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Optimal dimension design of a hatch cover for lightening a bulk carrier

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ABSTRACT: *According to the increase of the operating cost and material cost of a ship due to the change of international oil price, a demand for the lightening of the ship weight is being made from various parties such as shipping companies, ship owners, and shipyards. To satisfy such demand, many studies for a light ship are being made. As one of them, an optimal design method of an existing hull structure, that is, a method for lightening the ship weight based on the optimization technique was proposed in this study. For this, we selected a hatch cover of a bulk carrier as an optimization target and formulated an optimization problem in order to determine optimal principal dimensions of the hatch cover for lightening the bulk carrier. Some dimensions representing the shape of the hatch cover were selected as design variables and some design considerations related to the maximum stress, maximum deflection, and geometry of the hatch cover were selected as constraints. In addition, the minimization of the weight of the hatch cover was selected as an objective function. To solve this optimization problem, we developed an optimization program based on the Sequential Quadratic Programming (SQP) using C++ programming language. To evaluate the applicability of the developed program, it was applied to a problem for finding optimal principal dimensions of the hatch cover of a deadweight 180,000 ton bulk carrier. The result shows that the developed program can decrease the hatch cover's weight by about 8.5%. Thus, this study will be able to contribute to make energy saving and environment-friendly ship in shipyard.*

KEY WORDS: Hatch cover; Hull structure; Lightening; Optimization; Bulk carrier; Environment-friendly ship.

INTRODUTION

Background of this study

Recently, according to the increase of the operating cost and material cost of a ship due to the change of international oil price rise, a demand for lightening the ship weight is being made from various parties such as shipping companies, ship owners, and shipyards. For example, it is known that in case of ship over 40% of total operating cost is caused by fuel cost (Journee and Meijers, 1980). To satisfy such demand, many studies for a light ship are being made like other vehicle industries such as automotive industry (Oujebbour et al., 2014). Some of them include the optimal design of an existing hull structure, the proposal of a hull structure having new concept, the application of composite materials such as Fiber Reinforced Plastic (FRP) to a hull

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structure, and so on. Among them, the former studies are producing actual and effective results due to their high possibilities of weight reduction. Thus, an optimal design method of an existing hull structure, that is, a method for lightening the ship weight based on the optimization technique was proposed in this study.

First, a target for optimization, that is, ship type and hull structure to be applied was selected in this study by considering the followings and requirements of shipyards. Even though the Baltic Dry Index (BDI) value had a sudden fallen after America's financial crisis in 2009, but it has been rising recently. It is expected that such a rise of BDI can lead to an increase in demand of a bulk carrier (ship for carrying dry cargo, hereafter referred to as B/C) and an increase in order quantity from the ship owners.

The hatch cover which covers cargo tanks of the B/C is very important part. In the B/C, the cost of hatch cover equipment is accounting for 5~8% of shipbuilding cost (Ha, 2011), and various types of hatch covers are being applied according to the ship type. That is why as well as domestic companies, foreign companies in Europe and Japan also have been competing in the market. To survive the fierce competition in the lightening design of the hatch cover, many efforts have being made in technology development.

The optimization technique is based on iterative design and review to find an optimum with some design considerations (called constraints) by minimizing or maximizing a certain criteria (called objective function). As the objective function and constraints become diverse and subdivided, the optimization technique is getting more and more difficult to be performed by hand; it requires a lot of time. Thus, the importance of automation has increased and a variety of optimization techniques have being studied. With this, an optimization problem which is comprised of design variables, constraints, and objective function(s) should be well formulated to yield a good optimum.

In this study, with two requirements of the structural safety and weight reduction, a hatch cover of a bulk carrier was selected as an optimization target, and the optimization technique was applied to determine optimal principal dimensions of the hatch cover. For this, an optimization problem to determine optimal principal dimensions of the hatch cover was mathematically formulated. Some dimensions representing the shape of the hatch cover were selected as design variables and some design considerations related to the maximum stress, maximum deflection, critical buckling stress, and geometry of the hatch cover were selected as constraints. In addition, the minimization of the weight of the hatch cover was selected as an objective function. To solve this optimization problem, an optimization program based on the SQP was developed with C++ programming language. To evaluate the applicability of the developed program, it was applied to a problem for finding optimal principal dimensions of a deadweight 180,000 *ton* bulk carrier.

Related works

Many studies related to an optimal design method of a hull structure such as longitudinal and transverse strength members have been made since 1960s. Moe and Lund (1968) proposed an optimal design method for longitudinal strength members of a tanker having minimum cost and weight according class rule and Moe (1969) studied an optimal design method for statically indeterminate frames based on nonlinear programming. Na et al. (1985) proposed an optimal design method for transverse strength members having minimum weight based on finite element analysis. Jang and Na (1996a; 1996b; 2000) developed an optimal structural design system for double hull tankers. Their research include an optimal design method for longitudinal strength members of a tanker having minimum weight according the DNV class rule, an optimal design method for transverse strength members having minimum weight based on the generalized slope deflection method, and an optimal design method for whole hull structure having minimum weight by considering tank arrangement. Yum (1990) proposed an optimal design method for a corrugated bulkhead of a B/C having minimum weight based on the generalized slope deflection method. Lee et al. (2002) studied an optimization technique for optimal structural design of midship section of a tanker and a corrugated bulkhead of a B/C based on the hybrid optimization algorithm. Jung (2008) studied on minimum weight design of transverse strength members of a B/C based on finite element analysis (ANSYS). Lim (2009) proposed an optimal design method for panel blocs of a double hull tanker having minimum weight based on the genetic algorithm and finite element analysis (NASTRAN) by considering structural safety and productivity.

Some studies related to design of a hatch cover have been also made. Han et al. (2002) studied on a method for lightening a hatch cover of a large-size container ship based on finite element analysis (PATRAN and NASTRAN). They proposed an improved design for the hatch cover where buckling stiffeners are removed under less stress and the thickness of the top plate of the hatch cover are changed, and however they did not use any optimization technique to do that. Lee et al. (2010) studied the behavior of global bending deflection caused by welding while the production hatch covers of a container ship. At this time, they used thermoelastic analysis for bending analysis of the hatch cover. Ha (2011) studied on the design of a hatch cover of a dry cargo ship for reducing its weight. He assumed most severe conditions for design loads of an open girder structure of the hatch cover and performed analytical approach through finite element analysis.

Many researches related to an optimal design method of a hull structure have been made but most of them focused on optimization of longitudinal and transverse strength members. Moreover, some of them related to design of a hatch cover focused on its design improvement based on finite element analysis or global bending behavior based on thermoelastic analysis without any integration with optimization technique.

Thus, one of methods for lightening the ship weight based on the optimization technique was proposed in this study. Especially, this study focused on a hatch cover which is one of core parts in a B/C, and thus the hatch cover of the bulk carrier was selected as an optimization target. For this, an optimization problem in order to determine optimal principal dimensions of the hatch cover was formulated, and then an optimization program was developed.

The reminder of this paper is organized as follows: Section 2 gives the mathematical formulation of an optimization problem for finding optimal principal dimensions of a hatch cover. Section 3 gives detailed description of the developed program for optimal design of the hatch cover, based on the mathematical formulation of optimization problem in Section 2. Section 4 shows the comparative test of the selected optimization algorithm for optimization of the hatch cover in this study, in order to verify the efficiency, accuracy, and applicability of the algorithm. And Section 5 provides an application of the developed program to optimal design of the hatch cover of a deadweight 180,000 *ton* B/C and discussion about the result. Finally, Section 6 provides conclusions and directions for future work.

OPTIMIZATION PROBLEM FOR THE HATCH COVER DESIGN

Optimization target

A bulk carrier (simply, B/C) is a dry cargo ship of transporting grains, ores, coals, and so on without cargo packaging. In the B/C, the opening for loading and off-loading the cargo is called a hatch, and a cover plate on the hatch for protecting the cargo is called a hatch cover. The hatch cover has a structure of stiffened plate which consists of a plate and stiffeners. In general, the cost of hatch cover equipment is accounting for 5~8% of shipbuilding cost. In spite of the importance of the hatch cover in the B/C, it has hardly been optimized. Thus, the hatch cover was selected as an optimization target for the lightening of the ship weight in this study. That is, the thickness and shape of the stiffened plate of the hatch cover tried to be optimized in this study. Fig. 1 shows the hatch cover of the B/C which is the optimization target of this study.

Fig. 1 Hatch cover of the B/C.

As mentioned earlier, the hatch cover has a structure of stiffened plate which consists of a plate and stiffeners and looks like a corrugated plate, as shown in Fig. 1. Thus, the hatch cover can be idealized for the effective optimization and the idealized model will be used as the optimization target in this study. Fig. 2 shows a real, 3D CAD, and idealized model of the hatch cover, respectively.

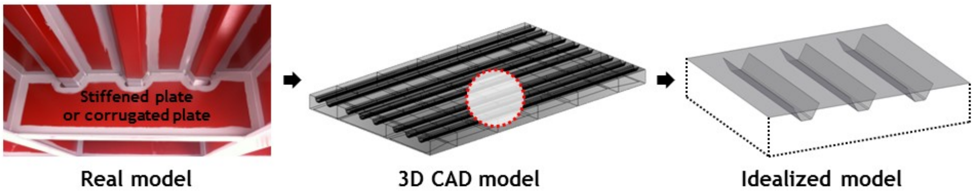

Fig. 2 Real, 3D CAD, and idealized model of the hatch cover.

Mathematical formulation of an optimization problem

The purpose of this study is to find optimal principal dimensions which represent the thickness and shape of the stiffened plate of the hatch cover for reducing the weight of the hatch cover which affects total weight of the B/C. To do so, an optimization problem which consists of design variables, constraints, and an objective function should be mathematically formulated. In this study, the plate thickness, stiffener thickness, and stiffener size which represent the principal dimensions of the hatch cover were selected as the design variables of the optimization problem. When designing the hatch cover, the structural safety should be considered according to class rule (CSR; Common Structural Rules) (IACS, 2012; Germanischer Lloyd, 2014). Thus, the maximum permissible stress and deflection, minimum thickness of a plate, minimum section modulus and shear area of stiffeners were considered as the constraints of the optimization problem, including some geometric limitations related to the shape of the hatch cover. In addition, an optimal hatch cover means a hatch cover having minimum weight. Thus, the weight of the hatch cover was selected as the objective function of the optimization problem. Now, this optimization problem for finding optimal principal dimensions of the hatch cover can be formulated as follows.

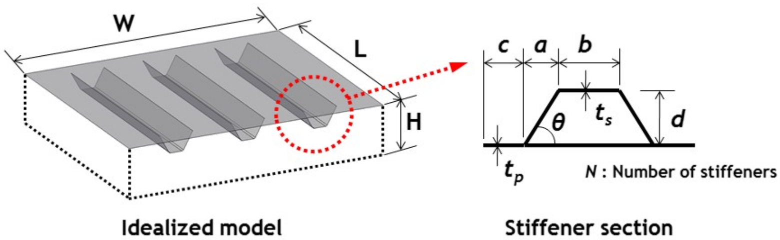

Fig. 3 Design variables for finding optimal principal dimensions of the hatch cover.

Design variables

The shape of the hatch cover, that is, principal dimensions can be represented with six parameters, as shown in Fig. 3; the plate thickness (t_p), stiffener thickness (t_s), stiffener size (b, a, d), and number of stiffeners (N). Thus, these parameters are design variables of the optimization problem.

Constraints

In this study, design considerations related to the structural safety of the hatch cover according to class rule (IACS, 2012; Germanischer Lloyd, 2014) and geometric limitations related to the shape of the hatch cover were used as constraints of the optimization problem. More details about them are as follows;

• <u>Requirement on yield stress</u>

The maximum permissible stress of the hatch cover can be given as

$$\sigma_v \leq 0.8 R_{eH} \;\; [N/m^2] \tag{1}$$

where

σ_v: Von Mises equivalent stress [N/mm^2] at the center of a shell element of the hatch cover. For FEM calculations, the equivalent stress σ_v may be taken as follows (Germanischer Lloyd, 2014):

$\sigma_v = \sqrt{\sigma_x^2 - \sigma_x \cdot \sigma_y + \sigma_y^2 + 3\tau^2}$ $[N/m^2]$ (σ_x : normal stress in x-direction, σ_y : normal stress in y-direction, τ : shear stress in the x-y plane)

R_{eH} : yield strength, given as: 235×10^6 [N/m^2] for mild steel, 315×10^6 [N/m^2] for AH32, 355×10^6 [N/m^2] for AH36.

• Requirement on stiffness

The maximum permissible deflection of the hatch cover can be given as

$$f \le 0.0056 \cdot l_g \; [m] \quad (2)$$

where

f : deflection [m] of the hatch cover

l_g : The largest span [m] of girders in the hatch cover.

• Requirements on thickness

The minimum thickness of a top plate of the hatch cover can be given as

$$t_{\min} \le t_p \; [m] \quad (3)$$

where

$t_{\min} = \max(t_1, t_2, t_3)$

$$t_1 = \left(16.2 \cdot c_p \cdot c \cdot \sqrt{\frac{p}{R_{eH}}} + t_k\right) \cdot 10^{-3} \; [m]$$

$$t_2 = \left(10 \cdot c + t_k\right) \cdot 10^{-3} \; [m]$$

$$t_3 = \left(6.0 + t_k\right)^{-3} \; [m]$$

t_k : corrosion additions (2.0 mm for hatch covers in general (See Table 17.1 in CSR (Germanischer Lloyd, 2014))

t_{net} : net thickness [mm], defined as: $t_{net} = t_p - t_k \; [m]$

c_p : coefficient, defined as:

$$c_p = 1.5 + 2.5 \cdot \left(\frac{|\sigma|}{R_{eH}} - 0.64\right) \ge 1.5 \quad \text{for} \quad p = p_H$$

c : spacing [m] of stiffeners

p : design load [kN/m^2]

p_H : load [kN/m^2] on the hatch cover on freeboard deck for ships with less freeboard than type B according to ICLL (See Table 17.2 in CSR (Germanischer Lloyd, 2014)), defined as:

$$p_H = 9.81 \cdot \left[(0.1452 \cdot L_{c340} - 8.52) \cdot \frac{x}{L_c} - 0.1089 \cdot L_{c340} + 9.89\right]$$

x : distance of mid point of the assessed hatch cover from aft end of length L or L_c, as applicable

L_c : 96% of the total length on a waterline at 85% of the least moulded depth measured from the top of the keel, or as the length from the fore side of the stem to the axis of the rudder stock on that waterline, if that be greater

L_{c340} : length of the ship as L_c, but L_{c340} is not to be taken greater than 340 m.

The minimum section modulus and shear area of stiffeners of the hatch cover are given as

$$M_{\min} \le M_{net}(b, a, d, t_s) \; [m^3] \quad (4)$$

$$A_{\min} \le A_{net}(b, a, d, t_s)\ [m^2] \tag{5}$$

where

M_{net} : net section modulus [m^3], which is a function of stiffener thickness (t_s) and stiffener size (b, a, d)

$M_{\min}$: minimum section modulus, defined as:

$$M_{\min} = \left(\frac{104}{R_{eH}} \cdot c \cdot l^2 \cdot p\right) \cdot 10^{-6}\ [m^3]$$

A_{net} : net shear area [m^2], which is a function of stiffener thickness (t_s) and stiffener size (b, a, d)

$A_{\min}$: minimum shear area, defined as:

$$A_{\min} = \left(\frac{10 \cdot c \cdot l \cdot p}{R_{eH}}\right) \cdot 10^{-4}\ [m^2]$$

l : unsupported span [m] of stiffener.

• Requirements on critical buckling stress

The compressive stress in the hatch cover plating, induced by the bending of primary supporting members, parallel to and perpendicular to the direction of ordinary stiffeners is to comply with the following formula:

$$\sigma \le \frac{0.88}{S} \sigma_{C1,2}\ [N/m^2] \tag{6}$$

where

σ : compressive stress [N/m^2] of the hatch cover

S : safety factor, given as 1.1 for structures which are exclusively exposed to local loads such as hatch cover (IACS, 2012)

σ_{C1} : critical buckling stress [N/m^2], defined as:

$$\sigma_{C1} = \sigma_{E1} \quad \text{for} \quad \sigma_{E1} \le \frac{R_{eH}}{2}$$

$$\sigma_{C1} = R_{eH}\left(1 - \frac{R_{eH}}{4\sigma_{E1}}\right) \quad \text{for} \quad \sigma_{E1} > \frac{R_{eH}}{2}$$

$$\sigma_{E1} = 3.6E\left(\frac{t_{net}}{s}\right)^2 \cdot 10^{-6}\ [N/m^2]$$

s : length [m] of the shorter side of the elementary top plate of the hatch cover

σ_{C2} : critical buckling stress [N/m^2], defined as:

$$\sigma_{C2} = \sigma_{E2} \quad \text{for} \quad \sigma_{E2} \le \frac{R_{eH}}{2}$$

$$\sigma_{C2} = R_{eH}\left(1 - \frac{R_{eH}}{4\sigma_{E2}}\right) \quad \text{for} \quad \sigma_{E2} > \frac{R_{eH}}{2}$$

$$\sigma_{E2} = 0.9mE\left(\frac{t_{net}}{s_s}\right)^2 \cdot 10^{-6}\ [N/m^2]$$

s_s : length [m] of the shorter side of the top plate of the hatch cover

l_s : length [m] of the longer side of the top plate of the hatch cover

m : coefficient, defined as:

$$m = C\left[1 + \left(\frac{s_s}{l_s}\right)^2\right]^2 \frac{2.1}{\psi + 1.1}$$

C : coefficient, given as 1.3 when the plate is stiffened by ordinary stiffeners of U type (IACS, 2012).
ψ : Ratio between smallest and largest compressive stress

• Requirements on geometric limitations
Finally, geometric limitations related to the shape of the hatch cover are given as

$$N(2a+b) < W \tag{7}$$

$$d < H \tag{8}$$

$$0^\circ < \theta \le 90^\circ \tag{9}$$

where
W : width [m] of the hatch cover
H : depth [m] of the hatch cover
θ : angle between the plate and stiffener.

Thus, this optimization problem has 9 inequality constraints.

Objective function

As mentioned earlier, an optimal hatch cover means a hatch cover having minimum weight. Thus, the weight of the hatch cover was selected as the objective function of the optimization problem. The weight of the hatch cover (top plate and stiffeners only) can be calculated by
Minimize

$$Weight = \rho_p \cdot L \cdot W \cdot t_p + \rho_s \cdot L \cdot \left\{ (2a \cdot (\cos\theta)^{-1} + b + c) \cdot N + c \right\} \cdot t_s \ [kg] \tag{10}$$

where
ρ_p and ρ_s : specific gravity [kg/m^3] of plate and stiffener, respectively
L : length [m] of the hatch cover
t_s : stiffener thickness [m].

Now, this optimization problem for finding optimal principal dimensions of the hatch cover which can reduce its weight can be summarized as follows.

Find the plate thickness (t_p), stiffener thickness (t_s), stiffener size (b, a, d), and number of stiffeners (N) which minimize

$Weight = \rho_p \cdot L \cdot W \cdot t_p + \rho_s \cdot L \cdot \left\{ (2a \cdot (\cos\theta)^{-1} + b + c) \cdot N + c \right\} \cdot t_s \ [kg]$; weight of top plate and stiffeners

subject to
$\sigma_v \le 0.8 R_{eH} \ [N/m^2]$; maximum permissible stress,
$f \le 0.0056 \cdot l_g \ [m]$; maximum permissible deflection,
$t_{\min} \le t_p \ [m]$; minimum thickness of a top plate,
$M_{\min} \le M_{net}(b, a, d, t_s) \ [m^3]$; minimum section modulus of stiffeners,

$A_{min} \le A_{net}(b,a,d,t_s)\ [m^2]$; minimum shear area of stiffeners,

$\sigma \le \frac{0.88}{S}\sigma_{C1,2}\ [N/m^2]$; critical buckling stress

$N(2a+b) < W$; geometric limitations,

$d < H$; geometric limitations,

$0^\circ < \theta \le 90^\circ$; geometric limitations.

Thus, we can see that this problem is a single-objective optimization problem having 6 design variables (unknowns) and 9 inequality constraints. This problem can be solved with any optimization algorithm such as global or local optimization method.

Optimization procedure

To solve the optimization problem which was formulated above, the following optimization procedure was established. First, initial values for design variables are assumed. At this time, the values can be generated randomly or by using the values of manual design or existing design. Now, these values are transferred to an optimization algorithm, the values of an objective function and constraints are calculated. At this time, the finite element modeling and analysis for the current values of the design variables should be automatically performed in order to calculate some structural responses such as the stress and deflection of the hatch cover for the values of the design variables. For performing the finite element modeling and analysis, any structural analysis program can be used. Then, we check whether the current values of the design variables are an optimum or not. If yes, the optimization process finishes and the result will be visualized, and if not, the above steps will be repeated until the optimum is found. Fig. 4 shows this optimization procedure for finding optimal principal dimensions of the hatch cover.

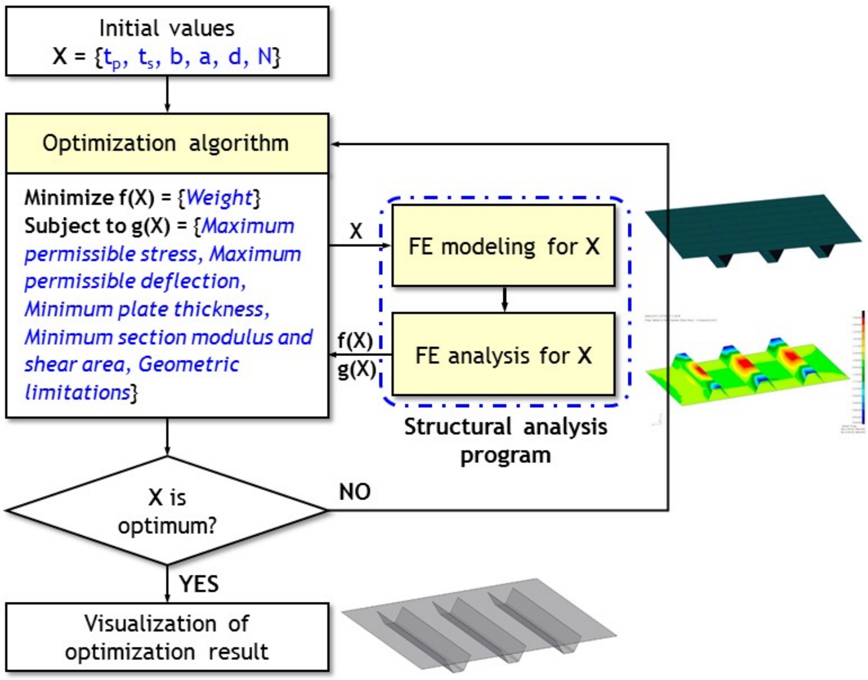

Fig. 4 Optimization procedure for finding optimal principal dimensions of the hatch cover.

OPTIMIZAION PROGRAM FOR THE HATCH COVER

According to the optimization procedure described in Section 2, an optimization program which can yield optimal principal dimensions of the hatch cover was developed by using C++ programming language in this study. Fig. 5 shows a configuration of the developed program. As shown in this figure, the developed program consists of five modules (input module, optimization module, preprocessor module, postprocessor module, output module) and is connected with a structural analysis program. A role or function of each module is described below.

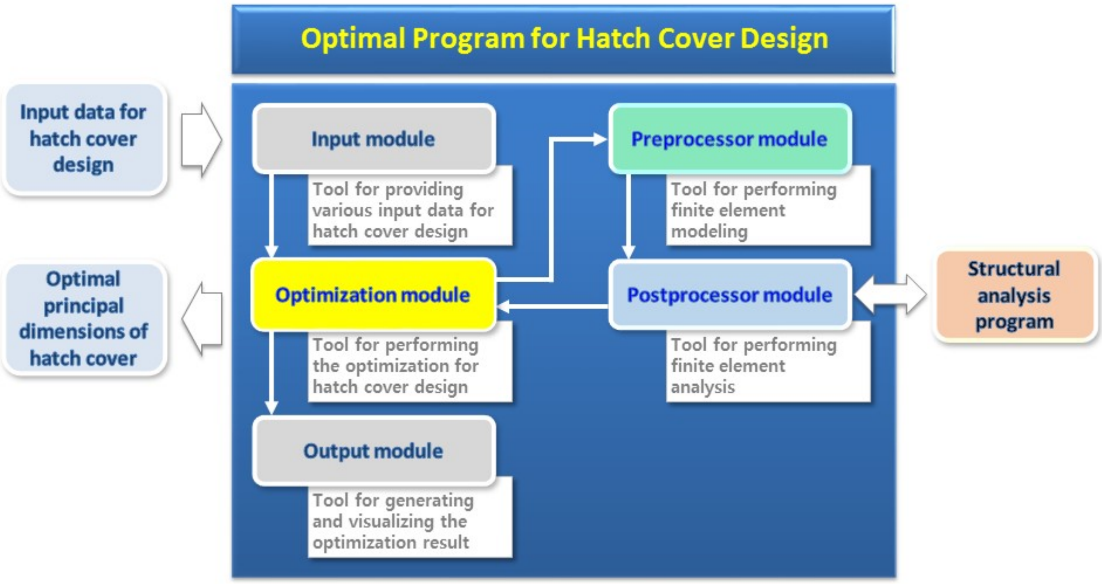

Fig. 5 Configuration of the optimization program for the hatch cover design.

Input module

The input module inputs some data for optimization of the hatch cover from a designer. The data includes the size (length, width, and depth) of the hatch cover, materials of plate and stiffeners, and so on. In addition, the input module generates initial values for design variables and transfers them to the optimization module.

Optimization module

Optimization algorithms are generally divided into two categories; global and local optimization algorithms. Several classes of the global optimization algorithms are now available including Genetic Algorithm (GA) (Goldberg, 1989; Davis, 1991), simulated annealing method, and so on. These algorithms are suitable for large-scale problems that have many local optima. However, these algorithms require a lot of iteration to get an acceptable optimum as compared with the local optimization algorithms. Several classes of the local optimization algorithms also exist including the Sequential Linear Programming (SLP) (Arora, 2012), the Sequential Quadratic Programming (SQP) (Arora, 2012), the Method of Feasible Directions (MFD) (Vanderplaats, 1984), and so on. Each of these algorithms can find the optimum effectively. However, in some cases, these algorithms find the relative optimum that is closest to the starting point. To overcome the difficulties in the global and local optimization algorithms, various attempts were made by many researchers to combine these two algorithms (Lee et al., 2002; Stork and Kusuma, 1992; Porsani et al., 1993). Most of them combined a global optimization algorithm (e.g., GA) and a local optimization algorithm, and thus they are called a hybrid optimization algorithm. However, the hybrid optimization algorithm (HYBRID) requires somewhat long time (but less than the GA) to find an optimum because the algorithm is based on the GA. As mentioned earlier, the problem to be solved in this study requires much time due to the execution of the finite element modeling and analysis. Thus, a simple but efficient algorithm was used in this study considering computation time. The selected one is a multi-start optimization algorithm based on the SQP (See Appendix). This algorithm intends to find a global optimum by using multiple local optimization with the SQP and performs optimization from multiple starting points (various sets of initial variables for design variables) generated randomly. Finally, it selected the best optimum obtained from multiple starting points as the global optimum.

The optimization module includes the Multi-Start optimization algorithm (MS). The module calculates the values of an objective function and constraints are calculated. By using the values, the module improves the current values of the design variables. At this time, the finite element modeling and analysis for the current values of the design variables should be performed in order to calculate some structural responses such as the stress and deflection of the hatch cover for the values of the design variables. Thus, this module is linked with the preprocessor and postprocessor modules, and calls them when needed.

Preprocessor module

To calculate the structural responses by using a structural analysis program, a finite element model is required. The preprocessor module is used to generate the finite element model for the current values of the design variables. That is, the role of the module is the finite element modeling. In this module, an input file for the execution of the structural analysis program is generated with the current values of the design variables. The input file is transferred to the postprocessor module.

Postprocessor module

In the post processor module, the structural analysis program is executed with the input file from the preprocessor module. That is, the role of the module is the finite element analysis. In this study, the ANSYS which is one of commercial structural analysis programs was used for the structural analysis. After performing the finite element analysis with the structural analysis program, the structural responses such as the stress and deflection of the hatch cover can be acquired. The values of the structural responses are written in the output file by the structural analysis program. The postprocessor module parses the output file by the structural analysis program, and transfers the values of the structural responses to the optimization module.

Output module

The output module outputs an optimization result from the optimization module. The result includes optimal dimensions (optimal values of the design variables), weight, maximum stress, maximum deflection of the hatch cover, and so on.

COMPARATIVE TEST OF MULT-START OPTIMIZATION ALGORITHM

Experiment on the mathematical optimization problem was performed to verify the efficiency, accuracy, and applicability of the multi-start optimization algorithm which was used for optimization of the hatch cover. The selected problem which is a Rastrigins's problem, one of benchmark problems, is being widely used to check the efficiency of the optimization algorithm (Willi and Klaus, 1981).

The mathematical formulation of the Rastrigins's problem is as follows.

Minimize

$$f(x_1, x_2) = 20 + x_1^2 - 10\cos(2\pi \cdot x_1) + x_2^2 - 10\cos(2\pi \cdot x_2)$$

subject to

$$\begin{aligned} g_1(x_1, x_2) &= -5.12 - x_1 \le 0 \\ g_2(x_1, x_2) &= -5.12 - x_2 \le 0 \\ g_3(x_1, x_2) &= x_1 - 5.12 \le 0 \\ g_4(x_1, x_2) &= x_2 - 5.12 \le 0 \end{aligned}$$

The known solution for this problem is $f^* = 0.0$ at $x_1 = 0.0$ and $x_2 = 0.0$. This problem has a global minimum and a number of local minima, as shown in Fig. 6. Table 1 shows the comparison of the Rastrigins's problem for multi-start optimization algorithm (MS), sequential quadratic programming (SQP), genetic algorithm (GA), and hybrid optimization algorithm (HYBRID). In the case of the MS, the best optimum was selected from 30 starting points as the optimum. The optimization was performed in the Intel Pentium Dual Core system (3.06 *GHz*, 2 *GB* RAM).

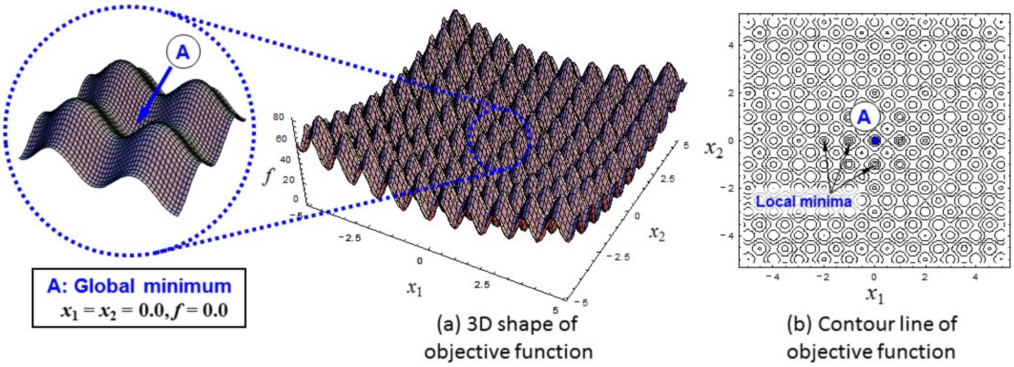

Fig. 6 Global minimum and local minima of the Rastrigins's problem.

Table 1 Optimization results for the Rastrigins's problem.

	True solution	**MS**	SQP	GA	HYBRID
x_1	0.0000	**0.0000**	0.0000	-0.0014	0.0000
x_2	0.0000	**0.0000**	0.9950	0.0005	0.0000
f	0.0000	**0.0000**	0.9950	0.0004	0.0000
CPU time (*sec.*)	-	**0.02**	0.00	0.05	0.05
Remark	-	**Global minimum**	Local minimum	Near global minimum	Global minimum

As shown in the table, the SQP yielded one of local minima not the global minimum. MS, GA, and HYBRID yielded the global minimum. The MS and HYBRID yielded better results than the GA in accuracy. The HYBRID required longer than the MS because it is based on the GA. As shown in this comparative test, it can be seen that the MS provides more accurate results in less time.

APPLIXATION TO THE HATCH COVER DESIGN OF A DEADWEIGHT 180,000 TON BULK CARRIER

Input data for the hatch cover design

To evaluate the applicability of the developed program, it was applied to a problem for finding optimal principal dimensions of a deadweight 180,000 *ton* B/C. The length, breadth, and depth are 283.5 *m*, 45.0 *m*, 24.7 *m*, respectively. Fig. 7 shows a sketch general arrangement. As shown in this figure, this ship has nine hatch covers. In this study, the foremost hatch cover (No. 1 HC) is selected to be optimized because it will have the largest reaction force. The idealized half model for No.1 HC is shown in Fig. 8.

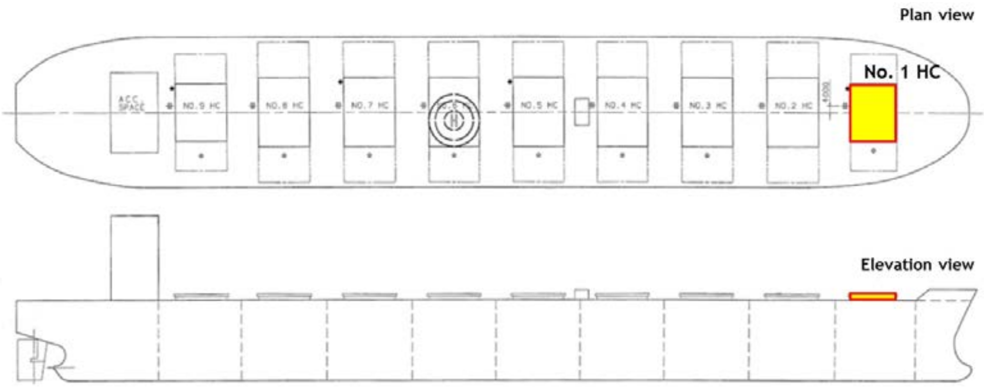

Fig. 7 Sketch general arrangement of the deadweight 180,000 *ton* B/C.

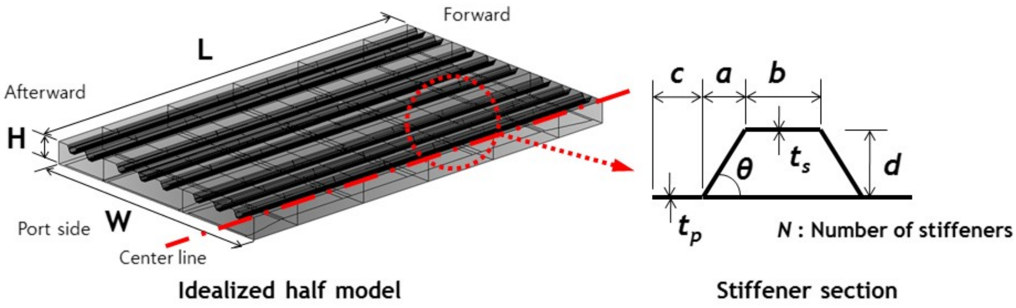

Fig. 8 Idealized half model of No. 1 HC to be optimized.

The input data of No. 1 HC for optimization of the hatch cover is as follows.

- Length (L) of the hatch cover: 14.929 *m*
- Width (W) of the hatch cover: 8.624 *m* (actually, half width of No. 1 HC)
- Height (H) of the hatch cover: 0.880 *m*
- The largest span of girders (l_g) in the hatch cover: 3.138 *m*
- Load (p_H) on the hatch cover by CSR (Germanischer Lloyd, 2014): 86.28 kN/m^2
- Materials of the hatch cover: AH32
- Specific gravity of plate and stiffeners (ρ_p, ρ_s): 7,850 kg/m^3

Mathematical formulation of an optimization problem

Now, an optimization problem for finding optimal principal dimensions of No. 1 HC can be formulated as follows, by using the general problem described in Section 2.2.

Find t_p, t_s, b, a, d, and N
which minimize

$$\begin{aligned} Weight &= \rho_p \cdot L \cdot W \cdot t_p + \rho_s \cdot L \cdot \left\{(2a \cdot (\cos\theta)^{-1} + b + c) \cdot N + c\right\} \cdot t_s \ [kg] \\ &= 7.85 \cdot 14.929 \cdot 8.624 \cdot t_p + 7.85 \cdot 14.929 \cdot \left\{(2a \cdot (\cos\theta)^{-1} + b + c) \cdot N + c\right\} \cdot t_s \end{aligned}$$
; weight of top plate and stiffeners

subject to Eqs. (1) to (9), which represent the constraints on maximum permissible stress, maximum permissible deflection, minimum thickness of a top plate, minimum section modulus of stiffeners, minimum shear area of stiffeners, geometric limitations, geometric limitations, respectively.

Now, this problem can be solved with the optimization program for the hatch cover design which was described in Section 3.

Finite element modeling

For strength calculations of hatch covers by means of finite elements, the cover geometry was idealized as realistically as possible. During optimization, a finite element model for structural analysis of No. 1 HC is being automatically generated by using the values of design variables. Fig. 9 shows the finite element model of No. HC, including the boundary condition and loading condition. A shell element ('SHELL63' in ANSYS) was used to make the finite element model. As the boundary condition, a simple support condition was used at some bottom nodes of No. 1 HC, as shown in Table 2. According to CSR (Germanischer Lloyd, 2014), the surface load (p_H) of 86.28 kN/m^2 was applied on the top of the hatch cover as the loading condition.

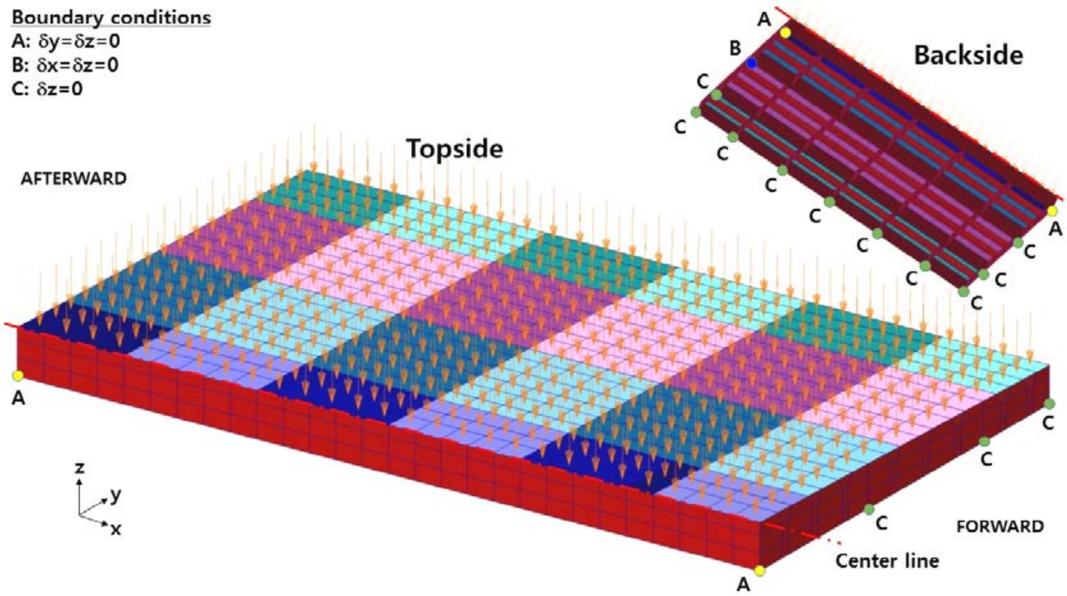

Fig. 9 Finite element model for structural analysis of No. 1 HC, including the boundary condition and loading condition.

Table 2 Boundary conditions for structural analysis of No. 1 HC.

Position	Linear displacement constraint			Angular displacement constraint		
	δx	δy	δz	θx	θy	θz
Direction	Longitudinal	Horizontal	Vertical	Around the x axis of rotation	Around the y axis of rotation	Around the z axis of rotation
Horizontal restrictor (Point A)	-	Fixed	Fixed	-	-	-
Longitudinal restrictor (Point B)	Fixed	-	Fixed	-	-	-
Supporting block (Point C)	-	-	Fixed	-	-	-

Optimization result

The developed program was applied to the formulated problem for finding optimal principal dimensions of No. 1 HC of the deadweight 180,000 *ton* B/C. To get an optimum, a multi-start optimization algorithm based on the SQP in the optimization module of the developed program was used with the SQP, GA, and HYBRID. The MS selected the best optimum obtained from 10 starting points as the optimum. The optimization was performed in the Intel Pentium Dual Core system (3.06 *GHz*, 2 *GB* RAM) and it took about five hours to get the optimum with the MS. The optimization results from the developed program were compared with manual design, as shown in Table 3. In this table, MS, SQP, GA, and HYBRID represent the results by using multi-start optimization algorithm, SQP only, genetic algorithm, and hybrid optimization algorithm, respectively. In Table 3, The MS and HYBRID yielded better results than the SQP and the GA in accuracy. The MS required shorter than the HYBIRD which is based on the GA.

As shown in this table, the weight of a half of No. 1 HC before and after optimization (MS) is 26,225 *kg* and 23,975 *kg*, respectively. If we infer the weight of a full of No. 1 HC and then it will be 52,430 *kg* and 47,949 *kg*, respectively. Thus, the difference and the reduction ratio between the weight before and after optimization is 4,481 kg and 8.546%, respectively. This means that the weight of No. 1 HC can be reduced about 8.5% if an optimization technique is applied to the hatch cover design.

As shown in Fig. 7, the target ship has nine hatch covers, and if the optimization is applied to all hatch covers, the reduction ratio of the weight will be increased.

Table 3 Comparison of principal dimensions of No. 1 HC between manual design and optimization result.

Item	Unit	Limit by rules	Manual design	Optimization result			
				MS	SQP	GA	HYBRID
t_p	*m*	-	0.016	**0.014**	0.015	0.014	0.014
t_s	*m*	-	0.008	**0.008**	0.008	0.008	0.008
b	*m*	-	0.170	**0.160**	0.170	0.160	0.160
a	*m*	-	0.120	**0.111**	0.115	0.112	0.111
d	*m*	-	0.220	**0.198**	0.200	0.197	0.198
N	-	-	8	**8**	8	8	8
Weight	*kg*	-	26,215	**23,975**	24,736	24,077	23,975
Maximum stress	N/m^2	252×10^6	218×10^6	$\mathbf{252\times10^6}$	235×10^6	252×10^6	252×10^6
Maximum deflection	*m*	0.018	0.006	**0.006**	0.006	0.006	0.006
CPU time	*hour*	-	-	**4.8**	0.4	6.2	6.0

Figs. 10 and 11 show the comparison of the stress (Von Mises equivalent stress) distribution and deflection of No. 1 HC between before (manual design) and after optimization (MS), respectively.

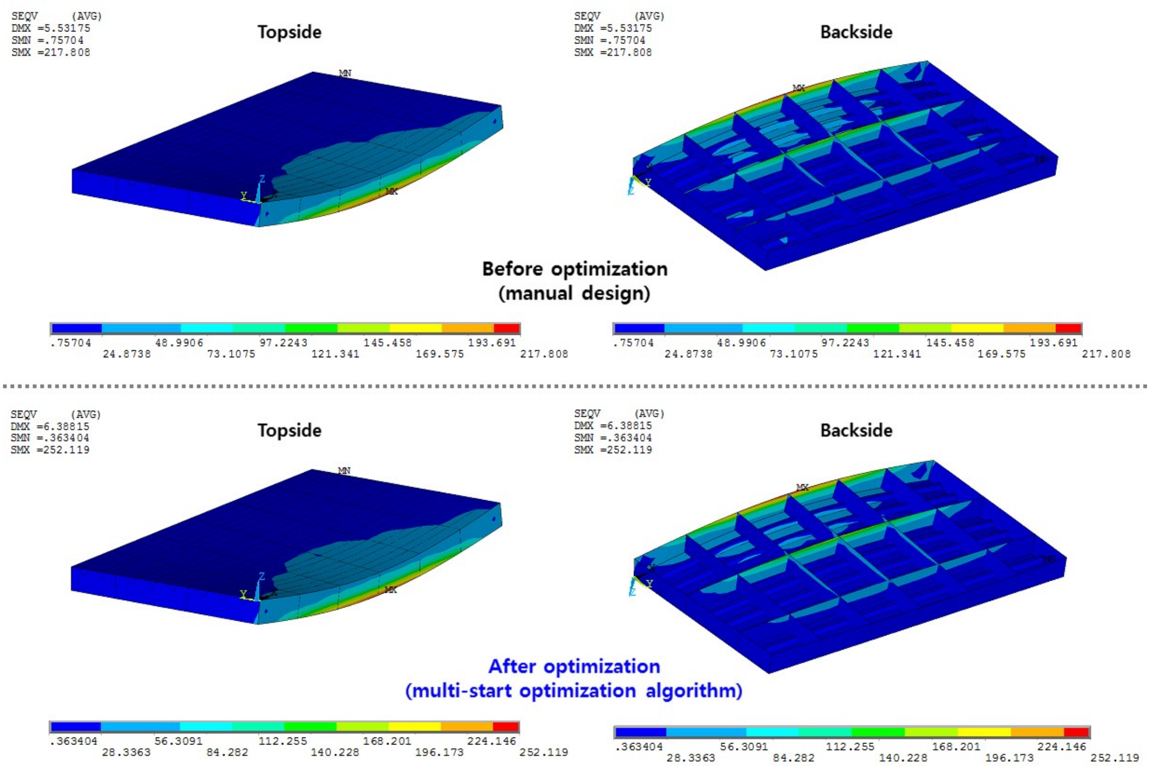

Fig. 10 Comparison of the stress distribution of No. 1 HC between manual design and optimization (MS) result.

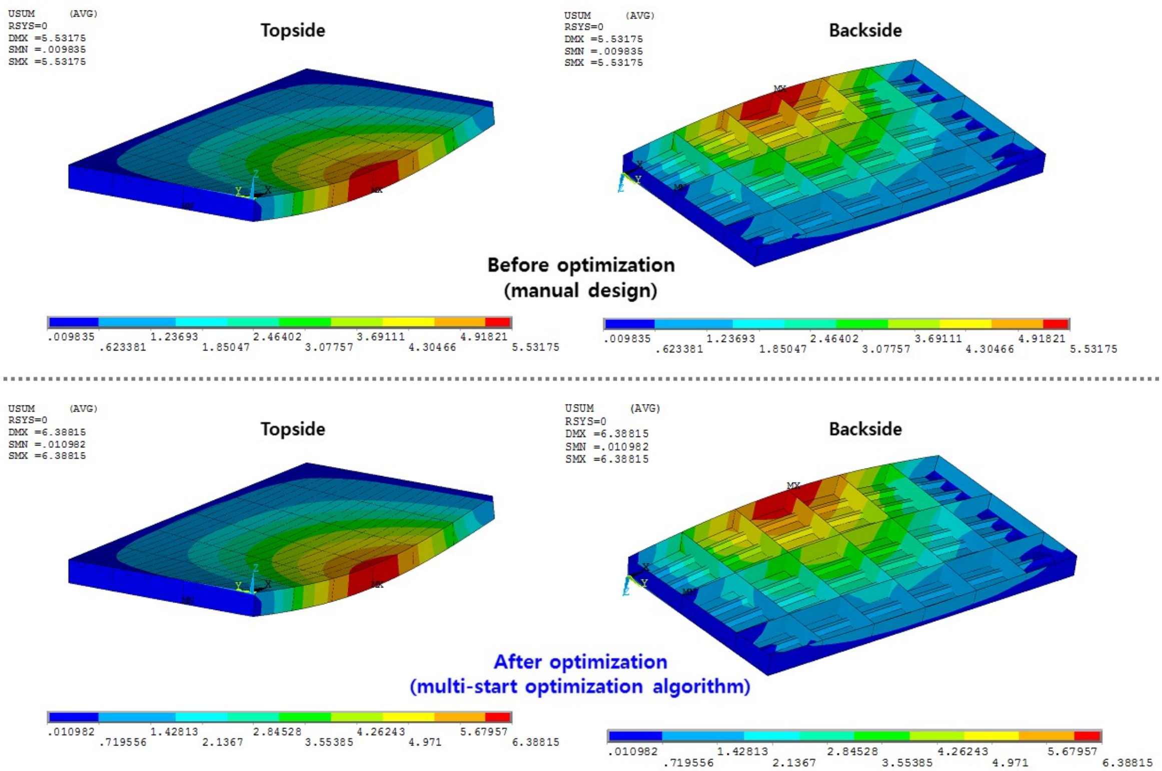

Fig. 11 Comparison of the deflection of No. 1 HC between manual design and optimization result.

CONCLUSION AND FUTURE WORK

In this study, one of methods for lightening the ship weight based on the optimization technique was proposed. Especially, this study focused on a hatch cover which is one of core parts in a B/C, and thus the hatch cover of the bulk carrier was selected as an optimization target. For this, an optimization problem in order to determine optimal principal dimensions of the hatch cover was first formulated. To solve this optimization problem, an optimization program based on the SQP using C++ programming language was developed in this study. Finally, to evaluate the applicability of the developed program, it was applied to a problem for finding optimal principal dimensions of the hatch cover of a deadweight 180,000 *ton* B/C. When the developed program was applied to the design of No. 1 HC in the B/C, the result shows that the developed program can decrease the hatch cover's weight by about 8.5%. If the optimization is applied to all hatch covers, the reduction ratio of the weight will be increased. Thus, this study will be able to contribute to make energy saving and environment-friendly ship in shipyard.

In the future, this program will be improved to be applied to a hatch cover of a container ship. In the case of the container ship, cargo is intended to be carried on the hatch cover, and thus additional design load should be considered when designing the hatch cover. The developed program requires somewhat long time to get an optimum because the finite element modeling and analysis should be repeated performed during the optimization. Thus, a strategy to reduce the computation time of the developed program should be further studied by improving the optimization algorithm or by introducing meta-modeling such as the response surface method.

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d) Engineering Research Institute of Seoul National University, Republic of Korea

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APPENDIX

The brief description of the sequential quadratic programming (SQP) is as follows. More details can be found in the reference (Arora, 2012). The general statement of a non-liner programming problem is given as follows.

Minimize

$$f(\mathbf{x}) \tag{11}$$

subject to

$$g_i(\mathbf{x}) \le 0, i = 1, \cdots, l \tag{12}$$

$$h_i(\mathbf{x}) = 0, i = 1, \cdots, p \tag{13}$$

First, the objective function of the original problem of Eqs. (11) to (13) is augmented using Lagrange multipliers so that the constrained optimization problem can be transformed to an unconstrained optimization problem as follows:

Minimize $$\phi(\mathbf{x}^{(k+1)}) = f(\mathbf{x}^{(k+1)}) + \sum_{i=1}^{l} u_i \left[\max\left\{0, g_i(\mathbf{x}^{(k+1)})\right\} \right] + \sum_{i=1}^{p} v_i \left| h_i(\mathbf{x}^{(k+1)}) \right|, \tag{14}$$

where u_i and v_i are the Lagrange multipliers for the inequality constraints of Eq. (12) and equality constraints of Eq. (13), respectively. Here, the Lagrange function $L(\mathbf{x}, \mathbf{u}, \mathbf{v})$ can be stated as follows:

$$L(\mathbf{x}, \mathbf{u}, \mathbf{v}) = f(\mathbf{x}) + \sum_{i=1}^{l} u_i g_i(\mathbf{x}) + \sum_{i=1}^{p} v_i h_i(\mathbf{x}) \tag{15}$$

In Eq. (4), a new design point can be defined as follows:

$$\mathbf{x}^{(k+1)} = \mathbf{x}^{(k)} + \alpha \mathbf{d}^{(k+1)}, \tag{16}$$

where α represents a step size.

The important parts of the optimization task of the SQP consist of the following; (11) Determination of the search direction (12) Determination of the step size (13) Test for convergence criteria.

• Determination of the search direction

We begin the optimization process by determining the desired search direction. This is done by creating a quadratic approximation to the objective function of Eq. (11) and a linear approximation to the constraints so that the sub-problem in order to find the search direction $\mathbf{d}^{(k+1)}$ becomes

Minimize $$\nabla f(\mathbf{x}^{(k)})^T \mathbf{d}^{(k+1)} + \frac{1}{2} \mathbf{d}^{(k+1)T} \mathbf{H} \mathbf{d}^{(k+1)} \tag{17}$$

subject to

$$\nabla g_i(\mathbf{x}^{(k)}) \cdot \mathbf{d}^{(k+1)} + g_i(\mathbf{x}^{(k)}) \le 0, i = 1, \cdots, l \tag{18}$$

$$\nabla h_i(\mathbf{x}^{(k)}) \cdot \mathbf{d}^{(k+1)} + h_i(\mathbf{x}^{(k)}) = 0, i = 1, \cdots, p \,, \tag{19}$$

where the matrix **H** is a positive-definite matrix which is initially the identity matrix, and is updated through subsequent iterations to approach the Hessian matrix of the Lagrange function of Eq. (14). This problem of Eqs. (17) to (19) can be written in matrix form, can be converted to the linear programming problem, and can be solved using the Simplex method.

• Determination of the step size

Having determined the search direction $\mathbf{d}^{(k+1)}$, we update a current design point by using Eq. (6) as a one-dimensional search problem in the usual manner. Usually, the golden section method or the polynomial interpolation method is adequate for obtaining the optimal step size α^*. At this point, we have determined the search direction and performed the one-dimensional search to update the current design point.

• Test for convergence criteria

To test for convergence to the optimum, the following criteria can be used; (a) Limit of maximum iteration number (b) Variation of the objective function value (c) Satisfaction of Kuhn-Tucker necessary conditions.

• Updating of hessian matrix **H**

If convergence to the optimum is not achieved, it will be necessary to update matrix **H** of Eq. (17) at this point, in order to provide an improved quadratic approximation for the objective function. To accomplish this, the Broydon-Fletcher-Shanno-Goldfarb (BFGS) (Arora, 2012) update formula can be used. The new matrix $\mathbf{H}^{\circ}$ now replaces **H** in Eq. (17) and the optimization process is repeated to convergence.