Design and application of carbon fiber composite material in end box of rail transit vehicles

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Abstract. Carbon fiber composites have great application prospects in the field of rail transit. In order to study the application of carbon fiber composite materials in rail car end boxes. Firstly, the carbon fiber paving structure was designed, and then the product performance of carbon fiber car end box was studied by finite element analysis calculation and sample test verification method. The research results show that the weight of the car end box of carbon fiber composite is about 45% of the weight of carbon steel and stainless steel box, about 72% of the weight of aluminum alloy box, and the weight reduction effect is remarkable. The static strength and fatigue life of the box are the test results of insulation withstand voltage and protection grade all meet the standard requirements and have passed the test verification. The carbon fiber composite car end box can be used and promoted on rail transit.

Keywords: Rail Transit Vehicles; Carbon Fiber Composite Material; End Box.

1. Preface
As the speed of the rail vehicle is getting higher and higher, the energy consumed by the vehicle itself is getting larger and larger, and the energy consumption of the vehicle itself limits the speed of the vehicle. Lightweight rail vehicles are the main way to reduce energy consumption and an important direction for the development of rail transit. Optimized design of structure, use of light metal materials, composite materials is the main way to reduce the weight of rail trains[1]. Due to the complex and variable working environment of the rail transit field, the physical and chemical properties of the materials are also increasingly high. The commonly used light metal materials are mainly aluminum alloy, magnesium alloy, titanium alloy, etc., which can not fully meet the rail transit field. Strict weight reduction requirements, non-metallic materials have become a key breakthrough. Aramid fiber composite (AFRP), glass fiber composite (GFRP), and carbon fiber composite (CFRP) with low density, high strength, good weatherability, etc., have anistropic properties and design properties. Widely used in aerospace, weaponry, rail transit, wind power, sports equipment, etc. [2-3]
The carbon fiber composite material has the advantages of high tensile strength, large modulus of elasticity, high temperature resistance, good medium resistance, etc. Compared with other fibers, it can meet the strength and fatigue life of the lightweight design process of the rail end box structure of the rail train, resistance to large temperature differences, large humidity changes, etc. [4] Wang Mingmeng [5] designed the high-speed train head cover using carbon fiber composite material, and verified the strength and rigidity of the structure through experiments. The results showed that it met the design requirements. Wang Yonggang [6] introduced the requirements of the urban rail transit vehicle to the cab structure, analyzed the advantages and disadvantages of the existing structure and proposed the carbon fiber material cab and its implementation plan. G Zhu [7] and other numerical models of different cross-section shapes were used to simulate the fracture test of CFRP tubes. The results show that tubes with circular cross-section are more suitable for CRFP materials than square tubes. Denkena B [8] introduced the new design method of CFRP materials, that is, how to determine the matching process chain according to the preliminary structural design. For the fuselage panel of the aircraft, the method can quickly evaluate the products under different production schemes. Production cost and weight. Hosseini A [9] studied the fatigue strength of the structure when CFRP materials were mixed with metal steel. It was found that CFRP materials can prevent the existing fatigue cracks in steel members based on the unbonded reinforcement system. Fleischer J [10] proposed a new method for the mixing of metal and CFRP materials, and discussed the scheme of mixing CFRP in the field of lightweight research with metal materials.

At present, domestic research on the application of carbon fiber in rail transit vehicles is mainly an application review and feasibility. There are few reports on engineering applications. In order to optimize the weight reduction of the car end box in the rail vehicle, this paper uses carbon fiber composite material to design the car end box, analyzes the static strength and fatigue strength of the car end box under various working conditions, and fatigues it. The life calculation is carried out numerically and the performance of the vehicle end box is verified by experiments. This study can provide important reference value for the promotion of carbon fiber materials on rail vehicles.

2. Different material cabinet parameters
The structure of the car end box is 787×607×433 (unit: mm), as shown in Figure 1. The car end box consists of the box body, the box cover, the lifting ears and internal electronic components.

![Fig 1. Car end box structure diagram](image)

The box structure parameters of carbon steel, stainless steel, aluminum alloy and carbon fiber composite materials are shown in Table 1. Comparing the data in the comparison table, the carbon fiber composite car end box wall thickness is 2.5mm and the minimum weight is 18kg, which is only 45% of the weight of carbon steel and stainless steel, and 72% of the aluminum alloy. In contrast, the carbon fiber material has the lightest weight and the remarkable weight reduction effect.
Tab 1. Cabinet parameters of different materials

| Material          | Thickness[mm] | Weight[kg] | Yield Strength[Mpa] | Tensile strength[Mpa] | Elongation |
|-------------------|---------------|------------|--------------------|-----------------------|------------|
| Carbon steel      | 2             | 40         | 345                | 370-500               | 26%        |
| Stainless steel   | 2             | 40         | 205                | 520                   | 40%        |
| Aluminum alloy    | 3             | 25         | 125                | 275-350               | 13%        |
| Carbon fiber      | 2.5           | 18         | /                  | 1000                  | /          |

3. Carbon fiber box design
Considering that the car end box is installed with electrical auxiliary equipment under the steel frame of the rail transit body, the safety factor is high. Therefore, the reasonable ply design will greatly improve the finishing, continuity and impact resistance of the box structure, structural strength. The thickness of the carbon fiber laminate is initially designed to be 2.5 mm, and the thickness of the single-layer carbon fiber is about 0.2 mm. The layers of the layers of the box are butt jointed, and the butt joints of the layers are staggered by 50 mm. Thus, assuming that the number of layers is 12 layers, the structural strength of 11 layers can be ensured on the 2.5 mm plate thickness, and the wall thickness of 2.5 mm can be ensured.

In this project, the carbon fiber box is a monolithic structure in which the metal mold is integrally formed. The whole box has no joints and fasteners, which reduces the risk of failure of the traditional process connection such as welding, riveting and screwing, and the sealing performance is also superior. At the same time, the use of metal molds can also ensure the dimensional consistency and surface flatness of the cabinet. The box forming process uses a bag press forming process, and the basic flow of the bag pressing process is shown in Figure 2.

![Fig 2. Bag pressure process flow chart](image)

In order to ensure the stability of the box and the car body, the mounting feet of the box and the car body are still designed in stainless steel. The material design of each part of the box is shown in Figure 3.

![Fig 3. Vehicle end box material design](image)
4. Finite element analysis

In order to verify the structural strength, overall modality and fatigue life of the pre-designed carbon fiber end box, the finite element analysis of the vehicle end box was carried out. The vehicle end box is numerically modeled by finite element software, and the internal electronic components are equivalent to weight blocks. The car end box is meshed, and the divided mesh model is shown in Figure 4. The coordinate system in the numerical calculation model and the direction in which the load is applied are both the coordinate system specified in the standard EN 12663:2000 and the specified load. The specific load conditions are shown in Table 2.

![Fig 4. Car end box numerical model](image)

| Load Cases | Dir-X | Dir-Y | Dir-Z |
|------------|-------|-------|-------|
| 1          | 3g    | 0     | -g    |
| 2          | 0     | g     | -g    |
| 3          | 0     | 0     | -3g   |

The material parameters in the numerical calculation are shown in Table 3, Table 4 and Table 5, respectively.

**Tab 3.** 06Cr19Ni10 Stainless steel material parameters

| Elastic modulus [GPa] | Poisson’s ratio | Density [kg/m3] | Yield Limit [MPa] |
|-----------------------|-----------------|-----------------|------------------|
| 210                   | 0.3             | 7850            | 205              |

**Tab 4.** 5754-H22 material parameters

| Elastic modulus [GPa] | Poisson’s ratio | Density [kg/m3] | Yield Limit [MPa] |
|-----------------------|-----------------|-----------------|------------------|
| 71                    | 0.32            | 2700            | ≥130             |

**Tab 5.** Carbon fiber material parameters

| Modulus [GPa] | Various shear modulus [GPa] | Poisson's ratio |
|---------------|-----------------------------|----------------|
| E1 60         | E2 60                       | E3 7           |
| G12 4.7       | G13 4.7                     | G23 3.1        |
| v12 0.3       | v13 0.3                     | v23 0.3        |

4.1. Static strength analysis

Numerical results as shown in Figure 5, the maximum deformation of the vehicle end box under Working Condition 1 is 0.069mm, the maximum stress is 16.61MPa, the maximum deformation of the vehicle end box under Working Condition 2 is 0.047mm, the maximum stress is 7.84MPa, the maximum deformation of the vehicle end box under the working Condition 3 is 0.201mm, and the maximum stress is 22.54MPa. Under three kinds of working conditions, the maximum stress of the vehicle end box is
much smaller than the yield strength of the material, and the vehicle end box can withstand the static strength load stipulated in the standard EN 12,663:2000 railway application-structural requirements of the track.

![Von Mises Stress Contour](image1)
![Von Mises Stress Contour](image2)
![Von Mises Stress Contour](image3)

![Displacement Contour](image4)
![Displacement Contour](image5)
![Displacement Contour](image6)

Fig 5. Numerical calculation results

4.2. Fatigue life analysis

Table 6. is the characteristic life of the carbon fiber vehicle end box in different directions. The calculated fatigue limit life is not much different from the characteristic life, and the fatigue life of the part can be estimated by the characteristic life of the part, and the shortest life of the carbon fiber box is 55,000 hours.

| Feature Life h(x10^6) | X direction | Y direction | Z direction |
|------------------------|-------------|-------------|-------------|
|                        | 29          | 24          | 11          |

From the above analysis can be seen that carbon fiber composite box has a good anti-fatigue performance, so the box fatigue failure before the sudden damage, easy to timely repair or replacement, can avoid damage to personnel and equipment, with better safety.

4.3. Modal analysis

Modal analysis of the car End box, the first six-order vibration model as shown in Figure 6., the first six-order natural frequencies are: 61.003Hz, 74.058Hz, 87.367Hz, 94.337Hz, 101.6Hz, 102.74Hz, much higher than the natural frequency of the vehicle body (10-15 Hz), Does not resonate with the vehicle body.
Fig 6. Front six order vibration type

From the above modal analysis and calculation results, carbon fiber composites have a high specific stiffness, its self-vibration frequency is high, carbon fiber composite matrix is a viscoelastic material, the material damping is high, which makes the whole box has a good damping effect, will not resonate with the vehicle body.

5. Test validation

Through the finite element theory analysis, the static strength, fatigue strength and mode of the carbon fiber box meet the design requirements, and in order to further verify the performance of the box, the carbon fiber sample and the Carbon fiber vehicle end box are tested and verified respectively.

5.1. Tensile test

Room temperature 20°C, environmental relative humidity of 40%, in the WDW-T100 universal testing machine in accordance with the test criteria for the performance of carbon fiber composites testing, the data as shown in Table 7.

| Test standard           | Test results |
|-------------------------|--------------|
| PAP hardness            | 45 HBa       |
| Impact toughness        | 85 KJ/m²     |
| Tensile properties      | 571.9 MPa    |
| Bending performance     | 630.7 MPa    |
| Water absorption        | ≤0.2%        |
| Oxygen Index            | 35           |

5.2. Vibration shock test

In accordance with IEC61373-2010 "Railway application-Rolling stock equipment-Shock and vibration tests" standard, the vehicle end box is tested horizontally, longitudinally and vertically on the vibration impact test bench, as shown in Figure 7. After the completion of the test, the appearance of the box without cracking, hanging ear without deformation, to meet the standard requirements.
6. Summary
Car End box facing lightweight, complex use of the environment and changeable situation. In the case of satisfying or even higher than the design requirements, the subway car End box is lightweight design. Use carbon fiber composites to replace traditional metal materials. Compared with traditional metal materials, the weight of carbon fiber vehicle end box is about 45% of the weight of carbon steel and stainless steel box, about 72% of the weight of aluminum alloy box, and the lightweight effect is remarkable. Through the finite element calculation analysis and test verification of the designed Carbon fiber vehicle end box, the reasonable carbon fiber pavement design can ensure that the box has reliable tensile, anti-fatigue and impact resistance.

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