Optimization of Lightweight Structure for Ship Railings Based on Abaqus

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Abstract: With the development of the shipbuilding industry, the requirements for the safety and corrosion resistance of ship structural components are becoming increasingly high. Most of the components used in traditional ships are made of steel, which cannot meet the requirements of corrosion resistance and safety for existing ships. In order to improve the structural safety and corrosion resistance of ship railings, as well as their requirements for lightweighting, this article proposes a lightweight design for ship railing structures based on the existing T700 carbon fiber composite material railing structure. Carbon fiber composite materials have the advantages of light weight, high strength, and high modulus. Based on the anisotropy of carbon fiber composite fibers, the characteristics of overlapping/weaving structures, and the influence of the interface between carbon fiber composite materials and metal materials on the strength of ship railing structures, a finite element simulation model of carbon fiber composite materials is established. By setting constraints such as volume fraction, stress, strain, displacement, etc. based on the simulation model, the layout of materials in the optimization results is used to guide the design of the structure. The size parameters of the ship railing barrel are optimized, and the topology structure is optimized. Thus achieving lightweight design of ship railings and meeting the requirements for lightweight, safety, service life, and corrosion resistance of ship structural components.

Keywords: composite materials; ship railings; lightweight

I. INTRODUCTION

In recent years, with the further development of large-scale ships and the international shipping industry, the pace of upgrading and replacement of ocean going cargo ships has gradually accelerated, and new types of ships have emerged one after another. However, with the continuous advancement of technology and the increasing awareness of environmental protection, as well as the further improvement of people's requirements for the use of ship structures, traditional metal structures still have some significant problems in terms of weight and corrosion resistance. As a key equipment for the safety protection of personnel on board, the design and materials of ship railings are becoming increasingly diverse. The railings of cargo ships are mainly designed to protect the crew, and their structure is relatively uniform. However, the working environment of ocean going cargo ships is relatively complex, which makes the design of railings even more complicated. In addition to meeting the protection needs of crew members such as structural strength and clearance, safety measures must also be taken into account to prevent rusting of ship railings and unexpected incidents. Carbon fiber composite materials are favored due to their lightweight, high strength, and corrosion resistance, making further research on marine railings particularly important.

This article first establishes a reasonable numerical analysis model based on the structure of ship railings, sets material properties, divides reasonable grids, and defines correct contact constraints, boundary conditions, and loads. After calculating the results, topology optimization based

on conditional algorithms is carried out, and it is found that the optimized ship railing structure improves the stress distribution effect. A new model is established again based on the optimization results. The simulation calculation of the optimized ship railing model shows that the maximum stress of the ship railing structure meets the allowable stress of the material, and the volume of the optimized railing column structure material is reduced by 10%, greatly reducing the weight of the ship railing.

II. MATERIAL AND METHOD

This article takes a reversible railing for inland waterway ships as the research object.[1] The ship's reversible railing consists of components such as railing posts, support posts, and coated steel cables. The reversible railing has the functions of quick folding and standing, quick disassembly and assembly. In the standing state, it can prevent personnel from falling from the open part of the deck edge, ensuring personnel safety.

Technical Rules for Statutory Inspection of Inland Waterway Vessels (2019) and the Code for Construction of Steel Inland Ships of the China Classification Society, as well as applicable amendments, have clear regulations on the installation of ship railings: railings should be installed in the open parts of the passenger decks (such as the freeboard deck, deck room, and superstructure deck) of inland passenger ships at positions where no bulkheads are installed, as well as at deck openings, stairwells, and platform edges; On the canopy deck, if it is not a place where crew members often move and work, safety protection facilities such as low railings or anti-skid boards can be installed.[2]

The main design points of the outdoor deck railing for inland passenger ships are as follows:

(1) When designing the dimensions of ship railings, it is necessary to consider the actual area, size, and spatial layout of the loaded cargo, as well as its coordination with the overall environment.

(2) Ship railings need to meet the requirements for their weight and structure, that is, structural lightweight design should be carried out to meet the safety requirements of the ship's operating environment.[3]

(3) Layer design for carbon fiber composite materials Optimization, in order to meet the performance requirements of composite ship railings and optimize the tensile performance of carbon fiber composite materials.[4, 5]

(4) Strength: The railing columns, handrails, and crossbars must meet the requirements of regulations and specifications; Carrying capacity, capable of withstanding a lateral force of 700N from the crew.[6, 7]

(5) Height: The height of the railing should be greater than or equal to 1000mm, but generally should be less than or equal to 1200mm; The height of the railing on the outdoor inclined ladder should not be less than 1000mm from the step surface to the top of the railing when measured vertically.

(6) Service life: Titanium based reinforced carbon fiber composite materials are selected as marine railing materials to meet the requirements of anti-corrosion and other service life for marine railings.

According to technical requirements and relevant specifications and standards, referring to the design of marine metal railings, the overall structural design of marine carbon fiber composite material railings is carried out. The structural schematic diagram is shown in Figure 1.

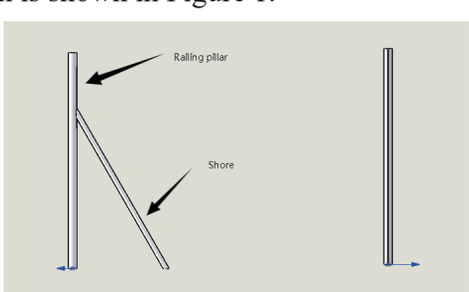

Figure 1 Schematic diagram of carbon fiber composite railing structure

A. MATERIALS

The composite material used in this study is a lightweight and high-strength carbon fiber reinforced epoxy resin based material. (Table 1) Through structural design, it can meet the requirements of lightweight, stiffness, and strength for railings made of marine carbon fiber composite materials. The steel connecting components and fixing parts used are all made of stainless steel. Stress and safety analysis was conducted on the railing. Applying protective coatings that can resist marine environments on the surface of railings made of carbon fiber composite materials can further extend the service life of carbon fiber composite railings.

Table 1 Mechanical performance parameters of T700 carbon fiber composite single-layer board

Parameter	Numerical	Parameter	Numerical	Parameter	Numerical
E11/GPa	152.00	G12/GPa	5.50	Yc/MPa	98
E22/GPa	10.00	G13/GPa	5.50	Zt/MPa	25
E33/GPa	10.00	G23/GPa	5.30	Zc/MP	98
V12	0.34	Xt/MPa	2438	S12/MPa	72
V13	0.34	Xc/MPa	1097	S13/MPa	72
V23	0.28	Yt/MPa	25	S23/MPa	72

The carbon fiber composite materials and surface protective coatings used in this study have been validated through environmental adaptability tests. These materials can meet the requirements of the usage environment for their resistance to moisture, salt spray, high and low temperatures, solar radiation, and mold, effectively solving the corrosion problem of marine railings. Standard layer samples of railings were made using carbon fiber composite materials and subjected to fatigue testing to ensure compliance with the service life standards for marine railings.

B. STRUCTURAL DESIGN

According to the load characteristics and usage environment of the ship railing, its structure is mainly composed of several components such as railing columns and support columns, as shown in Figure 1. At the same time, the maximum outer diameter of the railing column is 42mm, the inner diameter is 36mm, and the outer diameter of the support column is 28mm, which meets the requirements of product function and performance.

The composite railing column is made of domestically produced T700 carbon fiber reinforced medium temperature epoxy resin based prepreg as the base material, and is formed into a whole component through the process of laying and wrapping and the solidification of the support column, ensuring the rigidity, strength, and sealing of the ship railing.

III. SIMULATION RESULT ANALYSIS

After simulating the railing column, the post-processing analysis results are as follows. According to the stress cloud map of the ship railing column (Figure 2), it can be seen that the stress of the ship railing column is concentrated at the connection between the railing column and the support column.

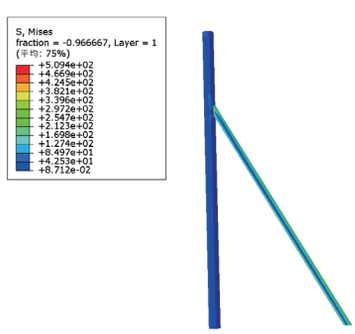

Figure 2 Stress cloud map of ship railing

According to Figure 3, the maximum deformation of the carbon fiber composite railing is 4.54mm; The railing columns and support columns mainly bear axial stress, and the structure is constrained and subjected to uniform pressure loads. They mainly move along the axial direction with uniform changes. The finite element analysis results show that the maximum Mises stress of the railing is

509.4MPa, which is lower than the material strength of 620MPa, indicating structural safety.

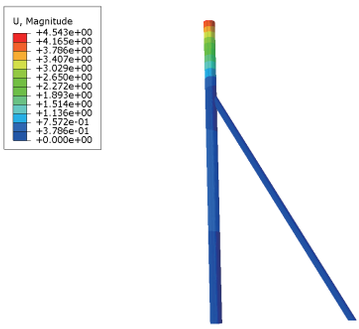

Figure 3 Stress cloud map of ship railing

According to the stress and strain cloud maps, the vertical stress bearing capacity of the railing column is relatively small, and there is a certain degree of lightweight optimization space that needs to be optimized to reduce the overall volume and mass of the vertical railing. Therefore, there is still some stress surplus area in the lower part of the vertical railing column support column, which has certain optimization space. On the basis of ensuring the lightweight design requirements of ship railings, continue to conduct structural optimization analysis on railing columns to reduce the weight of ship railings.

IV. STRUCTURAL OPTIMIZATION ANALYSIS

A Mathematical description of structural optimization design

Design variables:

$$X = [x_1, x_2, \dots, x_n]$$

Make the function:

$$f(x) = f(x_1, x_2, \dots, x_n)$$

Tend to the minimum and simultaneously satisfy the constraint conditions:

$$g_j(x) \le 0 \qquad j = 1, \dots, m$$

$$h_k(x) = 0 \qquad k = 1, \dots, m$$

$$x^P{}_i \le x_i \le x^Q{}_i \qquad i = 1, \dots, m$$

In the formula, $x = [x_1, x_2, \dots, x_n]$ is the design variable; n is the number of design variables; m is the number of performance constraints; P is the number of geometric constraint conditions; Q is the number of constraints between design variables; $f(x)$ is called the objective function or value function, which is defined as a function of the design variable x and is the weight of the entire structure; $g_j(x)$ is called inequality constraint, which states that a structure can only work under certain constraints, which may include stress, displacement, stability, vibration frequency, geometric dimensions, etc; $h_k(x)$ is called an equality constraint, which represents the balance and coordination equation of the entire structure.

The core concept in optimizing the structure of ship railings is to make every effort to save materials in order to achieve optimal material usage. Therefore, the core step of optimization is to remove unnecessary materials while ensuring that the optimized structure can carry the predetermined load, thereby achieving cost savings and structural lightweighting.

B. TOPOLOGY OPTIMIZATION ANALYSIS

Firstly, this study constructed a topology optimization task based on conditional algorithms, with a design cycle count of 15. Then, the design response was further established, which includes strain energy response and volume response, where the design response is a parameter set to define the target or constraint conditions. On this basis, a new multi-scale mixed finite element method was constructed, which transforms complex nonlinear programming into a linear optimization problem at a single scale and solves it using genetic algorithm. The core idea of the conditional optimization problem is to maximize the stiffness of the model structure by minimizing its flexibility, and there is an inverse relationship between these two factors. In the optimization region, the total strain energy of a single unit is used as a key parameter to measure the flexibility of the model structure, with the goal of enhancing the rigidity of the optimized results by minimizing the overall strain energy. The main

goal of topology optimization is to ensure that the maximum strain energy within the design area is minimized (equivalent to maximizing stiffness) while considering the constraints of actual production, with a relative volume constraint of 0.9 (excluding 10% relative volume). Edit the geometric constraints of the frozen area, fix the connecting parts of the ship railing model, and then submit it for optimization tasks for further optimization calculations.

C. OPTIMIZATION RESULT ANALYSIS

According to the optimization results, as shown in Figure 4, it can be seen that when establishing a new model in the next step, holes can be dug in the lower part of the ship railing column support column, so that the maximum stress in this area will not differ too much after further optimization The stress cloud map of the optimized ship railing is shown in Figure 4, and Figure 5 is the strain cloud map of the optimized railing column.

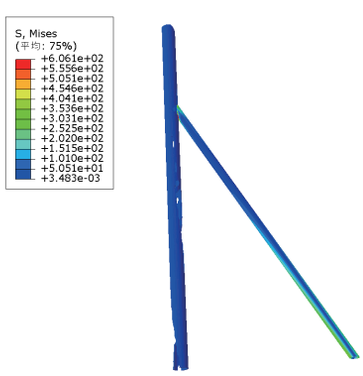

Figure 4 Stress cloud map of ship railing optimization

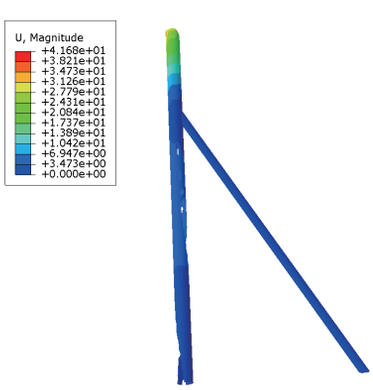

Figure 5 Strain cloud map of ship railing optimization

V. OPTIMIZE MODELING

A.ESTABLISH A NEW MODEL

Use the stress and displacement cloud map optimized by topology as a reference to establish a new model again The new model, as shown in Figure 6, involves drilling holes with straight slots of 383mm through the lower part of the ship railing pillar support column to achieve lightweight design After building the new model in SolidWorks, import it into Abaqus, simulate and analyze it according to the given load, fix the railing column and support column, and apply a 700N lateral load to the upper end of the railing column.

Figure 6 Optimization modeling of ship railings

B. OPTIMIZATION RESULT ANALYSIS

Following the previous analysis steps, the optimized railing column was analyzed. This analysis arranged grids of the same specifications and applied the same load to the railing column. The analysis results showed that the optimized railing column model could withstand the maximum Mises stress and maximum strain, as shown in Figure 7 and Figure 8.

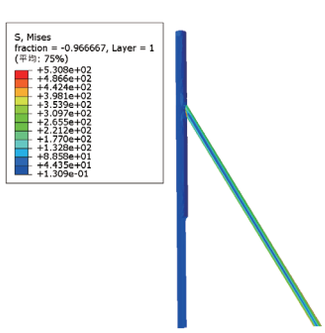

Figure 7 Stress cloud map of ship railing optimization

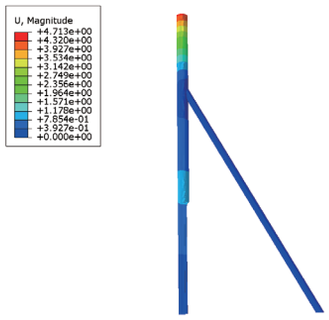

Figure 8 Strain cloud map of ship railing optimization

Overall, as shown in Figures 7 and 8, the stress and strain of the optimized ship railing columns have decreased to a certain extent, and the actual maximum stress is lower than the allowable stress of the material. Therefore, this optimization fully meets the requirements of material safety and lightweight design for ship railings.

VI. CONCLUSION

This article analyzes traditional ship railings and finds that they are heavy in weight, have a short service life, and poor corrosion resistance. On the basis of the original railing structure, carbon fiber composite materials were selected for topology optimization of marine railings. Carbon fiber composite railings can meet the mechanical performance requirements of marine railings, reduce weight by more than 10%, effectively solve the corrosion and weight problems of traditional marine railings, and meet the lightweight requirements of marine railing devices. The research results of this article provide a certain foundation for the optimization of ship structure of carbon fiber composite railings for ships. The optimized design scheme of carbon fiber composite railings for ships proposed in this article has certain reference value for ship designers.

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