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Key words: Ship chamber, Ship lift, Structure optimization, Multi-level optimization, Beam-plate structure, BESO, RSM.

ABSTRACT

Weight reduction of ship chamber is a main concern of ship lift design for improving the load capacity. The structure of ship chamber is typical of beam-plate structure. To deal with structural optimization problem of beam-plate structure, a multi-level structural optimization method was developed based on combining an improved bi-directional evolutionary structural optimization (BESO) method and surrogate model method, which covers three optimization levels, as dimension optimization, topology optimization and section optimization. The aim of the proposed optimization method is to determine global design parameters, integral structural topology, and locations and sectional parameters of structural members from an oversized ground structure. The kernel optimization procedure (KOP) is using BESO to obtain the optimal topology from a ground structure. In order to deal with beam-plate structures, cubic box is adopted as the unit cell to construct ground structure for BESO. In the first optimization level, based on different dimensional parameter combinations, a series of ground structures are generated and used to perform KOP. Response surface (RS) model is used to simulate the nonlinear relationship between the optimal objective values and dimension parameters, then the optimal dimensional parameters can be obtained. In the second optimization level, the optimal dimension parameters are used to generate the ground structure, and the optimal topology could be obtained by using KOP. In the third optimization level, RS model is also used to determine the section parameters. The proposed method is applied to structural design of ship chamber of a 500-ton class ship lift. The results show that the proposed method leads to a greater weight saving, compared with the original design and generic algorithm (GA)-based optimization results.

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I. INTRODUCTION

Vertical ship lift is a navigation structure vertically lifting and lowering ships to hasten them passing across dam by using mechanical devices. Compared with traditional ship lock, the vertical ship lift is more suitable for complex terrain and can shorten the time taken for ships to pass the dam. Therefore, it has developed rapidly in water conservancy projects in recent years. With huge and complicated load, when mechanical devices work, extremely small structural deformation is demanded. Usually, the main components of ship lift structure are two high reinforced concrete towers. As shown in Fig. 1, between the towers the steel ship chamber is suspended from ropes that are connected with counterweights via rope pulleys at the tops of the towers. Each pair of towers on the long sides of the ship chamber is flanked by shear walls. The walls and towers are connected by coupling beams distributed evenly over the height. The guided counterweights, made of high-density concrete, run in shafts inside the towers. The ropes are deflected by rope pulleys at the top of the structure which are supported by reinforced concrete girders mounted on the shear walls and the towers. The rope pulleys are protected by sheave halls, two steel structures on the top of the building with crane runways.

The ship chamber is a self-supporting orthotropic beam-plate structure, continuously suspended from ropes with counterweights. With fixed dimensions, if the self weight of ship chamber can be reduced, then the load capacity can be improved for carrying larger ships. This means the main concern of ship chamber design is to minimize the structural weight.

In the early period, numerical optimization focused on spacings and sizes of structural members based on a predetermined structural layout. However, it has been found that the weight of a structure strongly depends on its initial structural layout. Therefore, once the layout has been modified, sizing optimization needs to be conducted again. This results in an iterative de-

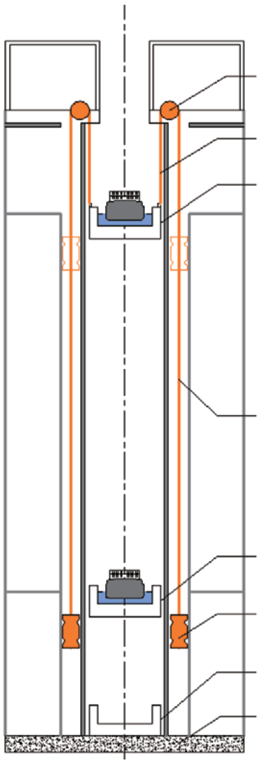


Fig. 1. Vertical section of ship lift.

sign procedure. It is of great importance for developing new methods to create the best possible topology or structural layout for given design objectives and constraints at a very early design stage. Over the past half century, tremendous efforts of fundamental research have been made in the field of beam-plate structure optimization (Arrieta and Striz, 2005; Kitamura et al., 2011; Yu et al., 2015; Yang et al., 2016).

With the traditional topological form, the structure optimization problem can be treated as discrete variable optimization and combinatorial optimization methods were used in previous studies. Usually the optimization parameters are spacings and sections of structural members. The total amount of optimization parameters is dependent on a number of technical considerations.

In recent decades, many heuristic methods such as evolutionary structure optimization (ESO) method (Chu et al., 1996; Xie and Steven, 1997), bidirectional evolutionary structure optimization (BESO) method (Yang et al., 1999; Querin et al., 2000; Huang et al., 2006), metamorphic development method (MD) (Liu et al., 2000), have emerged and made great progresses on continuum structure optimization, among these BESO is the most representative one. Many examples using BESO demonstrated the ability to find the best topological form, and the optimum usually presents a novel but highly efficient topology in contrast with the traditional topology. It is a simple idea to apply BESO in optimization of beam-plate structure, but it is found that satisfactory results hardly could be achieved by using the conventional solid cubic design domain. Through investigating the initial design domain and mesh type of BESO for the optimization problem of beam-plate structure, lattice architecture is adopted to form the initial design domain. A few numerical examples are considered using different levels of finite element grids and conclusions regarding convergence and the element size effect are reached.

The present work proposes a multi-level optimization procedure for beam-plate structure design that combines BESO with response surface method (RSM) to achieve structural topology and sizing design, which makes it possible to consider both restrictions related to global dimensions and local changes in the structural topology. The proposed approach is used to solve a steel bridge segment structure design problem considering the arrangement of structural members that support the deck. The design has structural weight as an objective and constraints on the main dimensions (length, width), strength and deformation. Different optimizations based on individual design approach are conducted to verify the optimization efficiency of the combined approach. In Section 2, some basic concepts of the proposed method are introduced. Based on these basic concepts, the proposed method of beam-plate structure optimization is presented in Section 3. In Section 4, the optimization process of a ship chamber structure is provided to validate this proposed method. Finally, this paper is wrapped up with the conclusion.

II. IMPROVEMENT OF 3D BESO METHOD FOR BEAM-PLATE STRUCTURE OPTIMIZATION

1. Investigation on Applying 3D BESO to Beam-Plate Structure Optimization

BESO method is a topology optimization method based on finite element analysis (FEA) (Querin et al., 2000), its principle is that inefficient material should be iteratively removed from the initial design domain while efficient material should be simultaneously added. BESO method was developed on the basis of ESO. As an extension of ESO method, BESO has two advantages over ESO. First, it is more robust for preventing prematurely removing elements because ESO can only remove elements. Second, compared to ESO using an over-sized ground structure, BESO can start from a simple initial design and thus decrease the computation cost. Full details of BESO procedures are presented by Yang et al. (1999).

Started from 2D age, ESO/BESO methods have entered into 3D stage. It is common that use brick element to create the initial design domain in practice of 3D BESO method. As have been mentioned, beam-plate structure is often used to provide enough working area, and the area of stiffened plate varies from several square meters to several thousand square meters whereas the thickness is usually millimeter-scale. The elements associated with working area should not be deleted, and the element size should be smaller than or equal to the minimum geometrical feature size, namely the thickness of stiffened plate, then the scale of whole FEA model will be very large (Tomas and Glaucio, 2016), hence the calculation cost of optimization process will be increased.

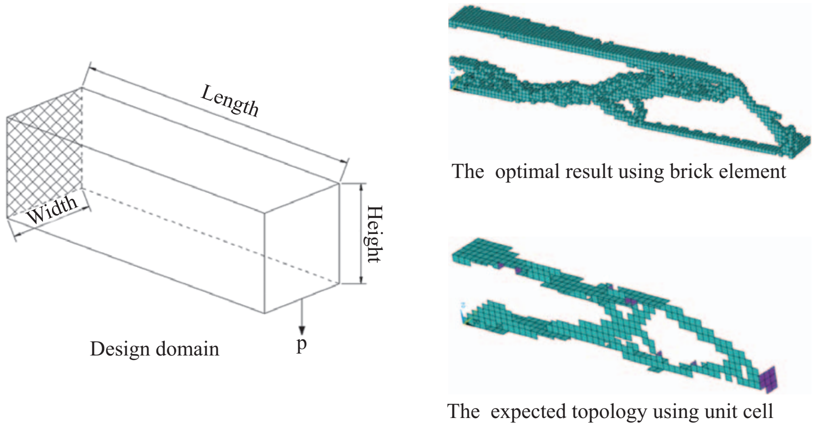


Fig. 2. Basic concept of modification of ground structure.

2. Modification of Ground Structure

It is well accepted that lattice structure has better structural performance than its counterpart, therefore, through the above analysis, this paper proposes using unit cell to replace the solid unit for generating initial design domain, which can further improve the performance of 3D BESO for beam-plate structure optimal design. Take a cantilever structure optimization problem for example, Fig. 2 shows the basic concept of modified ground structure modeling.

Using unit cell to create ground structure yields three key benefits. First, the optimal topology breaks through the traditional topological form of beam-plate structure, but still maintains good manufacturability. Second, both the locations and shapes of sections in the optimal topology can be simultaneously determined through classifying the remained elements by space planes, which are the difficulties of traditional optimization methods with traditional topological form. Third, the main dimensions of the unit cell can be adjusted to suit much more complicated design domain, which offers a much more flexible approach to ground structure modeling.

With a certain route of repeating unit cells, the overall ground structure can be generated. The size and amount of unit cells only reflect the geometry feature of the ground structure, which is independent of finite element mesh generation.

3. BESO-Based Beam-Plate Structure Optimization Method

The mathematical representation of the proposed BESO problem can be expressed as:

$$\begin{aligned}
&To\ find: X = \{x_1, x_2, \ldots, x_M\} \\
&Minimize: W = \sum_{i=1}^{M} \rho A_i t_i x_i \\
&s.t.: \sigma_{VM_i} \le [\sigma] \qquad (1) \\
&\quad t_{\min} \le t_i \le t_{\max} \\
&\quad A_i \in S = \{S_1, S_2, \cdots, S_N\}
\end{aligned}$$

where t_i is the thickness of the ith shell element in the initial structure, M is the number of shell elements in the initial structure, A_i is the area value of the ith shell element, S is the discrete set of shell element areas determined by the unit cell type, σ_{VM_i} is the maximum Von-Mises stress of ith shell element, $t_{\min}$ and $t_{\max}$ are the minimum and maximum thickness of the ith shell element, respectively. The binary design variable x_i denotes the absence (0) or presence (1) of an element. The general workflow of this algorithm is presented in Fig. 3. The detailed description of the main steps of the proposed optimization algorithm is given as follows:

Step 1. Set up FEA model. In this model, shell element is used to model the faces of the unit cell and all the shell elements share the same thickness value. All the shell elements are divided into two parts: the elements that cannot be deleted and the elements that can be deleted. The two parts are denoted as $SE1$ and $SE2$ respectively. In this step, working areas of the designed structure should be assigned, and then the elements belong to certain working areas cannot be deleted.

Step 2. Recognize all the neighbor elements of each element. For each element e, this step finds out the surrounding elements e_j with the same edge. Note that the maximum distance between centers of adjacent shell elements and the maximum number of neighbor elements is determined by the dimensions of the unit cell, so it is better to use the two parameters to check whether all the neighbor elements are found, which can increase searching efficiency. The IDs of the neighbor elements of each element are stored in the field "Neighbor_Element_IDs".

Step 3. Apply the boundary conditions, loads.

Step 4. Perform a linear static FEA of the structure.

Step 5. Calculate maximum Von Mises stress of each shell element in $SE2$, and sort them in ascending order. $SE2$ should be refreshed by excluding the elements already deleted before every iteration step. $\sigma_{VM_{iMax}}$ is the maximum Von Mises stress of the whole structure, $[\sigma]$ is

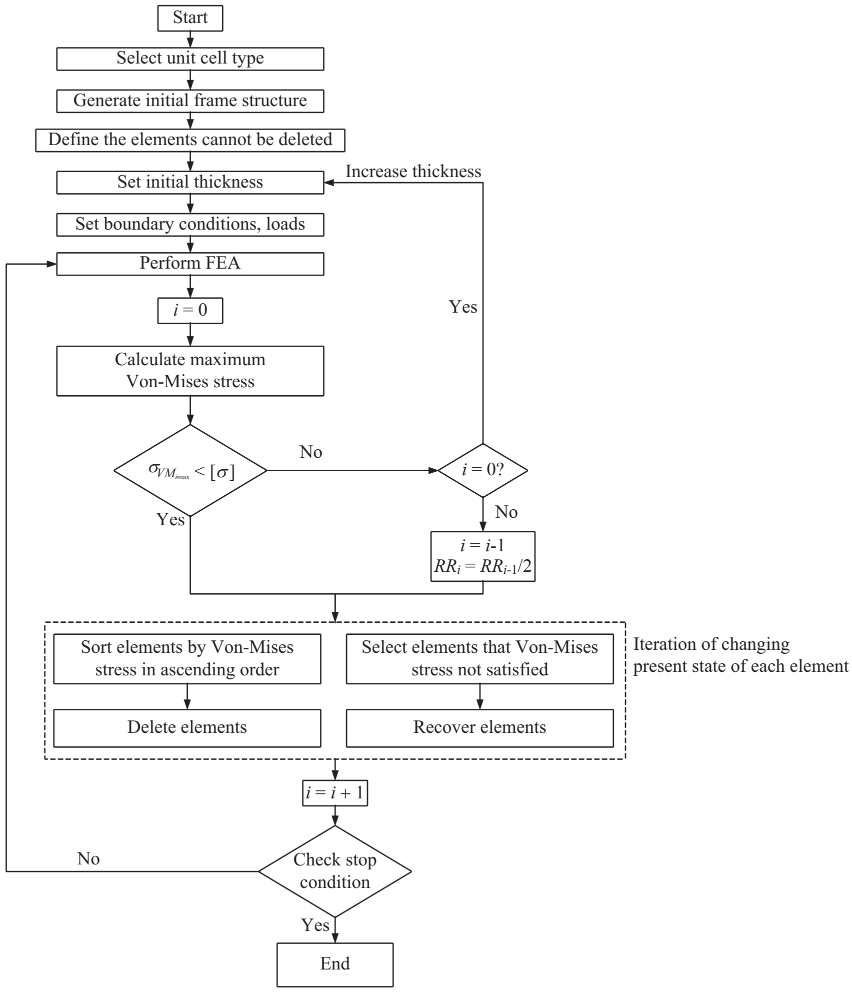


Fig. 3. The general workflow of BESO-based optimization algorithm.

the allowable stress of the material. If $\sigma_{VM_{i\max}} \le [\sigma]$, it means that parts of the structure can be removed, go to step 6. If $\sigma_{VM_{i\max}} > [\sigma]$, it means that the structure needs to be strengthened, go to step 7.

Step 6. According to a prescribed rejection ratio RR_i, the number of elements to be removed can be calculated by:

$$N_{DELi} = N_i \times RR_i$$

where N_{DELi} is the number of elements to be removed, N_i is the total number of elements in current *SE*2. The first N_{DELi} elements in *SE*2 can be removed in this iteration. The set of IDs of removed elements is stored in a list *del_elem_list_i*.

Step 7. If the iteration does not start, it means that the structure is too weak, so the thickness should be increased to make the structure have some redundancies, return to Step 1. If the iteration is in progress, it means that some efficient materials have been deleted in last iteration, which should be recovered in this iteration. There are two ways to recover the deleted elements. First, a higher initial rejection ratio will cause more elements to be deleted, then return to the previous iteration step and lower the rejection ratio, and continue the iteration process. If this method cannot lower the stress, then execute the second method, which selects the elements that the Von Mises stress has exceeded the allowable stress, and recovers the removed neighbor elements. The set of IDs of recovered elements is stored in a list *rec_elem_list_i*, and these elements should not be removed again in next iterations.

Step 8. Repeat step 3- step 7, when stop condition is not met.

III. MULTI-LEVEL BEAM-PLATE STRUCTURE OPTIMIZATION METHOD

1. Outline of the Procedure

The procedure of the proposed method covers three optimization levels: dimension optimization, topology optimization and sectional parameter optimization. The flowchart for the whole procedure is shown in Fig. 4, which can be explained as follows.

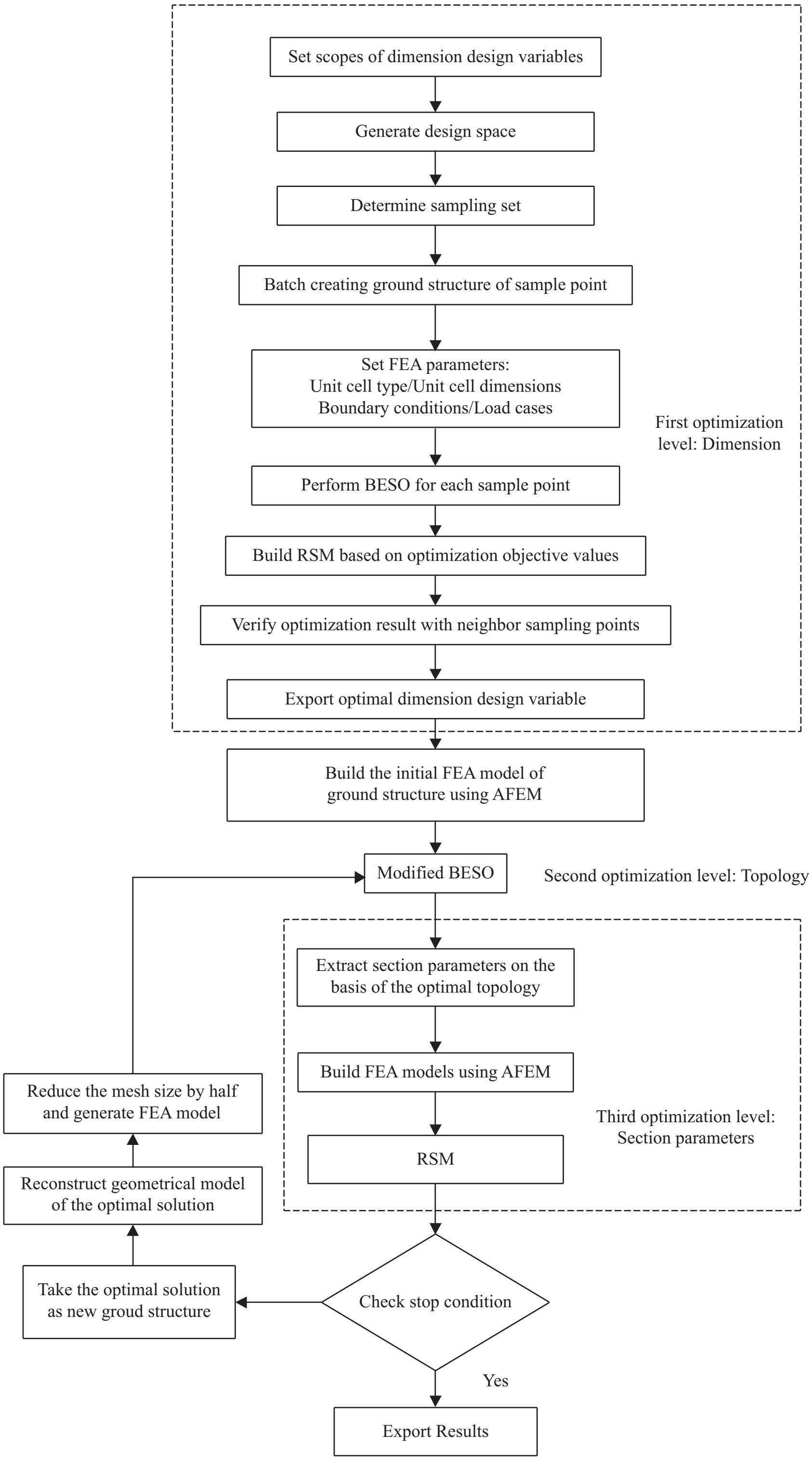
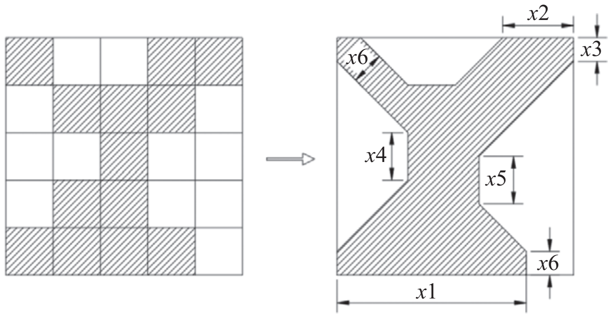
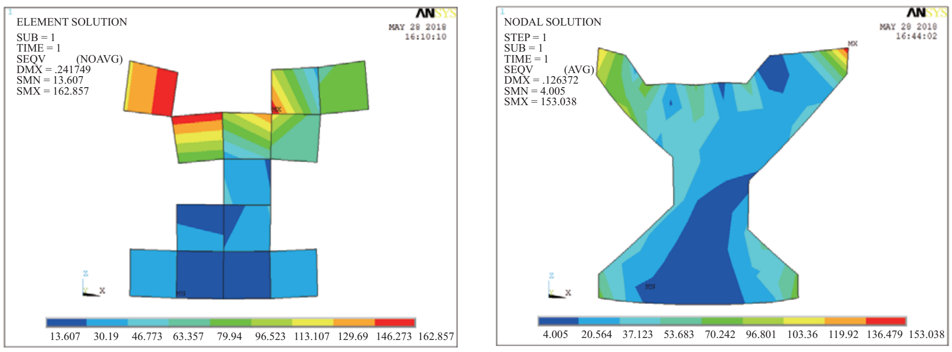


Fig. 4. The general procedure of multi-level beam-plate structure optimization method.

(1) Dimension optimization. It is very important to determine a set of the most appropriate dimensional parameters at the early design stage, because the general dimension parameters (GDPs) have the biggest influence on structural performance. The proposed improved BESO is used as kernel optimization procedure (KOP) to obtain the optimal topology from a ground structure decided by GDPs, through this way the optimization potential of each group of GDPs can be observed. However, change of structure dimension values usually leads to the reconstruction of FEA model, and



(a)



(b)

Fig. 5. The concept of conversion of optimal topology.

the calculation of sensitivity analysis will be much more and harder due to the non-linear relationship of element rigidity matrix and design variables. An effective and easy method is to use surrogate model to simulate the real problem. Response surface method (RSM) (Lee et al., 2015), design and analysis of computer experiments (DACE) (Su et al., 2005), artificial neural network (ANN) (Srinivas and Ramanjaneyulu, 2007) and Kriging method (Simpson et al., 2001) are some common approximations usually used to surrogate the original simulation model. In this paper, RSM is adopted to determine the most suitable dimensions based on the objective values and dimension values of selected samples. The sample data including GDPs and corresponding optimal results are used to create RS model.

(2) Topology optimization. Once the optimal GDPs are determined, the KOP should be performed again, which takes the configuration parameters of the ground structure, the boundary conditions and the load cases as input data and performs topology optimization by using the improved 3D BESO.

(3) Sectional parameter optimization. In general, the optimal topology obtained by BESO only provide hints as to how the optimum structure could look, in other words the manufacturability is not good enough for practical use, hence it is necessary to convert to make the connection parts smoother and turn the optimal results into a realistic engineering design plan. Fig. 5 shows the concept of shape converting through a simple example. In the left part of Fig. 5(a), the blank cells mean the elements are deleted while the shadowed cells represent the remained elements, which naturally form irregular edges. These irregular edges are composed of orthogonal lines. In the right part of Fig. 5(a), each irregular edge is smoothed by using line connecting the start point and the end point. And the converted shape can be described by a series of parameters. By reducing sharp angles on edges, smoothing these irregular edges is also good for preventing stress concentration, which can be observed from Fig. 5(b).
If applied to the whole structure, the conversion will cause many undetermined section parameters, which is a complex problem with high computational expense, and also a continuous variable optimization problem. To deal with this problem, surrogate model is also used. The whole procedure is that according to the optimal solution of topology optimization level, extract section parameters from the rough topology, set the scopes of section parameters to form the design space, create the corresponding FEA model of each section parameter combination, build the response surface model based on the objective values and section parameter values of selected samples, and finally, find the optimal solution. Thus, the final optimal structure can be determined.

(4) Iteration strategy. Mesh size has a great effect on the optimization result and optimization efficiency. Choosing a small mesh size results in high computation cost but good optimization result, and a large mesh size could only obtain

a rough result. In order to balance the optimization effect and efficiency, an iteration strategy is proposed to solve the problem. At first, the initial mesh size could be set to a modest value to create the ground structure and perform topology optimization by using improved BESO, and then the optimization result should be checked if the convergence criteria are fulfilled. If there were still space to improve, we may take the optimal topological solution as new ground structure, reconstruct the geometrical model, reduce the mesh size by half, generate the FEA model and repeat the topology optimization. Otherwise the optimization should be stopped.

It is obvious that conversion of the result of topology optimization in each iteration step will cause a lot of calculation while lowering the efficiency. Hence, it is recommended to execute the process of sectional parameters extraction and determination only at the end of the whole iteration, but not at each iteration step in the intermediate processes.

2. Application of RSM

RSM is based on employing the statistical and experimental techniques, when reasonably applied, to deal possibly with more configurations of the input parameters to be tested and explore deeply the domain of the problem's solutions (Lee et al., 2015). The RS function is a smooth, explicit and analytic form which is obtained simply by carrying out limited experiments and regression analysis. Among all types of RS model, the second-order model is widely used because of its flexibility and ease of use. With k variables, it can be written as

$$\hat{y} = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \sum_{i=1}^{k} \beta_{ii} x_i^2 + \sum_{j<i}^{k} \beta_{ij} x_i x_j + \varepsilon \qquad (2)$$

where x are the design variables of the considered problem, β are the regression coefficients, and ε is the random experimental error term and its mean value is zero. The unknown regression coefficients β are typically estimated by using the method of least squares.

As previously mentioned, to deal with the complex variable determining problem including dimension optimization and section optimization in a large design space, applying RSM can reduce computational expense and satisfy the computational precision simultaneously.

Based on the response surface model, the dimension optimization problem can be expressed as

$$\begin{aligned} &To\ find: X = \{x_1, x_2, \ldots, x_K\} \\ &Minimize: W = f(x_1, x_2, \ldots, x_K) \\ &s.t.: \sigma_{VM} \le [\sigma] \\ &\qquad x_{\min} \le x_i \le x_{\max} \end{aligned} \qquad (3)$$

where x are the dimension variables of the designed structure, K is the number of dimension variables, σ_{VM} is the maximum Von-Mises stress of current design plan, $x_{\min}$ and $x_{\max}$ are the minimum and maximum of the ith dimension variable, respectively.

And the section optimization problem can be expressed as

$$\begin{aligned} &To\ find: X = \{x_1, x_2, \ldots, x_P\} \\ &Minimize: W = \sum_{i=1}^{Q} \rho A_i t_i = \sum_{i=1}^{Q} \rho t_i f(x_1, x_2, \ldots, x_P) \\ &s.t.: \sigma_{VM} \le [\sigma] \\ &\qquad x_{\min} \le x_j \le x_{\max} \end{aligned} \qquad (4)$$

where x are the section parameters extracted from the optimal topology of BESO solution, P is the number of section parameters, A_i is the area of the ith plate that determined by x, t_i is the thickness of the ith plate, σ_{VM} is the maximum Von-Mises stress of ith shell element, $x_{\min}$ and $x_{\max}$ are the minimum and maximum of the ith section parameter, respectively.

Table 1. Design parameters of Silin ship lift.

Parameter	Design value
Upstream highest water level (m)	440
Upstream lowest water level (m)	431
Downstream highest water level (m)	374.5
Downstream lowest water level (m)	363.3
Maximum lifting height (m)	76.7
Ship tonnage (t)	500
Length of ship chamber (m)	70
Width of ship chamber (m)	16
Height of ship chamber (m)	7
Total weight of ship chamber (t)	3000
Rated lifting force (kN)	2100
Total weight of counterweights (t)	3000
Rope diameter (mm)	60
Pulley diameter (mm)	4000
Lifting speed (m/s)	0.2
Lifting acceleration (m/s^2)	0.04
Motor power (kW)	4 × 250

IV. STRUCTURAL OPTIMIZATION PROBLEM OF A SHIP CHAMBER

Silin Hydropower Station is located in the middle reach of the Wujiang River, in Sinan County, Guizhou Province. The main task of the hydropower station is generating electricity, and also includes shipping, flood control, and irrigation. Through comparative studies among different patterns of passing dam including ship lock, inclined ship lift and vertical ship lift, vertical ship lift is most suitable for architecture layout in canyon. The main design parameters of ship lift running are listed in Table 1.

The ship chamber is designed for passenger ships with a maximum water displacement of 500 tons, maximum length of 55 m, maximum width of 10.8 m and maximum draught of 1.6 m.

Table 2. Material properties of steel.

Material	Young's modulus	Poisson ratio	Yielding stress	Safety factor	Density
Steel	2.06 GPa	0.3	315 MPa	1.33	7860 kg/m^3

Table 3. Boundary conditions of calculation model.

Position	Linear displacement constraint			Angular displacement constraint		
	δx	δy	δz	θx	θy	θz
Lifting point (A)	-	Fixed	Fixed	-	-	-
Balanced lifting point (B)	-	-	Fixed	-	Fixed	-

Table 4. Design parameters of ground structure modeling.

Item	Meaning	Range	Step size
H	Total height (mm)	5000-6000	250
h	Bottom height (mm)	2500-3500	250
w	Wall width (mm)	1750-2250	250
t	Primary thickness (mm)	18-22	1

Table 5. Value of optimization setting parameters.

Unit cell type	Unit cell size	Initial rejection ratio	Maximum iteration time
Cubic box	250 × 250 × 250	0.1	200

The 70 m long and 16 m wide ship chamber structure will be built as a self-supporting steel construction. The depth of water in the chamber is 2.5 m and there is a freeboard of 0.5 m. On each side, 40 evenly distributed ropes are connected to the counterweights, with 10 ropes in each counterweight group. This results in a very even load transfer into the chamber. The ship chamber extends into the lower and upper bays at the ends.

For reducing the structural weight, the total height, the width of the wall and the height of the bottom are taken as design variables, which are shown in Fig. 6. The material properties are shown in Table 2. The design of the chamber was based on GB 51177-2016 'Design code for ship lift'. According to the code, the longitudinal maximum deformation should be less than 70 mm, and the transverse maximum deformation should be less than 21 mm.

As the worst condition, the extreme load case of the chamber completely filled with water is considered. The loads include static water pressure on the inner plate of wall and the top plate of the bottom, which is shown in Fig. 6. The boundary conditions of lifting ship chamber are applied at the rope pulleys, which is shown in Fig. 7 and Table 3. Due to the symmetry of the structure, loads and boundary conditions, only 1/4 of the whole domain is modeled.

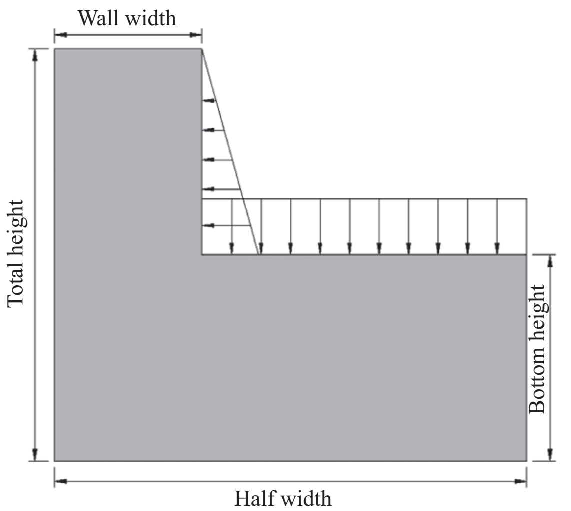


Fig. 6. Loads on the wall and bottom of the ship chamber.

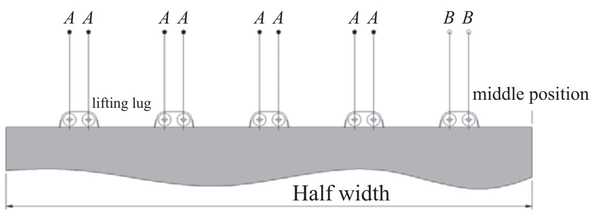


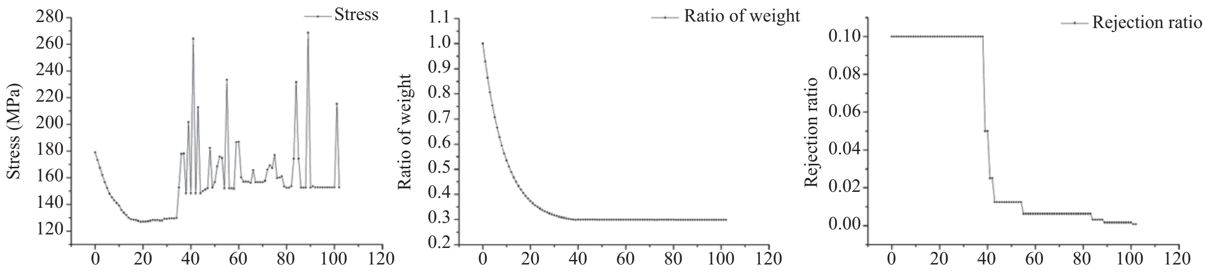
Fig. 7. Boundary conditions of calculation model (1/4 model).

1. Dimension Optimization

In the dimension optimization level, the design variables are those GDPs remained undetermined or not restricted, which in-

Table 6. Results of dimension optimization.

Item	Value
Total height (mm)	5000
Bottom height (mm)	2500
Wall width (mm)	2000
Primary thickness (mm)	20
Weight (t)	247.6
Maximum stress (MPa)	187.6
Deformation (mm)	18.6



(a) Iteration history of maximum equivalent stress (b) Iteration history of the ratio of weight to the initial weight (c) Iteration history of the rejection ratio

Fig. 8. History of design attributes of improved BESO.

clude the total height, the bottom height, the wall width, the frame spacing and the primary plate thickness. Based on the design parameters shown in Table 4 and the optimization parameters shown in Table 5, there are 225 design variable combinations in total, and these initial structures are generated and optimized.

According to the BESO results of these 225 design variable combinations, the function relationship between weight and design variables is presented as follows.

$$Weight = 2791.5 - 0.1886H \text{-} 0.1143h - 0.4515w - 163.48t + 2.1\times10^{-5}H^2 + 2.8\times10^{-5}h^2 + 1.16\times10^{-4}w^2 + 4.25t^2 \quad (5)$$

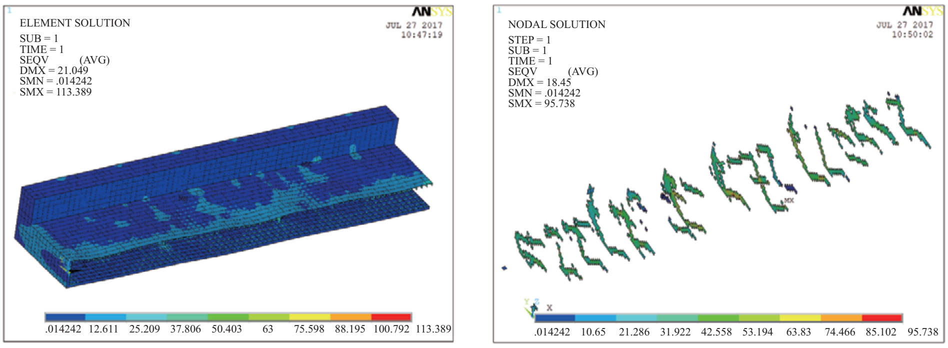
Based on these RS functions, the optimal factor combination is calculated and the results of BESO-based optimization are shown in Table 6.

To get better insight into the problem of convergence and the contribution of the proposed algorithm, the history of the optimization attributes of one design configuration (H = 5000 mm, h = 2500 mm, w = 2000 mm, t = 20 mm) is given in Fig. 8 with respect to optimization cycle number. The values of stress and weight are normalized to express the overall iteration history clearly. Fig. 8(a) shows the iteration history of maximum equivalent stress. Fig. 8(b) shows the iteration history of the ratio of weight to the initial weight. Fig. 8(c) shows the iteration history of the rejection ratio.

The initial rejection ratio is set as 0.1. In the first 37 iterations, the weight decreases quickly because there exist redundant elements in initial design domain, however, at the 38th step the maximum equivalent stress has exceeded the allowable stress, which means some efficient elements are mistakenly deleted. At the 39th step, the mistakenly deleted elements are recovered, and the rejection ratio is lowered as half of the initial value and the iteration is continued. It can be observed from Fig. 8(b) that the weight of step 38 is the same as the weight of step 40. These steps demonstrate the necessity of using dynamic rejection ratio, otherwise the iteration cannot continue. In the following steps the mechanism is repeated by 7 times, at last the rejection ratio has diminished to 0.00078. Fig. 8(a) also shows that in the last 3 steps, the maximum equivalent stress has exceeded the average value of its neighborhood once while the rejection ratio remains a very small value, and there is almost no change in the weight curve. Actually the changes are caused by deleting 2 elements and recovering them, which means that no more redundant elements can be deleted, no matter how small the rejection ratio is. Under this circumstance, the optimization converged for the stop condition is satisfied. Different from some existing methods as GA, ANN, the convergence criterion of the proposed method is clear and consistent with the nature of weight optimization problem. Therefore, the convergence of the proposed method can be assured.

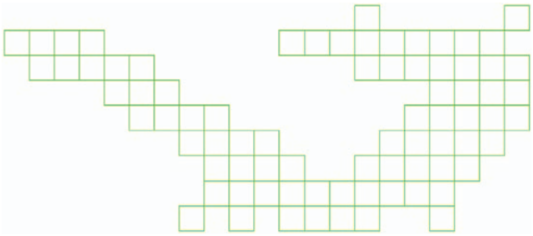
2. Topology Optimization and Section Optimization

According to the optimal GDPs, the corresponding ground structure is created, and then the topology optimization is performed by improved 3D BESO. Fig. 9 shows the optimal topology. Because the hull including deck, endplate, wall plate, bottom plate, and top plate of bottom must remain integral du-

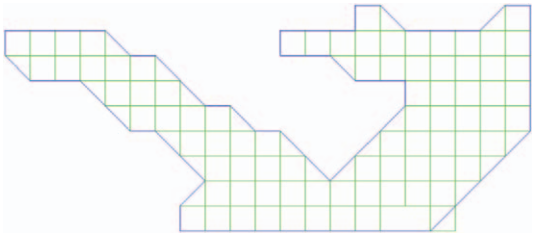


(a) Stress and deformation of optimal solution (b)Stress and deformation of inner transverse frames

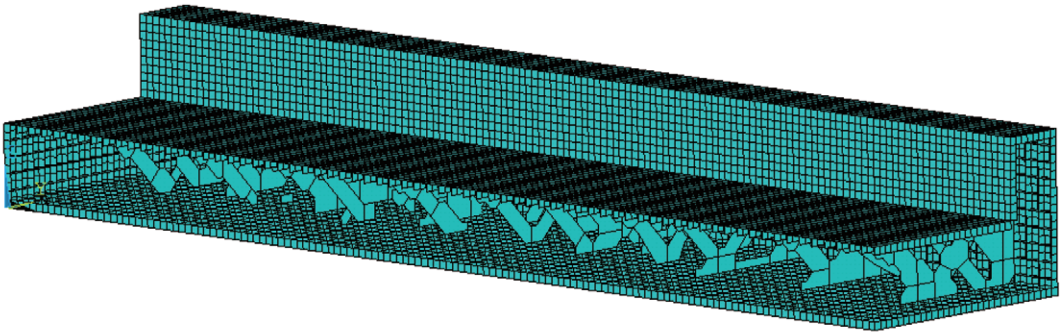
Fig. 9. Optimal topology based on the optimal GDPs.



(a) The original shape of No.3 transverse frame determined by the improved BESO



(b) The converted shape of No.3 transverse frame



(c) The converted geometrical shape of inner transverse frame structure

Fig. 10. The conversion of the topology of the improved BESO.

ring the whole optimization process, it will be removed in the following figures of optimal topology to show the inner support structures clearly, like Fig. 9(b).

Through reviewing the optimal results shown in Fig. 9, no element should be removed further, but some parts are still less efficient, hence it is necessary to refine the optimization. The process is to build the geometrical model according to the location and size of existed elements, set smaller mesh size to create the new meshes, and form a new ground structure. Before the refining optimization started, a conversion should be made, which is to replace the jagged edges by straight edges to form clear sections. No. 3 transverse frame is taken as an example to demonstrate how to convert the last optimization results to new ground structure. Fig. 10(a) shows the original shape of the transverse frame determined by the improved BESO, and Fig. 10(b) shows the converted shape of the transverse frame. Note that the conversion is only about geometrical shape, but not about the element type. Once the geometrical shape is determined, the mesh should be refitted to perform FEA. As shown in Fig. 10(c), the weight of the structure is 249.3 t (1/4 model).

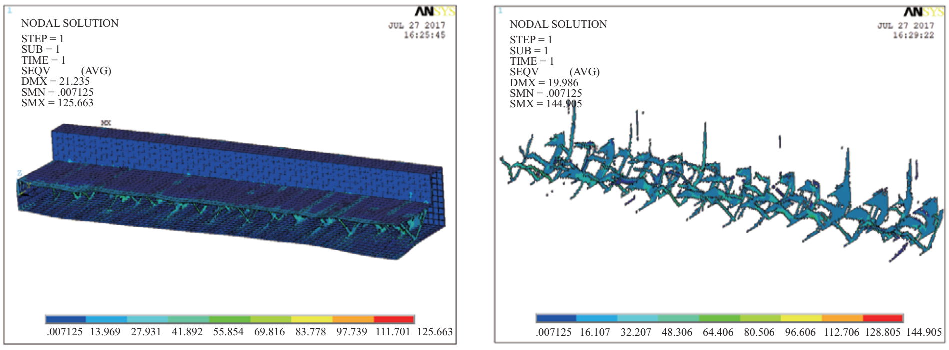
The refined optimization result is shown in Fig. 11. Compared with the preliminary optimal topology, the refined topology is more effective to reduce the weight and the maximum stress.

Still, the transverse frames need to be converted. Fig. 12(a) shows the shape of No. 3 transverse frame determined by the improved BESO, Fig. 12(b) shows the converted shape of No. 3 transverse frame and extracted section parameters. In total there are 7 extracted sectional parameters in the converted shape.

To lower calculation cost, the quadratic crossover items in (2)

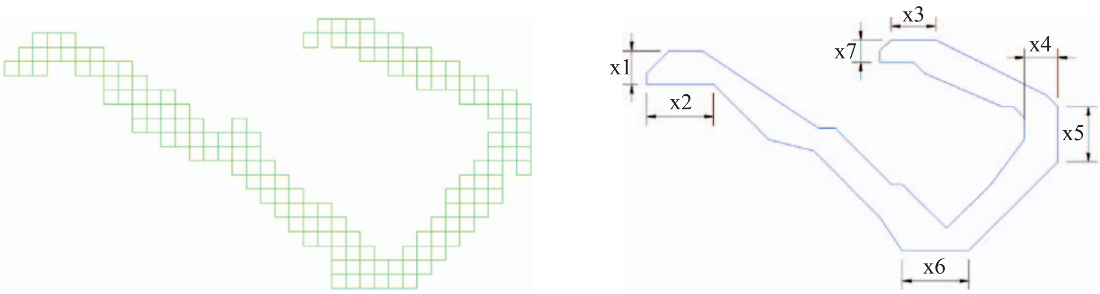
Table 7. Optimal values of section parameters.

Variable	Initial value (mm)	Optimal value (mm)	Minimum (mm)	Maximum (mm)
x1	375	353	250	500
x2	750	721	500	875
x3	500	536	375	750
x4	375	391	250	500
x5	500	506	375	625
x6	750	818	500	1000
x7	250	289	200	375



(a) Calculation result of whole structure (b) Calculation result of the inner transverse frame

Fig. 11. The refined optimization result.



(a) The shape of No.3 transverse frame in the refined optimal result (b) The extracted parameters of No.3 transverse frame

Fig. 12. Conversion of refined optimal topology.

are removed, the response surface model is built in the following form:

$$\hat{y} = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \sum_{i=1}^{k} \beta_{ii} x_i^2 + \varepsilon \tag{6}$$

With 336 sampling points, the constructed response surface model is expressed as:

$$\begin{aligned} Stress = {} & 98.37 + 0.27877x_1 + 0.20483x_2 - 0.11963x_3 \\ & + 0.041201x_4 - 0.50537x_5 \\ & + 0.060651x_6 + 0.831x_7 - 0.00044x_1^2 \\ & - 0.00005x_2^2 + 0.000008x_3^2 \text{-} 0.00318x_4^2 \\ & + 0.00019x_5^2 - 0.00031x_6^2 + 0.01607x_7^2 \end{aligned} \tag{7}$$

The 7 section parameters are treated as continuous variables, branch and bound algorithm is adopted to solve the weight optimization problem. Table 7 and Fig. 13 show the final optimization result.

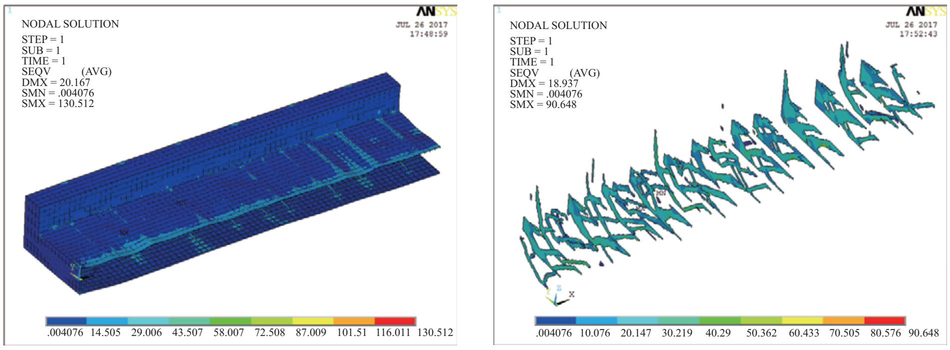
After sectional parameter optimization, the mass of ship chamber structure is further reduced by 5.01%, which is 236.8 t (1/4 model). The successful reduction of the mass is benefited from the proposed multi-level optimization method.

3. A Comparison with GA-Based Structural Optimization Method

To examine the effectiveness and computation efficiency of the proposed method, it is better to compare with existing methods. As a common structural optimization method, GA-based structural optimization method is selected to compare. To make a fair comparison, a conventional structural design is made by

Table 8. Structural optimization results of different methods.

Method	Conventional design	GA-based optimization method	The proposed method
Optimization parameters	-	Population size = 2834 Crossover rate = 0.6 Mutation rate = 0.09 Number of design variables = 98	Dynamic rejection ratio, $RR_0 = 0.1$
Optimization levels	-	Section	Dimension, topology, section
Total iterations	-	893	15 sampling points + 163 iteration steps + 215 sampling points
Mass (t)	310.3	286.7	236.8
Error	-	7.8%	-



(a) Calculation result of whole structure (b) Calculation result of the inner transverse frame

Fig. 13. The final optimization result.

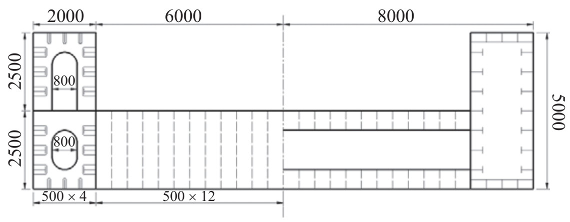


Fig. 14. Cross section of conventional design plan.

using the optimal GDPs, which consists of wall, bottom, transverse frames and longitudinal stiffeners. Fig. 14 shows the cross section of a conventional design plan. Based on this, GA-based structural optimization method is used. The used parameters and weights of the two structural optimization methods along with the conventional design plan are listed in Table 8. The biggest difference is that GA-based structural optimization method cannot change the topology but only some sections of the structural members, whereas the topology of solution of BESO is a little part, or even a transformation of the initial solution.

It should be noted that the optimization objective has a great effect on the optimal topology in BESO, if the optimization objective is changed, the produced optimal topology would be changed as well. In this paper, the objective is to seek a minimum weight. It is observed the proposed method produces the lower value of mass than GA-based optimization method while it takes less calculation.

It should be also noted that the improved BESO method usually requires a finer mesh, especially when the final volume is a low fraction of the initial volume. The computational efficiency of BESO methods highly depends on the parameters including rejection ratio and the mesh size. Usually, a small rejection ratio and a fine mesh could make the optimization process stable and produce a satisfied solution.

Compared with BESO, GA-based optimization method requires much more iterations and would result in higher value of objective function. In GA-based optimization method, the amount of computation highly depends on the amount of structural members and the value range of section parameters. The more the parameters selected, the greater the amount of computation required.

V. CONCLUSION

This paper presents the whole process of ship chamber structural optimization for vertical ship lift of Silin Hydropower Station. For this, a multi-level optimization method for beam-plate structure by using BESO and RSM is developed, which covers three optimization levels, as dimension optimization, topology optimization and section optimization.

In the first optimization level, optimal GDPs are obtained by performing RS-based optimization on the basis of a RS model built by different GDPs and preliminary topology optimization objectives. In the second optimization level, BESO method is used. To better fit the beam-plate structure design problem, the initial design domain is composed of box-shaped unit cells, instead of conventional solid elements. BESO-based topology optimization is a kind of discrete variable optimization, hence the optimal topology usually has an irregular structural layout, which would lead to the requirement of improving manufacturability. The conversion of optimization results produced by BESO-based topology optimization turned out to be the problem of determining the sectional parameters, which is a continuous variable optimization.

The results show that the proposed method can decrease the ship chamber's weight by about 23.69%. The optimization history and the comparison with GA-based method show that the multi-level optimization method can achieve greater weight saving with lower design time cost.

However, the work presented in this paper is just a preliminary effort in the beam-plate structure design. A large amount of work to make the proposed approach into practical use is necessary. Future efforts will be required to perfect the research on the effect of much more unit cell types on the BESO-based optimal topology. Future research will study using level set function to obtain smoother topology that can remove the sharp edges by relaxing the sharpness of the captured image. In the meantime, the module of reconstruction of optimal topology should be further extended by automatic acquisition of the irregular edge type.

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