Optimization Design of a Composite Hull Stiffened Panel Considering Structural Stability

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Abstract: The composite stiffened panels, as the main components of lightweight ships, its design rationality has an influence on safety and economy of ships. Based on response surface methodology and numerical analysis, the structural optimization design of a typical composite stiffened panel was carried out, taking structural stability into account. Through statistical calculations, eigenvalue buckling analysis and response surface optimization design, the anti-buckling capability and weight of composite stiffened panels were obtained. With the minimum weight as the objective function and factoring in requirements for the critical buckling value and the dimension parameters, the optimal design scheme of the composite stiffened panel was acquired by the multi-parameter optimization. The results show that the thickness of the plate and cap beams is very sensitive to the weight and buckling capacity of the stiffened panel. The optimized structure resulted in a weight reduction of 12% and a critical buckling load increase of 23%. This optimization method has practical value and can provide a reference for the design optimization and practical application of composite ships.

1. Introduction

As a new type of functional and structural material, advanced composite has a series of advantages, such as light weight, high specific strength and specific stiffness, corrosion resistance, anti-fatigue, insulation, non-magnetic, good absorption and permeability and strong designability. The application of advanced composite in the marine field is increasing[1-3]. As an important part of lightweight ship, composite stiffened panel is one of the most common units in ship hull structure[4, 5]. Its design is very important to the safety and economy of the ship, and it is an important issue to be considered at the preliminary design and even the whole service cycle of composite ship. Considering weight and cost requirements, a composite stiffened panel is usually designed as a thin-walled structure with a smaller section size and stiffness, and buckling failure easily occurs. The stability of composite stiffened panels is a serious issue, drawing much attention from scholars of ship structural mechanics.

In recent years, some achievements have been made in the study of stability and optimal design of composite hull stiffened panels[6-11],but more emphasis has been placed on unilateral studies such as mechanical properties and geometric optimization, and the combination of two aspects still need to be further studied. The minimum weight or cost of the structure is the goal of optimal design, and the stability requirement is an important constraint. Considering the stability of structure in the optimal design stage of composite ship, is not only helpful to the design and analysis of local structural strength, but also very important to the design and check of overall strength under different working conditions.

Therefore, considering the stability and lightweight of the structure, the typical composite hull stiffened panel was optimized by advanced optimization and numerical calculation method. Through structure statics calculation, eigenvalue buckling analysis and response surface optimization design, the buckling behavior of the composite hull stiffened panel under the dangerous loading condition was analyzed, and the effects of parameters (panel thickness and stiffener spacing, width and thickness) on weight and critical buckling load was Evaluated. Finally, the optimal design scheme with minimum weight and Maximum buckling capacity was obtained. This paper will be useful for the optimization design of composite hull structures.

2. Design Scheme of Composite Hull Stiffened Panel

2.1. Geometric and Material Models

In this paper, the most typical structural unit of composite ship was studied. The stiffened panel is composed of a panel and two stiffeners, which are commonly seen in important bearing positions of ship structures, such as deck, bottom and side (Figure 1). The specific dimensional parameters and material properties are shown in Figure 2, table 1 and table 2.

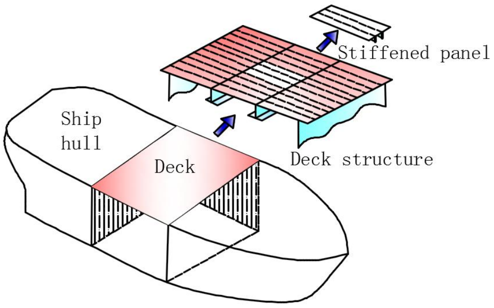


Figure 1: Composite stiffened panels and their position in the ship hull.

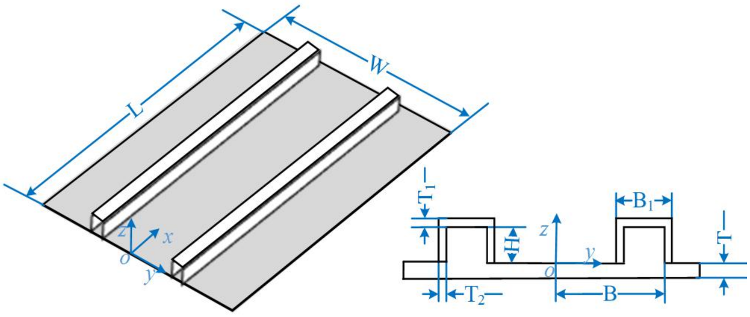


Figure 2: Parameters of the composite stiffened panel.

Table 1: Dimensions of the composite stiffened panel.

Property	Length	Width	Panel thickness	Hat beam spacing	Hat beam width	Hat beam height	Hat beam thickness
Symbol	L	W	T	B	B_1	H	T_1
Value	280 mm	160 mm	1 mm	50 mm	20 mm	20 mm	1 mm

Table 2: Material properties of the composite stiffened panel.

Property	Symbol	Value
Density	ρ	1490 kg/m^3
Elastic modulus in 1 principal material direction	E_1	121 GPa
Elastic modulus in 2/3 principal material direction	E_2/E_3	8.6 GPa
Shear modulus in 1-2 and 1-3 principal material planes	G_{12}/G_{13}	4.7 GPa
Shear modulus in 2-3 principal material planes	G_{23}	3.1 GPa
Poisson's ratios	v_{12}/v_{13}	0.27
	v_{23}	0.4
Tensile strength in fiber direction	X_T	2.23 GPa
Compressive strength in fiber direction	X_C	1.08 GPa
Tensile strength in transverse direction	Y_T	29 MPa
Compressive strength in transverse direction	Y_C	100 MPa
Shear strength	S	60 MPa

2.2. Design Condition and Boundary Conditions

Ships are subject to a variety of loads during the voyage. Practice has proved that when the deck and bottom bearing longitudinal compression loads are most dangerous, so the buckling behavior of hull stiffened panel under this condition has always been focused[8]. Considering the position and function of composite stiffened panel in the ship hull (Figure 1), the boundary condition are designed as deck under compression load of sag condition. In particular, one end of the panel is rigidly fixed, the other end is loaded along the X-axis, and the other two sides are free edges. The specific boundary conditions are as follows: x=0, $u_{x/y/z}=\theta_{x/y/z}=0$. $x=L$, $u_{y/z}=\theta_{x/y/z}=0$. Where, $u_{x/y/z}$ and $\theta_{x/y/z}$ represent the displacement and rotation degrees in the global coordinate system (x, y, z), respectively.

3. Optimization Design of Composite Hull Stiffened Panel

The basic principle of structural optimization is to construct the optimization model, select the appropriate optimization method, and carry out optimization iterative computation under certain constraints, obtain the theoretical extreme of the optimization objective, and then obtain the optimal design scheme of the structure.

3.1. Optimization Model

3.1.1. Objective Function

The objective function is used to measure the quality of a design. What kind of index is adopted to reflect whether the design is good or not has something to do with the technical and economic characteristics of the structure itself. The usual objective functions are weight, volume and cost of the structure. The structural weight is an important index of the optimal design for composite hull stiffened panels, and it can be easily written as a function of design variables. Therefore, the minimum weight of the stiffened panel is taken as the optimization objective.

3.1.2. Design Variable

Design variable, whose value is variable, is selected in the design process to describe the characteristics of the structure. It is usually divided into continuous design variables and discrete design variables. The main geometric parameters of composite stiffened panel include the thickness of the panel, the width and thickness the hap beam, There is also the hap beam spacing, which restrain the hap beam position. These parameters are a series of regular discrete variables in actual production.

3.1.3. Constraint Condition

There are two kinds of constraint conditions for structural optimization, geometric constraint conditions and behavior constraint conditions. In this paper, the optimal design of composite hull stiffened panel must meet the constraints of stability, section size and overall structure. The specific constraint scope is shown in the table 3.

Table 3: Constraint conditions of the composite stiffened panel unit/mm.

Property	Symbol	Original design variable	Lower bound	Upper bound
Panel thickness	T	1	1	2
Hat beam spacing	B	50	35	65
Hat beam width	B_1	20	10	30
Hat beam height	H	20	10	30
Hat beam thickness	T_1	1	0.5	1.5

3.2. Optimization Method

Response surface Methodology (RSM), proposed by Box et.[12], is an experimental design method, It uses regression equation to build the functional relationship between multiple factors and response values in the global scope, and then seeks the optimal design parameter. It is an optimization method which combines experimental design and mathematical modeling and can solve multivariable problems[13].

The response surface method performs experimental design on the set of sample points in the specified design space, fitting the global approximation result of the system response value to replace the real response surface. In the engineering optimization design, the response surface method can not only obtain the change relation between the response target and the design variable, but also output the approximate value of parameters without running the whole solution process completely, and achieve the optimal objective function[14]. In the field of structural engineering, the response surface method is mainly used in optimization design and reliability analysis. As an approximate calculation method, it has been developed and applied rapidly in the past ten years. At present, the response surface method has been used to the structural optimization of mid-section for large ships[15].

3.3. Optimization Calculation Process

Based on the ANSYS Workbench software platform, the composite hull stiffened panel was optimized. There are mainly three parts, geometric model design, mechanical performance simulation and structural optimization. Firstly, parameterized model was built in the design modeler. Secondly, finite element calculation is carried out in the simulation module for loading and solving, and the static analysis and buckling analysis of the composite stiffened panel model was completed. Thirdly, three optimization elements were extracted and the optimization parameters were evaluated in the design explorer. The optimization parameters (design variables, constraints, state variables and objective functions) extracted this time and last time were compared to determine whether the objective function of this cycle is optimal. If it is optimal, the optimal solution will be output at the end of the iteration; otherwise, the design variable would be adjusted to continue the cycle. The specific calculation process was shown in the Figure 3.

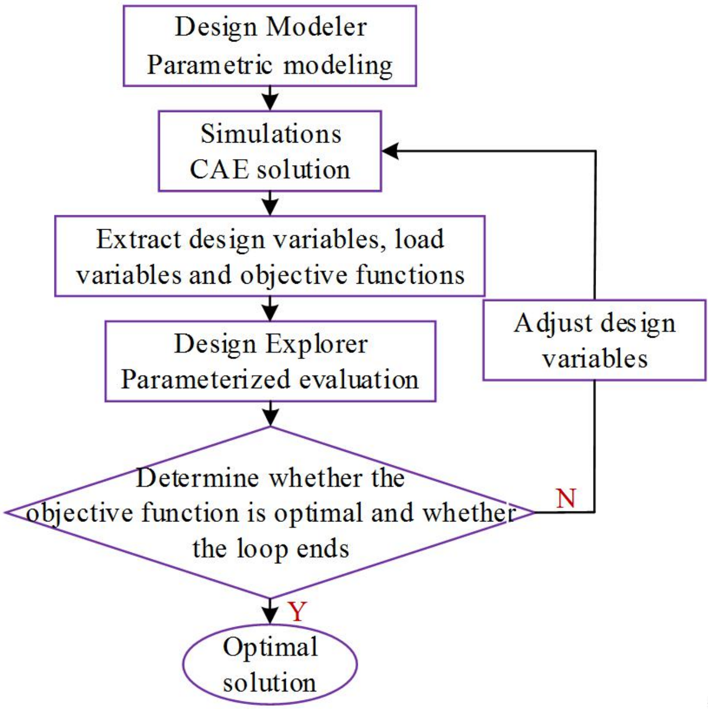


Figure 3: Optimization flow chart.

3.4. Results Analysis

Based on the ANSYS Workbench-Design Explorer module, the optimal design scheme was obtained through design of experiment (DOE) and response surface optimization (RSO) method. First of all, the parameters of the model were analyzed, and the position of the sample point was determined by using central composite design method (CCD). Then, 3D response surfaces were fitted by Full 2nd Order Polynomials, and the screening technology was applied to form 2000 sample points into optimization space. In the end, the response results of each sample points were investigated to get the optimal result.

3.4.1. Local Sensitivity

Figure 4 shows the local sensitivity of composite stiffened panel. As can be seen, the critical buckling load (P_{cr}) of the stiffened panel is affected by 5 parameters, and the influence degree is $T > T_1 > B > H > B_1$, respectively. The weight (m) of the stiffened panel is mainly influenced by the parameters T and T_1, followed by the parameters H and B_1. The parameter B has nothing to do with the weight. Where, the weight and critical buckling load increase significantly with the parameters T and T_1, and the two parameters need to find a suitable compromise point. Parameter *B* has no effect on weight, and a relatively large value within the constraint range can be selected based on the anti-buckling capacity.

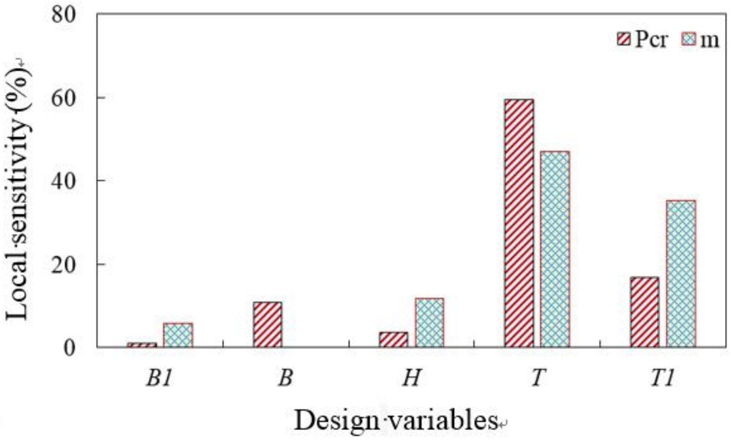


Figure 4: Local sensitivity.

3.4.2. Response Surface

As shown in Figure 5 to Figure 8, they are 3D response surfaces where different output parameters change with design parameters. It can be seen from Figure 5 and Figure 6 that the weight of stiffened panel increases linearly with the design variables (*H*, B_1, T_1 and *T*). And the changes of T_1 and *T* have a greater impact on the weight, which is consistent with the local sensitivity result in Figure 4. Figure 7 and Figure 8 indicates that critical buckling load rises with the same design variables (*H*, B_1, T_1 and *T*), and the influence degree is *T*, T_1, *H* and B_1, which is also agree with the local sensitivity result in Figure 4.

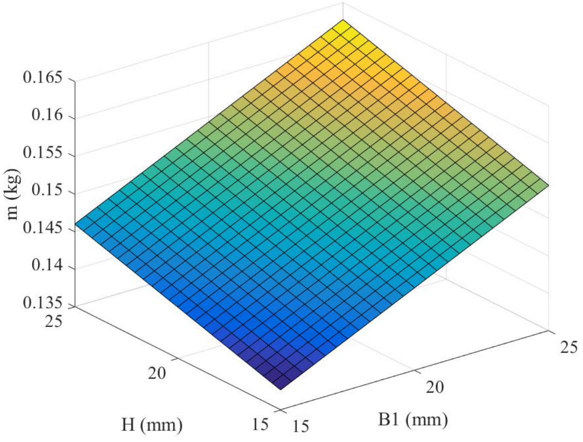


Figure 5: The response surface of m varying with parameters H and B1.

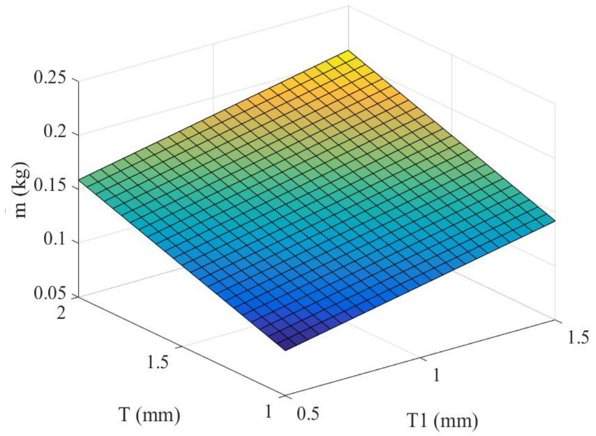


Figure 6: The response surface of m varying with parameters T and T1.

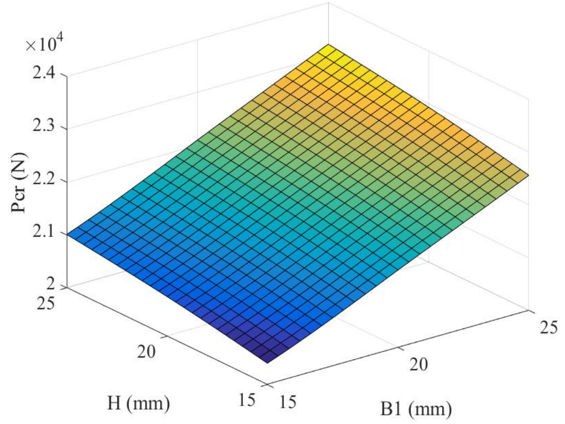


Figure 7: The response surface of Pcr varying with parameters H and B1.

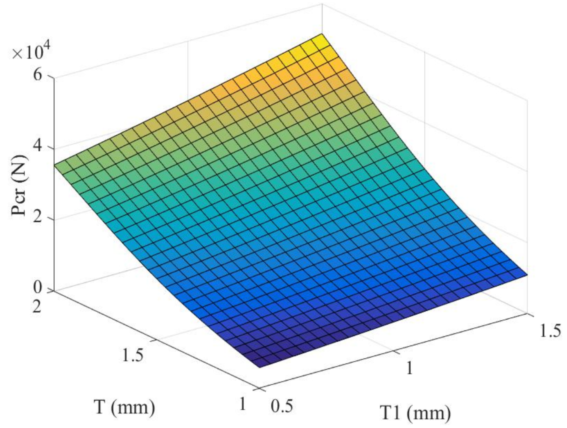
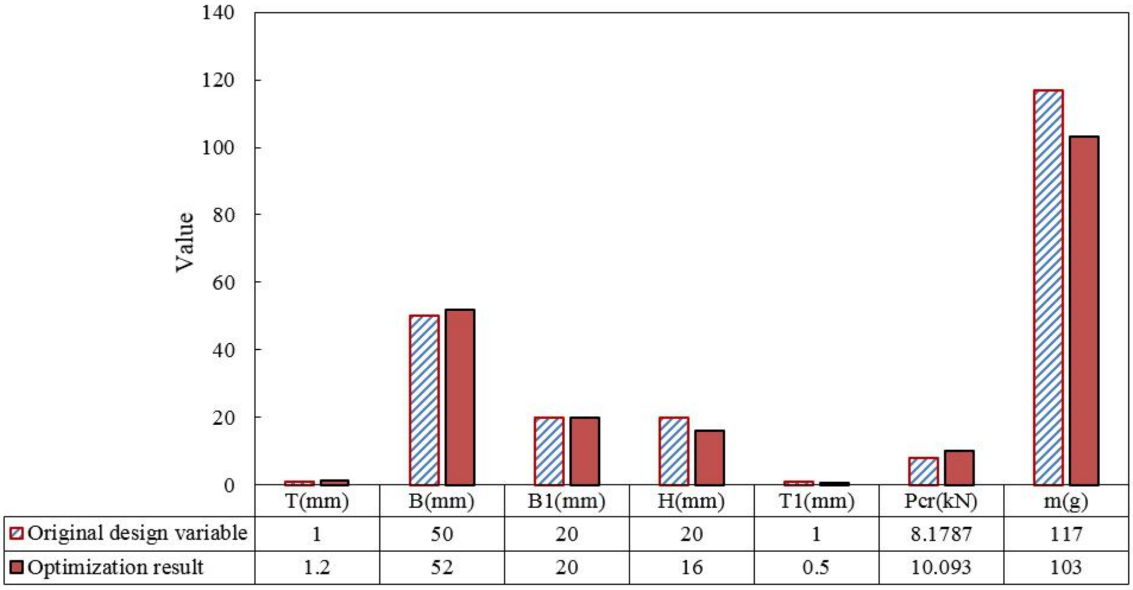


Figure 8: The response surface of Pcr varying with parameters T and T1.

3.4.3. Optimization Result

Entering the response surface optimization module, the optimal solution on the generated response surface was found with the goal of minimum weight and critical buckling load greater than 10 kN. According to the target requirement, the system automatically generated three candidate design points. Considering software evaluation results, the variable parameter with the lowest weight was selected as the final optimization result. The lightweight results of composite hull stiffened panel were shown in Figure 9. Comparing with the original design, the optimized result reduced weight by 12% and increased critical buckling load by 23%.



	T(mm)	B(mm)	B1(mm)	H(mm)	T1(mm)	Pcr(kN)	m(g)
▨ Original design variable	1	50	20	20	1	8.1787	117
■ Optimization result	1.2	52	20	16	0.5	10.093	103

Figure 9: Optimization results of the composite stiffened panel.

4. Conclusions

As a typical structural form of lightweight ship, composite stiffened panel is prone to buckling failure during operation. In order to effectively reduce the weight of the ship structure and ensure sufficient anti-buckling capacity, the dimensional parameters of typical composite stiffened panel was optimized by ANSYS simulation computing platform and response surface optimization method, and the optimal design scheme was obtained. The results show that the thickness of the panel and the cap beam has important effects on the weight and stability of the whole structure. The optimal design offers a weight reduction of 12% and increases the anti-buckling capacity by 23%. This paper has a certain practical value and can provide references for the design optimization and practical application of composite ships.

Acknowledgments

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