Experimental study on effect of loading rate on mechanical properties of CFRP equipment cabin skeleton laminates

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Abstract. With the development of high-speed train technology, the dynamic problems caused by track irregularity and the stress maximization of CFRP equipment cabin skeleton at the edge of the beam are becoming increasingly prominent. In this paper, the tensile and compressive properties of carbon fiber laminates under different loading rates are studied by means of universal material mechanics experimental machine. The curves of tensile and compressive strength under different loading rates are obtained. The variation trends of tensile and compressive stiffness are analysed and the failure modes are summarized. It is found that the tensile strength of carbon fiber laminates does not change with the change of loading rate, but the compressive strength increases with the increase of loading rate in the range of 0 mm/min-6 mm/min and considering the influence of certain error. When the load is less than 30kN, the tensile stiffness of the material is not affected by loading rate. As the loading rate increases, the stiffness and compression stiffness increase.

1. Introduction
The research on the application of composite materials in rail transit started late in China. Up to now it has been a semi-empirical and semi-theoretical state. Equipment compartment is a key component installed at the lower end of the car’s body to protect the undercarriage device and improve aerodynamic performance.

The equipment cabin skeleton is the main load-bearing component of the equipment cabin, which is composed of crossbeams, side beams and bending beams [1]. Laminate is the most basic unit in the application of fiber reinforced polymer matrix composites. The same material has different mechanical properties because of its different laying sequence and angle. The maximum stress is at the edge of the beam, so it is very important to study the influence of the mechanical properties of CFRP equipment cabin skeleton laminate.

Research institutions at home and abroad have done a lot of research on the application of CFRP equipment composite materials. Among them, the CFRP roof developed jointly by Japan Passenger Railway Corporation and Japan Railway Integrated Technology Research Institute can reduce the weight of each carriage by 300-500kg compared with the traditional aluminum alloy roof, and the mechanical properties meet the operation requirements[2]. The GFRP integral passenger carriage developed by Schindler Company in Switzerland reduces the total quality of passenger cars by 10%. Chen Zhenhua, a professor at Hunan University, has successfully developed a brake disc and brake disc made of aluminum matrix composites. Many researchers agree that the research results are in the
leading position in the world as a whole. Carbon fiber brake pads have been developed successfully in China and the friction coefficient and wear amount at 120km/h and 200km/h velocities have been measured by experiments. The results show that the carbon fiber reinforced composite brake is more wearable and has little change in temperature than the traditional cast iron brake [3, 5].

Therefore, the static tensile and compression tests are carried out by using laminates on the beam, and the tensile strength and compressive strength of the laminates at different loading rates are determined. The tensile and compressive stiffness are determined and the failure modes are summarized.

2. Structure and parameters of CFRP laminates

The specimens used in the experiment are the cross beam part. The material is made of two kinds of carbon fiber composite monolayers according to the prescribed laying mode. They are carbon fiber unidirectional reinforced composite monolayer (represented by A below) and carbon fiber twill orthogonal composite monolayer (shown by B below). The thickness of A monolayer is 0.16mm and that of B monolayer is 0.32mm. The mechanical properties of the two kinds of carbon fibre monolayers are shown in Table 1.

| Type | $E_1$/GPa | $X_1$/MPa | $E$/GPa | $X_1$/MPa | $G_{12}$/GPa | $S$/MPa | $\mu_{12}$ |
|------|-----------|-----------|---------|-----------|-------------|---------|-----------|
| A    | 67.5      | 696.8     | 24.8    | 362.5     | 8.5         | 62.5    | 0.3       |
| B    | 64.6      | 736.3     | 64.6    | 746.3     | 10.8        | 100.0   | 0.1       |

The structure of the tensile specimens was prepared according to GB/T3354-2014 "Test Method for Tensile Properties of Oriented Fiber Polymer Matrix Composites". The structural dimensions of the compression specimens are prepared according to the standard specimens stipulated in GB/T1448-2005 "Test Method for Compression Properties of Fiber Reinforced Plastics". The physical drawing of the tensile specimens is shown in Figure 1. The whole length of the specimens is 240mm, the reinforced sheets with thickness of 3mm and length of 70mm are pasted at both ends. The width and thickness of the specimens are 25mm and 5mm respectively. The physical drawing of the compression specimens is shown in Figure 2. The whole specimen is rectangular block, the width and height of the specimen are 10mm, the thickness of the specimen is 5mm.

**Figure 1.** Physical drawing of tensile specimens

**Figure 2.** Physical drawing of compressed specimens
3. Tensile test of CFRP laminates at different loading rates

3.1. The equipment of tensile testing
The test adopts the 300kN universal material mechanics testing machine produced by Metis Company. The force range is 0-300kN, the test force resolution is 1N, the large deformation measurement range is 10-800mm, the resolution of large deformation is 0.008mm, the displacement resolution is 0.015μm, and the speed adjustment range of cross beam is 0.001-250mm/min. It is mainly used for tensile, compression or bending tests of metal, non-metallic materials or components. Among them, the test machine fixture mainly adopts hydraulic drive clamping mode. The test machine and the test fixture are shown in Figures 3 and 4 respectively.

![Figure 3. Hydraulic testing machine](image1)
![Figure 4. The fixture of tensile test](image2)

3.2. The scheme of tensile test and result analysis
The test uses a microcomputer to control the universal material mechanics testing machine to adjust different loading rates. The mechanical properties of the specimens with loading rates ranging from 0mm/min to 6mm/min were studied by group test. Three groups of specimens, 1mm/min, 3mm/min and 5mm/min, were taken to exclude accidental factors. And three specimens were taken from each group for testing. When the first obvious failure occurs, the test is stopped. The maximum tensile force of each specimen under each loading rate is recorded. The tensile strength under this loading rate is calculated by formula (1). The average value is taken as the tensile strength under this loading rate.

\[ \sigma_t = \frac{F_{\text{max}}}{wh} \]  

(1)

Among them, \( \sigma_t \) is the compressive strength, the unit is MPa. \( F_{\text{max}} \) is the maximum tensile force that the specimen can bear, the unit is N. \( w \) is the width of the tensile specimen, the unit is mm. \( h \) is the thickness of the tensile specimen, the unit is mm.

The experimental data at different loading rates are shown in Table 2. The relationship between tensile strength and loading rate is shown in Figure 5.
Table 2. Test date of tension specimen under different loading rates

| rate mm/min | number | mean value of width/mm | mean value of thickness/mm | Maximum pulling force/N | mean value of tensile strength/MPa |
|------------|--------|------------------------|---------------------------|------------------------|-----------------------------------|
| 1          | 1-1    | 25.02                  | 4.95                      | 87722                  | 708.3                             |
| 1          | 1-2    | 25.01                  | 5.00                      | 88917                  |                                   |
| 1          | 1-3    | 25.01                  | 5.12                      | 90354                  |                                   |
| 3          | 3-1    | 25.12                  | 5.12                      | 92771                  |                                   |
| 3          | 3-2    | 25.03                  | 5.18                      | 91654                  | 712.9                             |
| 3          | 3-3    | 25.05                  | 4.99                      | 88723                  |                                   |
| 5          | 5-1    | 25.06                  | 5.10                      | 90761                  |                                   |
| 5          | 5-2    | 25.09                  | 5.09                      | 90665                  | 711.2                             |
| 5          | 5-3    | 25.01                  | 5.04                      | 89932                  |                                   |

According to the experimental data given in Table 2 and the relationship curve between the tensile strength and loading rate given in Figure 7, it can be concluded that the tensile strength of the special CFRP laminates does not change with the change of loading rate in the range of 0 mm/min-6 mm/min.

Considering that the tensile performance curves of the specimens under different loading rates are approximately the same, a curve is selected in each group to draw the force-displacement curves at different loading rates as shown in Figure 6.

As can be seen from the curve in the figure, when the applied load is less than 30kN, the tensile stiffness of the material is not affected by the loading rate. When the applied load is greater than 30kN,
the tensile stiffness of the material decreases slightly with the increase of the loading rate, but the overall change is not significant.

From Figure 8, it can be concluded that the force-displacement curves of the CFRP laminates are basically linear before the first failure of the specimens, that is, the elastic deformation is the main form of brittle fracture before the first failure of the specimens. From the failure diagram given in Figure 7, it can be seen that the mixed fracture is common, the fracture surface is flat and most of the faults occur on the surface of the laminate.

Figure 7. Failure diagram of tensile specimen

It is concluded that the failure modes can be divided into three types: one is that with the increase of loads, the initial failure of laminates occurs when a small amount of fibers break in the lowest strength layer of the laminates, resulting in the redistribution of loads in the laminates. As the load continues to increase, more fibers break down. Brittle fracture failure occurs when the tensile strength of a cross section is lower than the applied load. During the test, when the load is 60kN, occasional "cracking" sound occurs, indicating that a small amount of fibers break. When the load is 80kN, the "cracking" sound occurs frequently until the final breaking failure. The second is that with the increase of the load, the load is transferred between the laminates through structural glue. When the glue content between the two layers is not uniform or inclusions, the debonding between the layers will occur, and then the delamination failure will occur. The third is mixed failure, that is, brittle fracture coexists with interlayer delamination failure.

4. Compression test of CFRP laminates at different loading rates

4.1. Compression test equipment
The equipment used in the compression test is the same as that used in the tension test. The specimen is placed in the center of the upper and lower indenters. For the sake of safety, the limit switch installed near the longitudinal beam of the testing machine is adjusted to a suitable position to prevent the contact damage of the upper and lower pressure heads caused by the failure of the compression specimen due to the failure of shutdown in time. The pressure head of the test machine is shown in Figure 8.

Figure 8. Press head of test machine

4.2. Compression test scheme and result analysis
The effect of loading rate on the compressive properties of CFRP laminates with specific ply is studied. Three rate groups, 2 mm/min, 4 mm/min and 6 mm/min, are selected to exclude the impact of contingency. Three samples are tested in each group. The maximum compressive strength of each sample in each group was recorded. Compressive strength was calculated according to formula (2) and
the arithmetic average value was calculated as the reference value of compressive strength at this loading rate.

\[ \sigma_c = \frac{P_{\text{max}}}{bd} \]  

(2)

Among them, \( \sigma_c \) is compressive strength, the unit is MPa. \( P_{\text{max}} \) is the maximum pressure that can be withstood from compression to failure, the unit is N. \( b \) is the width of the compressed specimen, the unit is mm. \( d \) is the thickness of the compression specimen, the unit is mm.

The relationship between compressive strength and loading rate under different loading rates and the load-displacement curves under three different loading rates were compared to study the effects of loading rates on the mechanical properties of carbon fibre laminates with specific layers. The test data of compressive specimens at different loading rates are shown in Table 3. The relationship between compressive strength and loading rate is shown in Figure 9.

Table 3. Test data of compression specimens at different loading rates

| Rate (mm/min) | Number | Mean value of width (mm) | Mean value of thickness (mm) | Maximum pressure (N) | Mean value of compressive strength (MPa) |
|--------------|--------|-------------------------|----------------------------|----------------------|----------------------------------------|
| 2            | 2-1    | 9.97                    | 5.21                       | 21627                | 415.1                                  |
|              | 2-2    | 10.02                   | 5.30                       | 22621                |                                        |
|              | 2-3    | 9.93                    | 5.20                       | 20814                |                                        |
|              | 4-1    | 10.06                   | 5.19                       | 23352                |                                        |
| 4            | 4-2    | 10.03                   | 5.11                       | 21732                | 428.8                                  |
|              | 4-3    | 9.99                    | 5.06                       | 20986                |                                        |
|              | 6-1    | 10.12                   | 5.27                       | 26222                |                                        |
| 6            | 6-2    | 10.10                   | 5.07                       | 21606                | 451.7                                  |
|              | 6-3    | 10.04                   | 5.31                       | 23537                |                                        |

Figure 9. The relationship between compressive strength and loading rate

From Table 3 and Figure 9, it is found that the compressive strength of the CFRP laminates increases with the increase of loading rate in the range of 0 mm/min-6 mm/min.

Figure 10 shows the force-displacement curves at different loading rates. It can be seen from the figure that the compressive stiffness of the material is almost independent of the loading rate in the rate range of 0 mm/min-4 mm/min, while in the rate range of 4 mm/min-6 mm/min, the compressive stiffness of the material increases gradually with the increase of loading rate, but the overall change is not significant.
Figure 10. Compression performance curve at different loading rates

It can be seen from Figure 10 that the force-displacement curve maintains a certain linearity before failure occurs due to the maximum compressive load, which also indicates that there is no obvious plastic deformation in the process of loading to failure. The failure results of carbon fiber laminates under compression are shown below.

Figure 11. Failure Diagram of Compressed Specimens

According to its failure characteristics, the failure modes of this particular laminated carbon fiber laminate can be roughly divided into two types: one is longitudinal splitting, because the bond strength between laminates or between fibers and matrix is low, that is, during compression, the laminates break along the direction of force, between laminates or within the matrix. The second is the mixed failure of longitudinal splitting and buckling, that is, the specimen not only has a single longitudinal splitting, but also has a large deformation of the matrix or fiber, which results in the buckling failure under the continuous compression load, leading to fiber fracture or matrix fracture. The main reason is that after the longitudinal splitting, the load is redistributed further, and each dispersed part bears compressive load. Under the continuous load, love, because of the high bonding strength between the fiber and the matrix or between the layer and the layer, leads to the overall buckling failure, which leads to the fracture of the fiber or the matrix [8-11].

5. Conclusion
According to the above different loading rates on the tensile and compressive properties of CFRP equipment cabin skeleton laminates of EMU, the following conclusions can be drawn:

(1) Tensile and compressive tests show that the tensile strength of the CFRP laminates does not change with the change of loading rate, but the compressive strength increases with the increase of loading rate in the range of 0 mm/min-6 mm/min.

(2) When the applied load is less than 30 kN, the material's tensile stiffness is not affected by the loading rate. When the load is greater than 30 kN, the material's tensile stiffness decreases slightly with
the increase of loading rate. In the rate range of 0 mm/min-4 mm/min, the material's compressive stiffness is almost not affected by loading rate, while in the rate range of 4 mm/min-6 mm/min, the material's compressive stiffness will follow. The loading rate increases gradually.

(3) The failure modes of CFRP equipment cabin skeleton laminates in tension and compression tests are summarized through the tensile and compression performance curves at different loading rates.

References

[1] DING Sansan, TIAN Aiqin, WANG Jianjun, et al. Applied Research on Carbon Fiber Composites for High Speed EMUs [J], Electric Locomotives and Urban Rail Vehicles, 2015, 12 (38): 1-8.
[2] LIU Xiaobo, YANG Ying, Application of Carbon Fiber Reinforced Composites in Railway Vehicles [J], Electric Locomotives and Urban Planning Vehicles, 2015, 4(38): 72-76.
[3] JING Juhui, CHEN Jingju, Application and Development of Composites in Rail Transit [J]. FRP/Composites, 2009, 6:81-85.
[4] SU Yutang, XIAO Dao-rong, Application of Composites in Railway Transportation Abroad [J]. FRP/Composites, 1996, 4:37-39.
[5] LI Tianliang, Application Prospect Analysis of Carbon Fiber Composites on Railway Passenger Cars [J]. Equipment Manufacturing Technology, 2016, 4:159-161.
[6] SHI Xiaohong, LI Chengyou, WANG Tingting, et al. Experimental study on mechanical properties of composite laminates [J]. Engineering and experiment, 2014, 54 (1): 39-41.
[7] Tensile Fatigue Characteristics of T700/3234 Carbon Fiber Laminates [J]. Mechanical Design and Manufacture, 2013, 10:4-6.
[8] Experimental Method for Tensile Properties of GB/T3354-2014 Oriented Fiber Polymer Matrix Composites [S]. Beijing: China Standard Press, 2014.
[9] WANG Yongyan, ZHANG Xiangfeng, YAN Leilei. Study on the influence of loading rate on the shear performance of Huck rivets for EMUs [J]. Shandong Science, 2016, 12:62-67.
[10] TANG Zhongbin, GUO Weiguo, LI Yulong, et al. Study on dynamic tensile and impact properties of carbon fiber laminates [J]. Proceedings of the Fifth National Conference on Experimental Technology of Explosive Mechanics, 2008.
[11] GB/T1448-2005 Experimental Method for Compressive Properties of Fiber Reinforced Plastics [S]. Beijing: China Standard Press, 2005.