is a vector of N design variables, K, U and F are the stiffness matrix, the global displacement vector and the load vector. $\mathbf{K}(\mathbf{X})\mathbf{U}(\mathbf{X})=\mathbf{F}$ expresses that the design variable should satisfy the well-known linearly elastic equilibrium equation. von Mises stress constraints $\boldsymbol{\sigma}(\mathbf{X})\text{-}[\boldsymbol{\sigma}]\le\mathbf{0}$ for the model are considered based on the HCSR rule. Volume fraction $V(\mathbf{X})/V_0=$design volume at current iteration/initial design volume which describes a fraction of initial design space is also constrained. In practice, too small the upper limitation *f* makes the optimized structure looks like a slender beam which can hardly fulfill the buckling criteria in HCSR rule, on the other hand, too large the *f* will significantly increases the calculation time and usually makes the optimized structure fuzzy and indistinct. Therefore *f* is assumed based on trial calculations and be selected between 0.13~0.5 case by case to achieve sharp and clear results.

2.5.2 Optimization steps of BESO method

Based on the theory described in 2.2.2, BESO method is applied by the following steps:

1) Matlab is used as a control platform for data processing, iteration monitor and result judgment;
2) Combine Msc.Patran and PCL to achieve:
   a) Automatic FEM analysis results and other parameters;
   b) Based on the method of BESO, calculate sensitivity number of each element and judge which should be added and removed;
   c) Update the FEM model and generate analysis file(*.bdf);
3) Apply Nastran to analyze and get FEM result.

Evolutionary volume ratio(ER) can be taken about 5% when the volume fraction is above 40% (different due to scope of initial topology field) and 1% when the volume fraction is below 40%. It should be noted that the MaxRate is the only parameter and constraint of BESO for the control of optimization result. Different MaxRate will directly lead to different result. However, it is hard to determine its value just based on experience for different design field, structural type. Based on a lot of pilot calculations, the MaxRate should be under 20%. Nevertheless, its specific value could only be determined by enumerated calculation for different value step by step and then compared by the designer manually.

3 Definition of Structural Model, boundary conditions and load conditions in cargo tank FEA

3.1 Structural Model and boundary conditions

This section meets the requirements of HCSR fully. Structural Model is to see *Figure 4*. The Boundary Constraints at Model Ends are to see following *Table 1*.

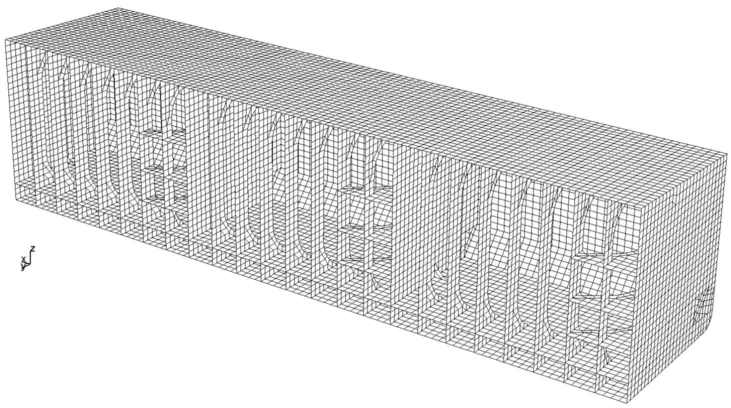


Fig. 4 Typical 3-Cargo Hold Models within Midship Region of Oil Tankers

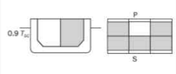
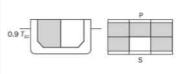
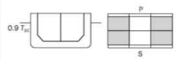
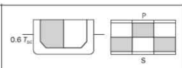
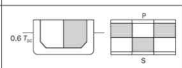
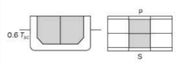
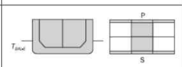
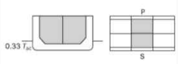
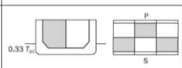
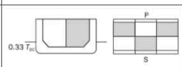
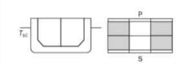
Table 1 Boundary Constraints at Model Ends

Location	Translation			Rotation		
	δ_X	δ_Y	δ_Z	θ_X	θ_Y	θ_Z
Aft End						
Crosssection	-	Rigid Link	Rigid Link	Rigid Link	-	-
Independent point	-	Fix	Fix	M_{T-end}	-	-
Cross section	End beam					
Fore End						
Crosssection	-	Rigid Link	Rigid Link	Rigid Link	-	-
Independent point	-	Fix	Fix	Fix	-	-
Intersection of CL&IB	Fix				-	-
Cross section	End beam					
Where: - no constraint applied (free)						

3.2 Load conditions and assembled coefficient

This section is mainly due to the requirements of HCSR.

Table 2 Load combinations for FE analysis for one centerline oil-tight bulkheads oil tankers

No.	Loading pattern	Still water loads			Dynamic load cases		
		Draught	C_{BM-LC} : % of perm. SWBM	C_{SF-LC} : % of perm. SWSF	Midship cargo region		
Seagoing conditions							
B1		$0.9T_{SC}$	100% (sagging)	100%	HSM-1 HSA-1	BSP-1P/S	N/A
			100% (hogging)	100%	HSM-2 FSM-2	BSR-1P BSP-1P	OST-2P
B2		$0.9T_{SC}$	100% (sagging)	100%	HSM-1 HSA-1	BSP-1P/S	N/A
			100% (hogging)	100%	HSM-2 FSM-2	BSR-1S BSP-1S	OST-2S
B3		$0.9T_{SC}$	100% (hogging)	100% (3) Max SFLC	HSM-2 FSM-2	N/A	N/A
				100% (4) Max SFLC	HSM-2 FSM-2	N/A	N/A
				100%	N/A	BSP-1P/S	N/A
			0%	100% (5) Max SFLC	HSM-1 FSM-1	N/A	N/A
B4		$0.6T_{SC}$	100% (sagging)	75%	HSM-1	BSP-1P	OSA-2P/S
B5		$0.6T_{SC}$	100% (sagging)	75%	HSM-1	BSP-1S	OSA-2P/S
B6		$0.6T_{SC}$	100% (sagging)	100% (3) Max SFLC	HSM-1	N/A	N/A
				100% (4) Max SFLC	HSM-1	N/A	N/A
				100%	N/A	BSP-1P/S	N/A
			0%	100% (5) Max SFLC	HSM-2	N/A	N/A
B7		T_{BAL-E}	100% (sagging)	100%	HSM-1	BSP-1P/S	N/A
Harbour and testing conditions							
B8		$0.33T_{SC}$	100% (sagging)	100% (1) Max SFLC	N/A		
				100% (2) Max SFLC	N/A		
B9		$0.33T_{SC}$	100% (sagging)	75%	N/A		
No.	Loading pattern	Still water loads			Dynamic load cases		
		Draught	C_{BM-LC} : % of perm. SWBM	C_{SF-LC} : % of perm. SWSF	Midship cargo region		
B10		$0.33T_{SC}$	100% (sagging)	75%	N/A		
B11		T_{SC}	100% (hogging)	100% (1) Max SFLC	N/A		
				100% (2) Max SFLC	N/A		

(1) The shear force is to be adjusted to target value at aft bulkhead of the mid-hold.
(2) The shear force is to be adjusted to target value at forward bulkhead of the mid-hold.
(3) For the mid-hold where $x_{b\text{-}aft} \le 0.5L$ and $x_{b\text{-}fwd} \ge 0.5L$, the shear force is to be adjusted to target value at aft bulkhead of the mid-hold.
(4) For the mid-hold where $x_{b\text{-}aft} \le 0.5L$ and $x_{b\text{-}fwd} \ge 0.5L$, the shear force is to be adjusted to target value at forward bulkhead of the mid-hold.
(5) This load combination is to be considered only For the mid-hold where $x_{b\text{-}aft} > 0.5L$ or $x_{b\text{-}fwd} < 0.5L$.

Not all the load conditions will affect the cargo hold structures scantling significantly. To reduce the calculation time, the most advanced existing ship should be analyzed for all the load conditions before the topology optimization. It should be estimated which ones are the key load conditions to determine the scantlings, which ones are secondary and which ones are unconsidered. But if the topological configurations are distinctly different from the existing ship structural form, No load conditions are unconsidered at the start of topology optimization unless they are proven to be replaced by other load conditions.

Because the topology optimization is a bran-new, time-consuming work, extensive test calculations are necessary. A few key load conditions are selected to carry out sensitivity analysis with some optimization parameters (sizing grid, elements thickness, scopes of unalterable elements, stress restriction, assemble forms of topological configurations) changed in certain ranges, so the most appropriate values of optimization parameters are confirmed before the all load condition calculations.

It's different for SIMP method and BESO method in the selections and assembled coefficients of load conditions. They will be introduced as follows.

3.2.1 Load combinations for topology optimization using SIMP method

For Altair Hyperworks/Optistruct solves topological optimization problems using SIMP method, the hull structure topology optimization is firstly performed using this commercial code. On this software platform, multiple sub-cases (loading patterns) can be considered, by default, they have the same calculation weight and cannot be modified. In order to keep stable convergence, the optimization procedure tends to minimize the global compliance and retain the smallest number of stress constraints using constraint screening algorithm automatically, thus some strange structures may appear in the results e.g., long slender beam-like structures with low stress level.

Consider the loading patterns of a double hull oil tanker with one longitudinal bulkhead, some loading pattern with cargo oil alternatively loaded along the ship length may have large strain energy while the maximum von Mises stress in transverse structure members is relatively low, on the contrary, some loading pattern with cargo oil loaded asymmetrically may have small strain energy but the stress level in the transverse structural members is high. Although the objective function is set to minimize the hull weight, a slender vertical beam-like structure throughout the entire cargo hold depth is usually generated in the optimization results when the loading patterns with large strain energy are included in the optimization subcases. Neither can this kind of slender structure be easily produced nor can it easily meet the buckling strength requirement of the HCSR rule.

Through multiple calculations, it is found that the vertical slender beam-like structures are easily generated in loading patterns B3 and B11 whether the optimization object is set to minimize the weight or the global compliance. For loading patterns B6,B7 and B8, the slender beam-like structures appears when the objective function is set to minimize the global compliance, but disappeared when the objective function is set to minimize the weight. Loading patterns B3 and B11 may be the dominant loading patterns of bottom shell and longitudinal bulkhead plates to meet the buckling strength and shear strength criteria, they are most probably the dominant loading patterns for longitudinal structural members, thus, in transverse structural member topology optimization they are considered as interference subcases and have to be abandoned. The influences of these load patterns will be considered in shape and scantling optimization later.

3.2.2 Load combinations for topology optimization using BESO method

BESO has an obvious advantage when dealing with multiple load case for its simple theory and flexible adjustment to the program by the designer according to different requirements.

Applying a weighting factor to different load cases is a usual method for this problem. However, it is hard to determine which load case is more critical than the others. While applying the equal weighting factor will ignore some special cases especially when the sensitivity numbers of these cases are relatively lower than the others for asymmetric load reason. For example, as asymmetric load cases, the high transforming or high stress area of B1 and B2 are almost half of those for B3 and B6, the symmetric cases. Thus, in order to minimize this unfair average, the following equation for determining the weighting factor shall be used:

$$\lambda = \frac{Max(e_{sumFE\_P}^{case.i}, e_{sumFE\_S}^{case.i})}{\sum_{i=1}^{n} Max(e_{sumFE\_P}^{case.i}, e_{sumFE\_S}^{case.i})}$$

Where, $e_{sumFE\_P}^{case.i}$ and $e_{sumFE\_S}^{case.i}$ are the subtotal of sensitivity number for port or starboard side of elements for the *ith* load case.

4 Brief introductions of topology optimization results in a VLCC with one centerline longitudinal bulkhead and applications on others oil tanker

On the basis of topology optimization theory, SIMP method and BESO method were applied separately to obtain PSM's topological configuration in a VLCC with one centerline longitudinal bulkhead, and then shape optimization and size optimization were carried out. All the structural drawings in cargo holds and calculation reports had been approved by ABS, which means topology optimization technology had achieved success in structural optimum design. The new structures designed by topology optimization method are much lighter than traditional structures, and much easier to manufacture. Also an invention patent is achieved according the research conclusion. The parameters are shown in following *table 3*.

Table 3 Typical parameter comparisons between VLCC with One centerline BHD and traditional VLCC

Ship type / Compared subjects	VLCC with One centerline bulkhead	Traditional VLCC	Comparisons (%)
Number of CH	12	15	80%
Number of transverse BHD	6	5	120%
Number of wash-BHD	0	4	—
Number of transverse webs	38	41	92.7%
Total effective cross-sectional area of longitudinal strength members(m^2, only based on HCSR, without FEA-based modifications)	9.5285	10.555	90.3%
Total length of the longitudinal plate cross section (m)	341.2	377.8	90.3%
Total number of longitudinals	374	415	90.1%

transverse webs space		5.95	5.66	105.1%
Surface areas of typical transverse webs (m^2)	SIMP	575.8	731.8	78.7%
	BESO	643.3		87.9%
Averaged weight of typical transverse webs (ton, except for wash BHD)	SIMP	100.8	143.14	70.4%
	BESO	111.3		77.8%
maximum designed still water bending moment (kN*m)		8,450,000	7,600,000	111.2%
Structural weight per meter in cargo hold (ton)	SIMP	111.75	127.3	**87.8%**
	BESO	112.55		**88.4%**

According to real ship design experience, the optimal structures obtained with SIMP method are simpler to manufacture and lighter in weight. When the structural drawings and calculation reports were submitted to ABS, the classification society was in agreement with this statement. On the other hand, there still exist some unsolved problems which will be mentioned in the next section.

The success of ship structural topology optimization depends on whether the result is convergent or not, whether the result is in accordance with the basic principles of classical structural mechanics or not, and whether the result is similar to mature ship structures or not. According to the definition of topology optimization, for the topology results that converge to low volume fraction tend to be like frame structures and truss structures. But for the structures with high initial strain energy, the optimal topology results are mainly composed of continuous structures which contain many holes. The topology optimization results of structures of VLCC with one centerline longitudinal bulkhead are in accordance with these mechanical rules. The optimal topology structure in cargo hold seems like the capital letter '*K*', while the optimal topology structures in bottom and side structures is continuous in geometry except for some holes. The typical transverse webs, horizontal stringers and corresponding structural drawings obtained with SIMP method are shown in *Figure 5* to *Figure 8*. The typical transverse webs and corresponding structural drawings obtained with BESO method are shown in *Figure 9* to *Figure 10*. The comparisons of outlines of typical webs and horizontal stringers between traditional VLCC and VLCC with one centerline longitudinal bulkhead are shown in *Figure 11* to *Figure 12*.

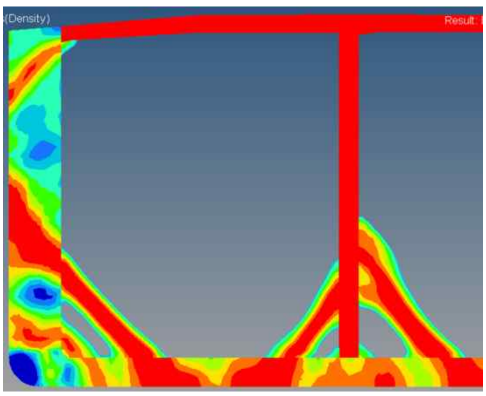


Fig.5 Typical topological configuration of web frame based on SIMP method

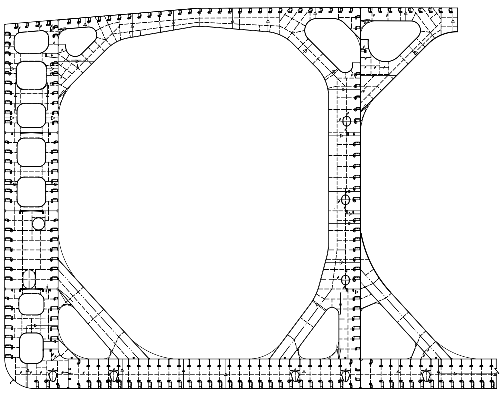


Fig.6 Drawing of typical topology optimal of web frame based on SIMP method

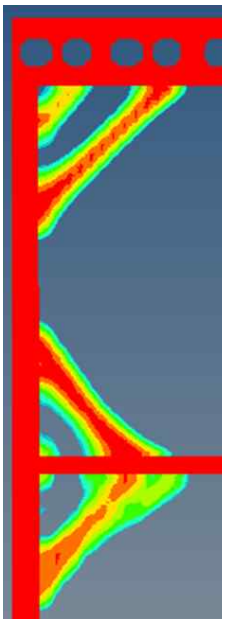


Fig.7 Typical topological configuration of horizontal stringer based on SIMP method

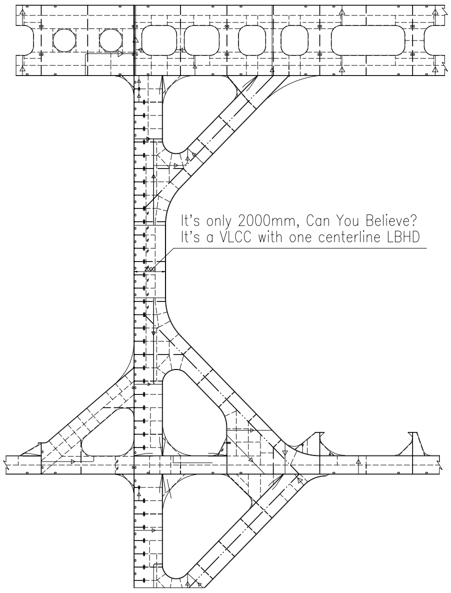


Fig.8 Drawing of typical topology optimal of horizontal stringer based on SIMP method

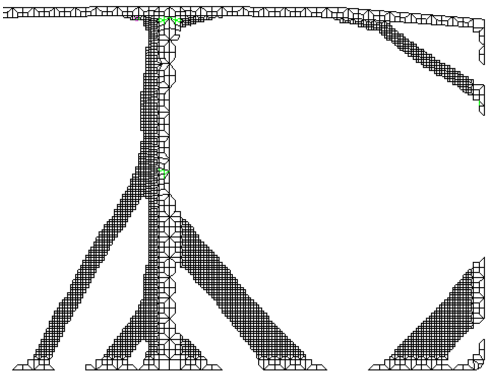


Fig.9 Typical topological configuration of web frame based on BESO method

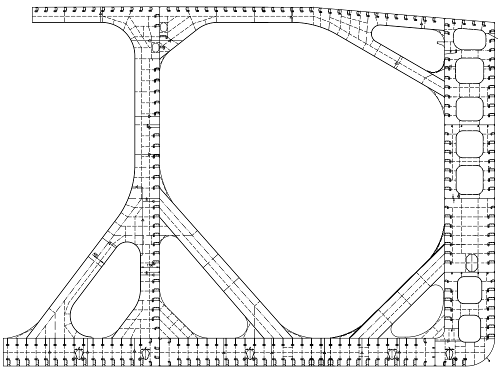


Fig.10 Drawing of typical topology optimal of web frame based on BESO method

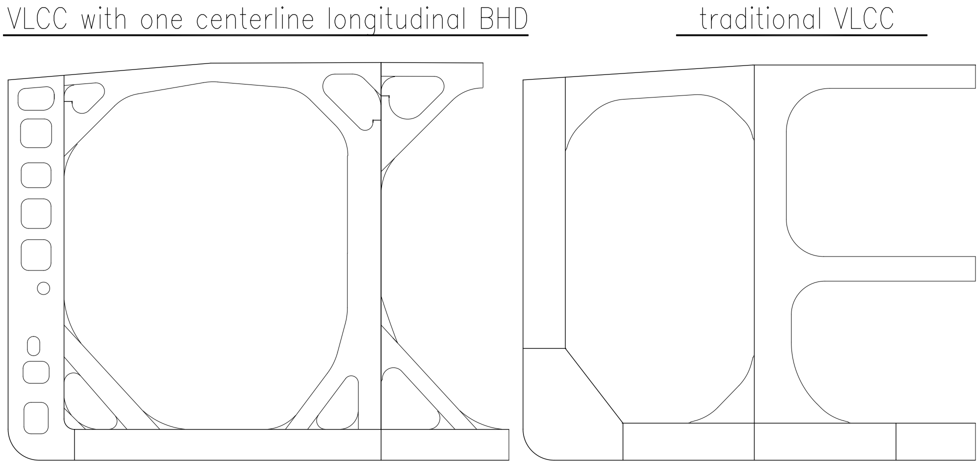


Fig.11 Comparison of typical web outlines between traditional VLCC

and VLCC with one centerline longitudinal bulkhead

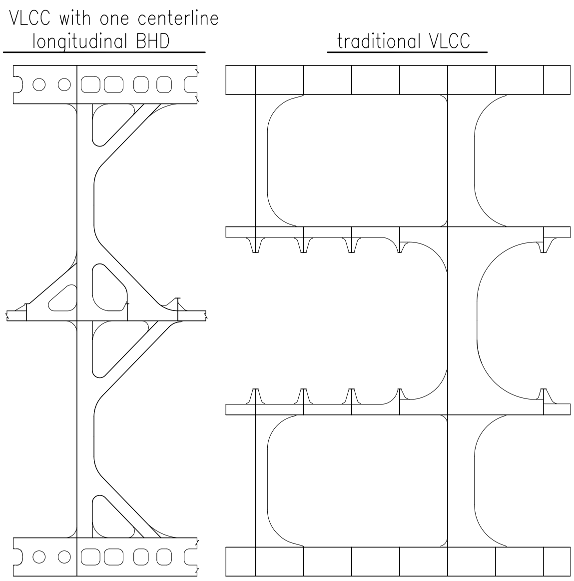


Fig.12 Comparison of typical horizontal stringer outlines between traditional VLCC

and VLCC with one centerline longitudinal bulkhead

Topology optimization technology can also be applied to new ship development of other kinds of oil tankers. Based on the basic theory of topology optimization and experiences achieved from development of a VLCC with one centerline longitudinal bulkhead, improved designs of cargo hold structures in Panamax oil tanker, Aframax oil tanker and Suezmax oil tanker were completed by MARIC, and the new developed structures satisfy HCSR, meanwhile are about 1.1 percent to 3.6 percent lighter in weight than traditional CSR structures. The comparisons of typical web frames between Aframax oil tanker satisfied with topology optimization theories and traditional oil tanker are shown in *Figure 13.* The knuckle line of inner hull bulkhead was adjusted slightly according to topology optimization theories, the ends of vertical girders and deck transverses tend to like truss structures, and the holes in side double hull structures are more and bigger. But in general, the differences of structures between new developed Aframax oil tanker and traditional Aframax oil tanker are not enormous.

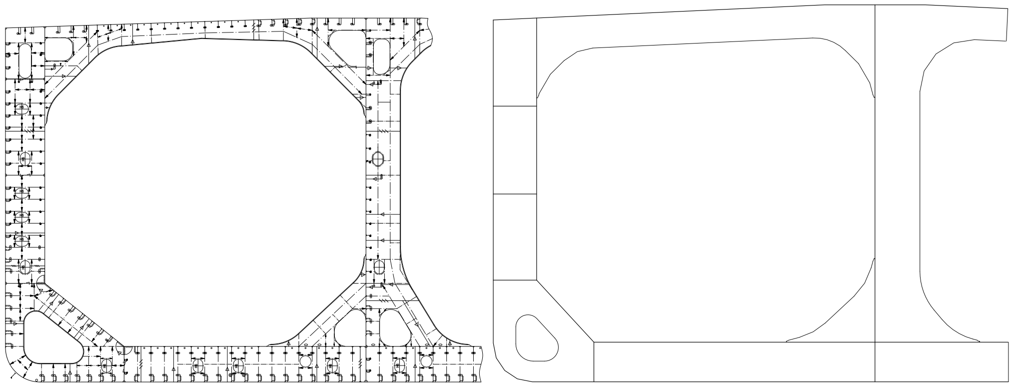


Fig.13 Comparison of typical web frame between Aframax oil tanker developed based on topology optimization and traditional Aframax oil tanker

5 Questions to be resolved in the future

5.1 The model test of bran-new structures

In the case that the topological configurations are similar to the existing ship structures except that there are more openings with large areas are in the low stress region and the shape of primary support member of cargo hold is more close to shape of *"K" see Figure 13*. The model test of structure could be avoided. However, if the topological configurations are completely different from the existing ship structure, the reduced-scale model test of local structures should be conducted as far as possible except that a series of detailed and intact calculation is done to persuade the ship-owners of a bran-new design. *see figure11 and figure 12.*

5.2 Application of solid elements on topology optimization

It is reasonable that 2D shell elements are used in topology fields in the start of topology optimization to improve the efficiency of topological operations. The flange plates of PSM are very important for PSM to bear the lateral pressure, but the shell elements cannot describe the positions and dimensions of the flange plates in topology fields. Therefore, before the shape optimization, it is necessary to carry out a topology optimization of typical transverse webs using solid elements. It is an essential extension of a 2D topology optimization in general.

The authors had picked out a typical primary support member on port side to perform a topology optimization by using the mixed shell and solid elements. In order to simulate the flange, the size of solid element is set to about 100x100x50mm(LxBxT), as a result, the optimization procedure is time consuming and the topological configuration after convergence is also not so ideal, *see figure 14*, but it also can give some useful hints to the designer, like as the setting routes and scantlings of flange plates. Because the calculation numbers of samples are too less to extensively represent the entire load cases. The mesh size is also not so accurate to satisfy the requirement of engineering instantiation. This is one of important problems which is to be resolved in the future.

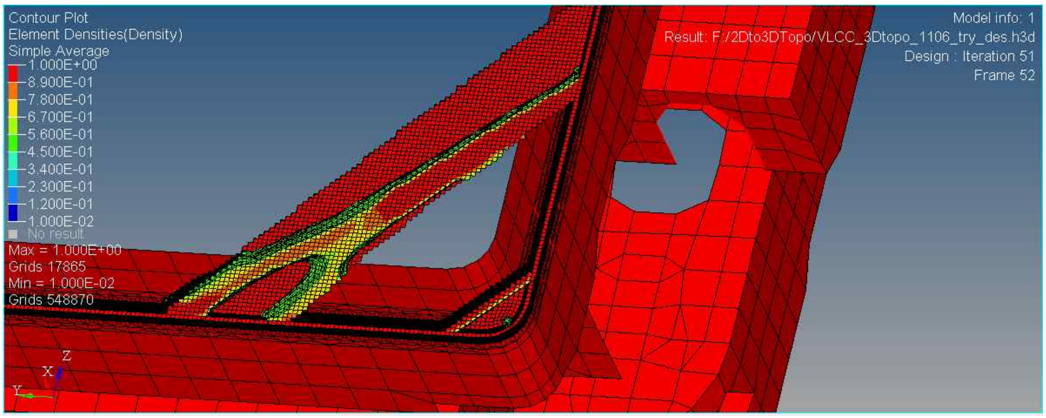


Fig.14 topological configuration of mixed shell elements and solid elements

5.3 Problems in the cargo structures' topology optimization

1. When software Hyperworks/Optistruct (SIMP method) is used in the cargo structures' topology optimization, the stress restrictions are not convenient to select. The definition of stress constraints can only be limited to single von Mises permissible stress and stress constraints cannot apply to 1D element. It's also difficult to freely select the elements satisfied with stress restrictions in the unalterable region. The stress restrictions are to be solved in the shape optimization, and the local geometrical shape parameters in the high stress areas are to be adjusted to reduce the peak stress.

2. Some key parameters in software Hyperworks/Optistruct cannot be changed, which is not convenient for the ship structures' topology optimization. Such as the assembled coefficient of the load cases, the overrun ratio of element stress, etc. In the topology optimization, some load cases which induce high strain energy but lower peak stress value are abandoned, and thus the result's applicability is limited.

3. It is not recommended to use mass of the entire model as an objective neither in SIMP optimization method nor in BESO method, for too large the global mass makes the objective function less sensitive towards design modifications made in the optimization. Also both the yield strength and buckling strength cannot be taken as restriction at the same time. These problems are to be solved in the phase of scantling optimization.

6 Conclusions

In this paper, the advanced structure topology optimization theories, methods and software have been adopted to achieve the optimization objective i.e. minimizing the weight of hull structures. The calculation is in accordance with HCSR, during which the difficulties such as huge calculation model of topology optimization, numerous loading conditions for calculation and the interference of ill-conditioned load cases have been overcome. In the end a topology optimization structure of tanker's cargo hold which can be applied to practical engineering design is provided .Taking the VLCC with one centerline longitudinal bulkhead as a specimen ship, the topology optimization and design for typical web frames and horizontal stringers in cargo hold has been done, and the methods also has been applied to developing new ship types for other large crude oil tanker which is in compliance with HCSR.

Although there are some defects in the software and process of topology optimization in some measure, relatively ideal topological configurations through the two topology optimization methods are obtained .Until now, no numerical optimization procedure can guarantee that global optimum result for large-scale optimization problem could be achieved, accordingly the structure configurations derived by topology optimizing may not be the most optimal solution using these methods, but they are thought to be very close to the most optimal solution.

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