

Research on the Performance of Carbon Fiber Composite Railings for Ships

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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 lightweight requirements, this article proposes a lightweight design for ship railing structures based on the advantages of carbon fiber composite materials, such as light weight, high strength, and high modulus, on the basis of the existing traditional metal railing structures for ships. 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. in the given simulation model, the layout of materials in the optimization results is used to guide the design of the structure, and the size parameters of the ship railing barrel are optimized for structural optimization. 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.

1. Introduction

In recent years, with the expansion of ship scale and the vigorous development of 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, 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 cargo ships, the design and materials of ship railings have become 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.

2. 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.

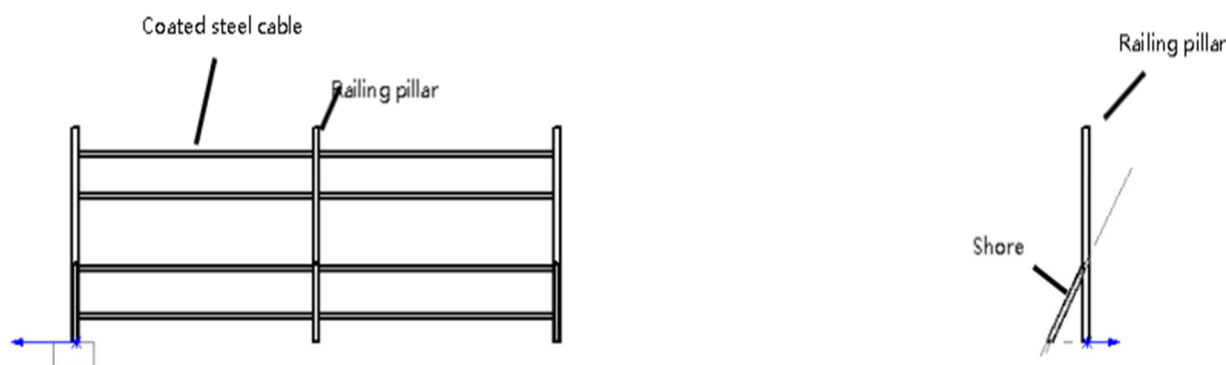


Figure 1. Schematic diagram of carbon fiber composite railing structure

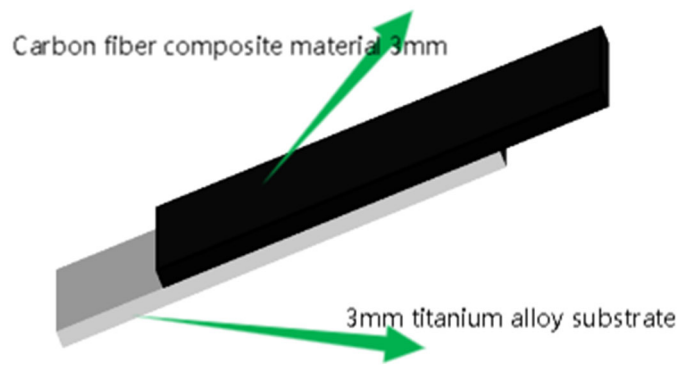


Figure 2. Sectional view of titanium based reinforced carbon fiber composite railing

The "2019 Statutory Inspection Rules for Inland Ships" of the China Maritime Safety Administration 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) 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 [3] [4].

(4) Improving the interface performance between metal and carbon fiber composite materials is the key to enhancing the performance of ship railings. The interface between metal and carbon fiber composite materials is optimized using sizing agents Preparation and Performance Study of Carbon Fiber Epoxy Coating Agent, in order to meet the tensile requirements of ship railings [5].

(5) 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]

(6) 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;

(7) 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 Fig. 1.

2.1. Materials

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

The titanium based reinforced 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 titanium based reinforced carbon fiber composite materials and subjected to fatigue testing to ensure compliance with the service life standards for marine railings.

3. 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 Fig. 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 material distribution of the composite railing column is shown in Fig. 2, which is the core area of the ship railing. The domestically produced T700 carbon fiber reinforced medium temperature epoxy resin based prepreg is used as the substrate, and the integral component is formed by the process of laying and wrapping and the solidification of the support column, ensuring the rigidity, strength, and sealing of the ship railing.

3.1. Structural analysis

Finite element analysis and calculations were conducted using ABAQUS software. This software is a universal finite element analysis software widely used in industries such as

aerospace, mechanical manufacturing, and automotive transportation. It has stable, good, and high-precision calculation results for complex engineering models. This ensures efficient and reliable calculation results.

Based on the geometric structure of the ship railing, define the local mesh size, set a reasonable mesh algorithm, and

perform finite element mesh division. As shown in Fig. 3, the ship railing adopts composite material conventional solid elements, assigning layer materials and sequences to each area. The ship railing adopts three-dimensional solid elements, and the final number of elements in the grid model of the ship railing is 1763.

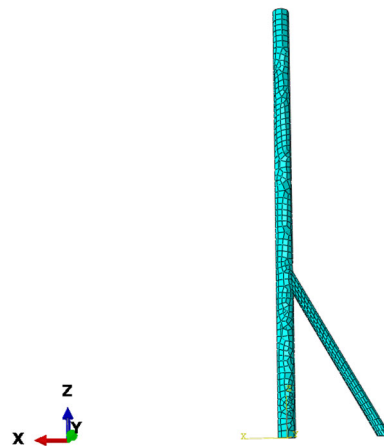


Figure 3. Schematic diagram of finite element model of ship railing

The traditional metal railings were used as the control group, and the railing columns and support columns were prepared using Q235 galvanized steel pipes. The mechanical performance parameters of the material are shown in Table 1. The experimental group's titanium based reinforced carbon fiber composite railing column has an outer diameter of

42mm and a wall thickness of 6mm, including a 3mm carbon fiber composite material layer and a 3mm titanium alloy. The support column has an outer diameter of 28mm and a wall thickness of 3mm. Among them, TC4 type titanium alloy is selected, and its relevant mechanical properties are shown in Table 1.

Table 1. Mechanical Performance Parameters of Materials

Numble	TC4 titanium alloy	Q235 galvanized steel
Density ρ /(kg/m ³)	4510	7850.00
Poisson's ratio	0.34	0.28
Young's modulus(E/GPa)	110	210.00
Yield strength σ_s /MPa	900	235.00

Maintain the size of the railing posts and support posts consistent with the metal railing, and design the titanium based reinforced carbon fiber composite railing. The railing columns and support columns form a truss structure, which mainly bears axial loads during operation. To meet the requirements of axial tensile performance and lightweight for railing columns, the layer design of carbon fiber composite materials is $[0^\circ/90^\circ/0^\circ/0^\circ/45^\circ/-45^\circ]_n$, with 0° layer as the main layer to meet its axial tensile performance requirements. Among them, the numerical value represents the direction of each layer, that is, the angle between the fiber and the x-axis (axis of the railing or support column); The subscript n represents a symmetrical layer. Based on the characteristics of the usage environment, domestically produced T700 carbon fiber composite materials (pre impregnated yarn and unidirectional cloth) are selected. The density of the carbon fiber composite material used is 1800kg/m³, and $0^\circ/45^\circ/-45^\circ$ pre impregnated cloth is used for overall layer laying and 90° pre impregnated yarn is used for winding layer laying. The thickness of single-layer prepreg fabric is 0.2mm, and the thickness of single-layer prepreg yarn is 0.17mm (with a tension of 80N). The mechanical performance parameters of

carbon fiber composite materials are shown in Table 2. Table 2: the fiber direction is referred to as direction 1 or X, the direction perpendicular to the fiber in the plane is referred to as direction 2 or Y, and the thickness direction is referred to as direction 3 or Z; E11, E22, and E33 are the Young's moduli; $\nu_{12}, \nu_{13},$ and ν_{23} are Poisson's ratios; G12, G13, and G23 are shear moduli; $X_t, Y_t,$ and Z_t are tensile strengths; $X_c, Y_c,$ and Z_c are compressive strengths; S12, S13, and S23 are intensities. Based on the structural characteristics and stress forms of marine railings, the axial performance of railing columns and support columns is mainly investigated. Here, the titanium based carbon fiber composite material is laminated and vacuum cured to form the railing column. The laminated railing column is then subjected to hot pressing in a vacuum hot pressing tank at a temperature of 140 °C, a pressure of 0.8 MPa, and a hot pressing time of 2 hours. After hot pressing, the titanium based reinforced carbon fiber composite railing column is obtained. According to the classical laminated panel theory, the axial equivalent modulus and axial equivalent strength of typical layer designs for carbon fiber composite railings are obtained, as shown in Table 3.

Table 2. Mechanical performance parameters of T700 carbon fiber composite single-layer board

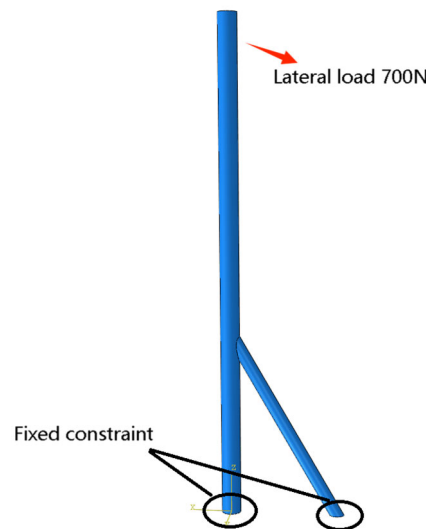
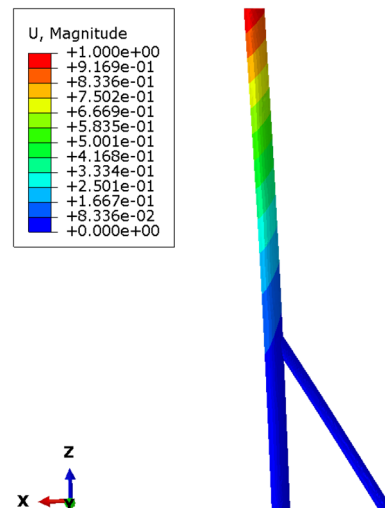
Parameter	Numerical	Parameter	Numerical	Parameter	Numerical
E11/GPa	152.00	G12/GPa	5.50	Yc/MPa	98
E22/GPa	10.00	G13/GPa	5.50	Zt/MPa	25
E33/GPa	10.00	G23/GPa	5.30	Zc/MPa	98
V12	0.34	Xt/MPa	2438	S12/MPa	72
V13	0.34	Xc/MPa	1097	S13/MPa	72
V23	0.28	Yt/MPa	25	S23/MPa	72

Table 3. Equivalent mechanical performance parameters of carbon fiber composite railings

Parameter	Numerical
Axial equivalent modulus/GPa	94.85
Axial equivalent tensile strength/MPa	458.00
Axial equivalent compressive strength/MPa	446.00

Perform finite element modeling analysis on one railing column component. Based on the structure and usage characteristics of marine railings, three-dimensional solid elements are used for finite element modeling in the titanium alloy pipe base section, and shell elements are used for finite element modeling in the reinforced carbon fiber composite material section to meet the requirements of railing columns for composite layer laying. The finite element model is shown in Fig. 3 Based on the daily work conditions of maritime crew

and their usage environment, fixed constraints are applied at the connection between the railing and support columns and the deck. A lateral load of 700N is applied at the connection position between the railing column and the topmost plastic coated steel cable (this is a stress simulation of a single railing column). The lateral load points horizontally towards one side of the support column, and the two support columns are asymmetrical with respect to the lateral load.

**Figure 4.** Simulation load diagram of ship railing**Figure 5.** Strain cloud map of marine railing metal railing

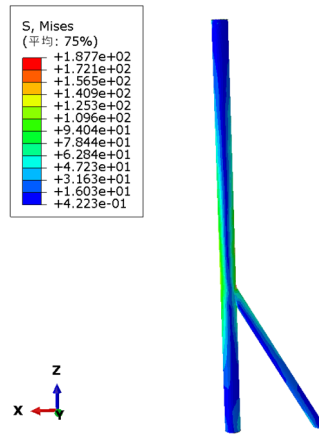


Figure 6. Stress cloud map of marine railing metal railing

According to Fig. 5, the maximum deformation of the metal railing is 0.917mm; According to Fig. 6, the maximum stress of the metal railing is 187.7N. 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 metal railing is 187.7 MPa, with a safety factor of 1.25, which is lower than the material area service strength of 235 MPa, indicating structural safety.

4. Optimization Design

Based on the geometric structure analysis of traditional

metal railings for ships, optimize the materials on this basis. By improving traditional metal railings to titanium based reinforced carbon fiber composite railings, the mechanism is to lay a 3mm T700 carbon fiber composite reinforcement layer on a 3mm TC4 titanium matrix. Before laying, the TC4 surface is treated with anhydrous ethanol to eliminate the influence of TC4 surface impurities on interfacial properties. Then carry out sizing agent treatment to improve the bonding strength of heterogeneous materials. Simulate using ABAQUS software, define local mesh sizes, set reasonable mesh algorithms, and perform finite element mesh partitioning. Apply the load shown in Fig. 4 to the ship railing and perform stress-strain analysis on it.

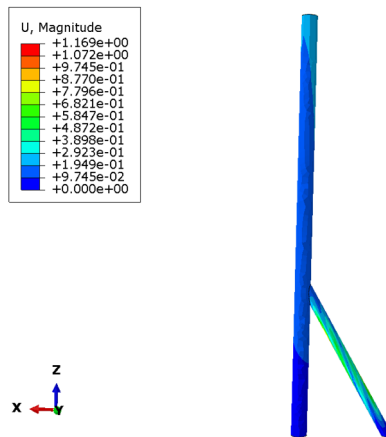


Figure 7. Strain distribution cloud map of titanium based reinforced carbon fiber composite material

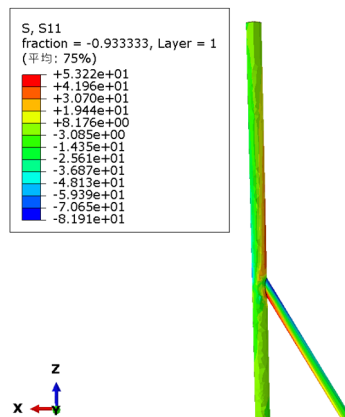


Figure 8. Strain distribution cloud map of titanium based reinforced carbon fiber composite material

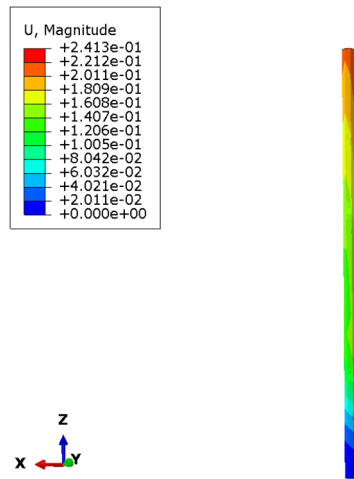


Figure 9. Strain distribution cloud map of titanium based reinforced carbon fiber composite railing column

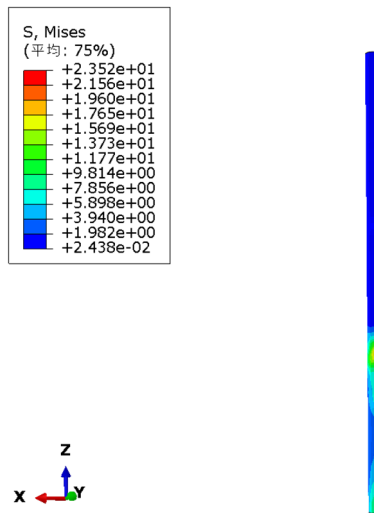


Figure 10. Stress distribution cloud map of titanium based reinforced carbon fiber composite railing column

According to Fig. 7, the maximum deformation of the titanium based reinforced carbon fiber composite railing is 1.17mm, and the maximum deformation occurs in the support column part. According to Fig. 9, the maximum deformation of the railing column is 0.24mm. According to Fig. 8, the maximum axial tensile stress of the titanium based reinforced carbon fiber composite railing is 53.22MPa, and the maximum axial compressive stress is 81.9MPa. According to Fig. 10, the maximum Mises stress of the railing column is 23.52MPa, and the maximum stress is concentrated at the connection between

the railing column and the support column. The safety factor is 8.61, which is lower than the axial equivalent tensile strength and is structurally safe.

Comparing the finite element analysis results (Table 4), it can be seen that the maximum deformation of titanium based reinforced carbon fiber composite railings is relatively large compared to traditional metal railings, and their stiffness is relatively lower than traditional metal railings. The safety factor and strength of titanium based reinforced carbon fiber composite railings are relatively high.

Table 4. Comparative Analysis

Material	Maximum deformation (stiffness)/mm	Safety factor (strength)	quality/kg	Weight loss
Galvanized Steel	0.92	1.25	4.73	—
Titanium based reinforced carbon fiber composite material	1.17	8.61	2.12	55.2%

Comparing traditional metal railings and titanium based reinforced carbon fiber composite railings of the same specifications, it can be seen that, while ensuring the safety factor requirements of the railings, the use of titanium based reinforced carbon fiber composite materials on the railing columns significantly reduces weight by 55.2%.

5. Conclusion

Through the analysis of traditional metal railings for ships, it is known that traditional metal railings have heavy weight, short service life, and poor corrosion resistance. On the basis

of the original metal railing column structure, titanium based reinforced carbon fiber composite materials were selected to improve the marine railing. The titanium based reinforced carbon fiber composite material railing effectively solves the corrosion problem of traditional marine metal railings while meeting the mechanical performance requirements of marine railings, and can achieve the lightweight requirements of marine railing devices. The research results of this article provide a certain foundation for promoting the application of carbon fiber composite railings in ship hull structures. The optimized design scheme of titanium based reinforced carbon fiber composite railings for ships proposed in this article has certain reference value for ship designers.

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