Mechanical Properties of CFRP Materials with Ply Splice Structures

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Abstract. With the development of science and technology, it is inevitable to apply ply splice to meet the requirements of engineering size and shape. The existence of splicing structure will inevitably produce complex stress distribution inside the material, which will lead to serious safety hazards. In this paper, tensile and bending properties of unidirectional carbon fiber reinforced plastic (CFRP) with ply splice structures were studied through tensile and four-point bending experiments. The results show that the higher the number of splicing layers, the lower the tensile strength, and the final strength is determined by the number of continuous fiber layers without splicing. However, there is almost no effects of the ply spliced structure on the four-point bending strength because of the loading features and the fracture mode.

1. Introduction

As a typical representative of advanced reinforced polymer, carbon fiber reinforced polymer (CFRP) have been widely used in aerospace and other fields [1]. However, as the size of reinforced polymer structures increases, new problems arise, for example, inadequate length or width of the reinforced polymer. In this context, splicing structures are needed to meet the dimensional requirement [2]; likewise, shearing and splicing are also needed for a complicated shape to avoid the wrinkles during the Plying process. When the Ply splice occurs, the splicing position introduces defects, which pose a safety hazard to the structural bearing force.

At present, there are relatively few studies directly on the spliced structure. Jia Purong et al. [3-7] of Northwestern Polytechnical University conducted a series of tests on the properties of the spliced structure of carbon fiber reinforced resin-based polymer laminates. They tested the tensile strength, the overall and local stiffness, the in-plane shear strength of the spliced layup materials by the test method, and carried out the numerical simulation, and obtained that the shorter the length of the interlaced splicing, the higher the local stress concentration, and that the failure mode of the Ply Splice laminate was the interlaminar shear failure and fiber break and other conclusions. Chen Dingding and Wang Manyi [8] tested the tensile properties of three unidirectional carbon fiber reinforced laminate Polymer with splicing structure, and analyzed the failure characteristics of the structure during the tensile process, and analyze the stress characteristics of the spliced structure during the tension process by
using finite element software to simulate the tensile process of different spliced structures. Huang Jianxian and Geng Xiaoliang [9] tested the dislocated Ply Splice laminates, measured the tensile strength and stiffness, observed the failure characteristics of the fracture and the stress distribution of the surface layer, and established a finite element model containing the damage evolution of the matrix, and studied load transfer and failure mechanism of the material. All manuscripts must be in English, also the table and figure texts, otherwise we cannot publish your paper. Please keep a second copy of your manuscript in your office. When receiving the paper, we assume that the corresponding authors grant us the copyright to use the paper for the book or journal in question. Should authors use tables or figures from other Publications, they must ask the corresponding publishers to grant them the right to publish this material in their paper. Hao minjuan et al. [10] studied the delamination evolution behavior of glass fiber reinforced composites under four-point bending load and the influence of delamination defects on the load-bearing capacity and service life of the composites. After the artificial delamination defect with different positions is set, the damage degree of delamination damage of composite material is determined by acoustic emission technology.

In order to understand the failure mechanism of CFRP with spliced structure in depth, this paper starts with the simplest splicing situation, and studies the tensile properties and bending properties of CFRP structures spliced with different number of ply at the same position to grasp the law of influence of the difference ply numbers in the same position of CFRP on the mechanical properties of the structure, so as to provide a study basis for the subsequent study of the influence of multiple splicing points on the structural strength at different locations, and further to provide a reference for the rational design of the spliced structure.

2. Experimental materials and methods

2.1. Material and Technology

This paper took the tensile properties of CFRP with spliced structure as study object. As shown in the Figure 1, the solid black line represents the fiber bundle, and the splicing position is in the middle of the laminate. The ply on both sides of the splicing are unidirectional carbon fibers, and the fiber direction is perpendicular to the splicing joint direction. Four kinds of CFRP samples with different number of layers were designed to study the influence of different number of layers on the mechanical properties at the same position. As shown in the Figure 1, 21 layers of unidirectional carbon fiber laminate was used. The four samples were respectively spliced structures of 0 layer, 3 layers, 5 layers, and 7 layers (as shown in the Figure 2). The joint was perpendicular to the fiber direction. The thickness of the finished reinforced polymer laminate was about 2.5mm. Mark CFRP laminates without spliced layer, with 3 layers, with 5 layers, and with 7 layers as D0, D3, D5, and D7.

![Figure 1. Schematic diagram of the research object](image-url)
Figure 2. Technological process of compression molding

The CFRP is produced by a press molding process. The prepreg used is a unidirectional carbon fiber prepreg provided by Weihai Huixing composite material Co., Ltd. The reinforcement is T300 carbon fiber produced by Toray Industries. The base material is E901 epoxy resin (T300/ E901), and the density is 125g/m². The temperature rise and pressure holding process is shown in Figure 2: 80°C heat preserved for 30min; 115°C heat preserved for 10min and then pressure (3MPa); temperature rise to 130°C and heat and pressure hold for 2h; cooling and demoulding.

2.2. The Experiment
Referring to GB/T 3354-2014 “Test Method for Tensile Properties of Directional Fiber Reinforced Polymer Matrix Composites”, this paper tested the tensile properties of fibers with spliced structures. The sample size is shown as Figure 3. The width is 13 mm, thickness is 2.5 mm, and length is 250 mm, using glass fiber reinforced polymer (GFRP) as a reinforcement sheet. The device used in the tensile test is shown in Figure 5. The sample was loaded using a computer-controlled electronic universal testing machine CMT5105 of MTS Industrial Systems (China) Co., Ltd. at a loading rate of 2 mm/min.

To ensure a better view of the destruction process, white paint was sprayed on the side of the sample. The entire stretching process was recorded with the camera. The photo-frequency is 1 frame/second, and each set of experiments was repeated more than 4 times.

For the convenience of comparison, the tensile strength of the sample with the spliced structure is defined by reference to the tensile strength in GB/T 3354-2014 “Test Method for Tensile Properties of Directional Fiber Reinforced Polymer Matrix Composites”, which were defined as follows:


\[ \sigma = \frac{F_{\text{max}}}{bh} \]  

(1)

Where \( \sigma \) is the tensile strength; \( F \) is the maximum load; \( b \) is the width of the specimen; \( h \) is the thickness of the specimen.

When the splicing position is in the middle position, the pressure head in the three-point bending experiment will generate greater pressure on the splicing position. Therefore, four-point bending is adopted to test the bending performance. Refer to GB/t3356-2014 "test methods for flexural properties of directional fiber-reinforced polymer matrix composites". The experimental device and sample size are shown in figure 4. In order to observe the failure process, white paint was also sprayed on the side of the sample, and the whole bending process was recorded with the camera.

![Figure 4. Schematic diagram of four-point bending loading method and bending specimen size](image)

Bending strength (i.e. the maximum stress corresponding to the appearance of the maximum load) is calculated as follows:

\[ \sigma_{f} = \frac{3P_{\text{max}}L}{4\omega h^2} \]  

(2)

Where \( \sigma \) is bending strength; \( P_{\text{max}} \) is the maximum load the sample can bear; \( L \) is the span; \( h \) is the sample thickness; \( \omega \) is the sample width.

3. Results and Discussion

3.1. The Tensile experiment

Figure 5 shows the tensile strength of the CFRP sample with different number of spliced layers along the fiber direction. As can be seen from the figure, the more the number of layers of the material, the lower the strength. The strength of CFRP with no ply is as high as 2.1GPa. When the number of spliced layers is 7 layers, the strength is reduced to 1.4 GPa, which is only 66.7% the original.
Figure 5. The strength varies with the number of splice structures.

It can be seen from the Figure 5 that the strength of the structure decreases linearly with the increase of the strength of the splicing layer. The relationship between the intensity and the number of layers is linearly fitted, and the relationship between the strength and the number of layers is:

$$\sigma_{D_m} = 2034.26 - 95.7485m$$  \hspace{1cm} (3)

Where $m$ is the number of failure layers and the strength unit is MPa.

Figure 6. Load-displacement curves of different ply splice structures.

Figure 7. Failure process of D5
The Figure 6 is a typical load-deformation curve of three CFRP with difference spliced layers. The failure processes of the three structures are similar. The CFRP sample with 5 spliced layers is used to illustrate the sample destruction process (Fig. 7). With the increase of tensile deformation, the force of the material is continuously increased. When the deformation reaches a certain degree, the end of the fiber bundle and the resin matrix are tensilely broken at the joint, resulting in visible voids and interlayer damage (A position); as the load is further increased, similar interlayer damage (B position) occurs below voids. In order to make the image clearer, the layered cracks are emphasized with black lines. When the load reaches the material strength, the material undergoes ultimate damage (C position).

![Figure 8](image)

**Figure 8.** Schematic diagram of ply splice structures of samples

The failure process is analyzed through figure 8. It can be seen from the process of the sample tensile experiment that ply splice causes severe deformation of the splicing area. Due to the low interfacial strength of resin and fiber, the damage occurs at the ① location first. At the same time of the damage, the stress is redistributed. With the further increase of stress, soon the ② location and the ③ location of the secondary shear failure also occurred. After the shear failure, the tensile load is completely carried by the continuous fiber layer in the sample. When the load reaches the limit of continuous fiber layer, the material is destroyed completely. From the perspective of the failure process, the final strength of the structure is completely determined by the continuous carbon fiber layer, that is, the more the continuous layers are, the greater the strength is, and the strength can be characterized by formula (4):

$$\sigma = \sigma_{\text{max}} \times \frac{n - m}{n}$$  \hspace{1cm} (4)

Where $\sigma$ is the tensile strength of the spliced structure; $\sigma_{\text{max}}$ is the tensile strength of structure without splicing; $n$ is the total number of layers; $m$ is the number of failure layers. In this experiment, $n$ is 21, and $\sigma_{\text{max}}$ is 2067.06MPa, which is consistent with (3).

### 3.2. The Four-point bending experiment

![Figure 9](image)

**Figure 9.** Bending strength of specimens with different ply splice structures
Fig. 9 shows the bending strength of the CFRP specimen containing different splicing layers of in the direction perpendicular to fiber direction. It can be seen from the figure that the intensities of D0, D3, D5, and D7 are respectively 1.213Mpa, 1.232Mpa, 1.286Mpa and 1.234Mpa showing that as the number of layers of the material changes, the intensity does not change significantly.

Figure 10 is a typical load-displacement curve of the experiment, which shows that as the deformation increases, the load increases continuously. When it reaches a certain level, the material suddenly fails, and the failure morphology is shear stratification, as shown in Figure 11.

Due to the the characteristics of four-point bending [11], the load form of the a-position (Fig. 12) between the support points of the upper clamp is pure bending moment. The maximum compressive stress and maximum tensile stress are generated on the upper and lower surfaces of the specimen, respectively, while the splicing position is in the middle and therefore bears less load. Shear load is applied to the areas from b position on the outside of the upper clamp support point to both ends of the specimen. From the failure morphology of the specimen, the interlayer shear stratification failure indicates that the failure was caused by the shear stress at the b position, instead of the tensile stress at the a position and the stress concentration generated at the splicing position. Therefore, the bending strength of the material is determined by the shear strength at the b position where there is no spliced structure. Therefore, in the four-point bending experiment, the splicing contributes little to the bending strength. Hao Minjuan [10] et al. have obtained similar experimental results when studying the bending properties of failure defects.
4. Conclusion
Through the tensile test in the fiber direction of the unidirectional carbon fiber reinforced polymer with different number of spliced layers, the influence of the number of spliced layers on the strength properties of the material was studied, and the following conclusions were obtained:

(1) When the splicing occurs at the same position, for the unidirectional carbon fiber reinforced polymer studied in this paper, the tensile load bearing capacity in the 0° direction is close to the total bearing capacity of the structure without splicing.

(2) In the four-point bending, the area between the upper two supporting points bears the maximum pressure and the tensile load for the upper and lower surfaces of the pure bending moment material, respectively, therefore the splicing structure in the middle contribute little to the bending strength. On the outside of the two support points, the material undergoes a large shear and thereby fails, resulting in the material failure.

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