Study on Flexural Strength and Flexural Failure Modes of Carbon Fiber/Epoxy Resin Composites

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Abstract: The flexural failure modes and flexural strength of unidirectional carbon fiber/epoxy (CF/epoxy) composites was theoretically analyzed and calculated. The hypothesis that the maximal flexural strength of unidirectional CF/epoxy composites occurred in outer sheet layer was brought forward. Load-displacement curve of unidirectional CF/epoxy composites also demonstrates that it is correct, which is consistent with the assume. Unidirectional CF/epoxy composites were fabricated with winding and compression molding, and three different kinds of fiber packing modes were proposed and the effects of these modes on flexural prosperities of composites had also been analyzed respectively. Three failure modes, namely fracture of fiber, fracture of epoxy resin and interfacial delamination between fiber and matrix, were analyzed by scanning electron microscopy (SEM). The load-displacement curve of unidirectional CF/epoxy composites indicates the plastic deformation is increased with increasing phenolic resin.

Keywords: Bending strength, carbon fiber, packing modes, failure mode, composite.

1. INTRODUCTION

The properties of carbon fiber reinforced polymer (CFRP), such as strength, modulus and designability, are better than traditional materials. But these properties are usually confined by the strength between layers under loading. At present, delamination is the main damage of fiber reinforced materials [1-2]. Composites, affected by the formation of bubbles in the processing of the laminated plates and uneven tow glue, can easily generate cracks when subjected to loadings. Crack expands to intact areas and causes delamination, which would reduce the strength of the composites. Thus, failure modes can reflect the performance characteristics of composites to some extent. With the research of the interface structure and optimization design of composite, the study on the mechanical behavior and failure mechanism of interface is becoming a hot point at the materials science [3-6]. Therefore, it has an important significance to understand the interface behavior and failure mode of composite material.

In order to fully understand damage and failure mechanism of fiber composite under the load, researchers take different finite element models of composites, including shear-lag model [7-10], fiber bundle models [11-12], to study the damage performance of laminates. At present, most of the above methods have the problem of the large amount of calculation and are mainly adopted for metal matrix composites. Unfortunately, researches scarcely are involved in resin matrix composite and mentioned for flexural failure of resin matrix composites.

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2. EXPERIMENTAL

2.1. Materials

Polyfunctional group tetraglycidyl diaminodiphenyl methane (TGDDM, trade name: AG80) with an epoxy value of 0.8 was produced from Shanghai Research Institute of Synthetic Resins (China). 4,4'-diaminodipheylsulfone (4,4'-DDS) was obtained from Sinopharm Chemical Reagent Co. Ltd., China. Thermoplastic phenolic (TP) resin was provided by Tianjin Chemical Factory (China). The reinforcement materials were continuous polyacrylonitrile (PAN)-based carbon fibers (3 K) manufactured by Institute of Coal Chemistry, Chinese Academy of Sciences. The mechanical and physical properties of the fibers used in this study are presented in Table **1**.

2.2. The Preparation of Carbon Fiber Composites

Weighed TP was mixed with TGDDM until the particles were uniformly dispersed in the epoxy resin. Subsequently, the mixture was diluted by acetone. Then 4, 4'-DDS was added to the solution while stirring. The obtained solution was coated on dry fibers by means of solution dip coating to form unidirectional

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Table 1: Mechanical and Physical Properties of Carbon Fibers

Line density ($g \cdot km^{-1}$)	Volume density ($g \cdot cm^{-3}$)	Tensile strength (GPa)	Tensile elongation (%)	Young's modulus (GPa)
199.6	1.78	4.05	2.07	211

prepregs. The mass ratio of matrix/CF is about 3:7. The fibers were in a sheet form, which were dried in a vacuum oven to remove the acetone. Prepreg layers were then stacked up with the same layer orientation (0 degrees) and cured at 90°C for 0.3 h, 150°C for 1 h and then postcured at 200°C for 2 h. During the curing process, the pressure was 0.6 MPa.

2.3. Measurement and Characterization

The flexural strength was performed on an universal testing machine (CMT4303) according to GB/T 3356-1993. The fracture surfaces of the samples were examined by scanning electron microscopy (SEM, JSM-6360LV) with an excitation voltage of 30 kV. Prior to examination, all the fracture surfaces were cleaned with alcohol in order to eliminate impurities like dusts, and then coated with a thin evaporated layer of gold to improve conductivity before test.

3. RESULTS AND DISCUSSION

3.1. Calculation of Flexural Strength

3.1.1. Hypothesis

A simple graph describing the stress distribution of the specimen is shown in Figure **1**.

Because the stress distribution of the sample along the thickness is bevel shape in the flexural strength test, and the stress is zero in the neutron layer. Stress gradient, namely flexural strength, appears between layers. In order to simplify the calculation, we make the following assumptions.

(1) Neutron layer is in the middle and the tensile strength of laminates (the lower half of the laminates in Figure **1**) should be equal to compressive strength (the upper half of the laminates in Figure **1**).

(2) Stress is no gradient in the same layer, which takes the average value.

(3) Before loading, stress would not exist in unidirectional composites. After loading, transversal stress would not appear between fiber and matrix.

According to the basic principles of mechanics of materials, flexural strength (σ_f) values were calculated by Equation (1):

$$\sigma_f = \frac{3PL}{2bd^2} \qquad (1)$$

Where *P* is the maximum applied load on the force-displacement curves in Newtons (N), *L* is the span of the specimen in mm, *d* is the thickness of the specimen in mm and *b* is the width of the specimen in mm. The results are expressed in Mega Pascal (MPa), which is the average of the results from six specimens. The relative error was estimated to be with 10% based on reproducibility of the data among different specimens. The flexural strains were also determined.

3.1.2. Calculation of the Flexural Stress between the Layers in Unidirectional CF/Epoxy Resin Composites

Only the 0°-laminate, which is about 2 mm of thickness and composed of 12 layers of prepregs is studied in this paper. The distribution of interfacial stress between prepreg layers is presented in Figure **2**.

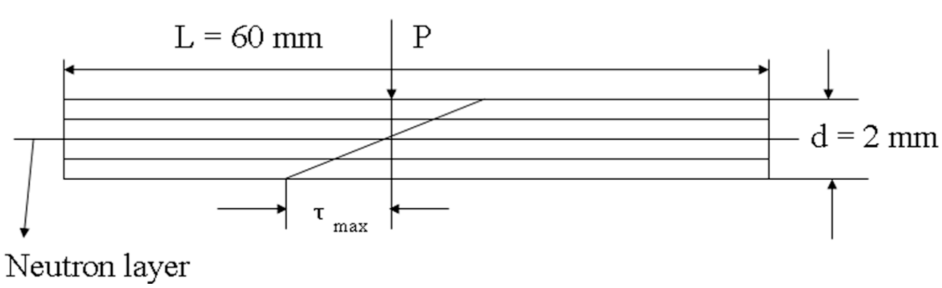

Figure 1: Schematic representation of force characteristic of 0°-laminate.

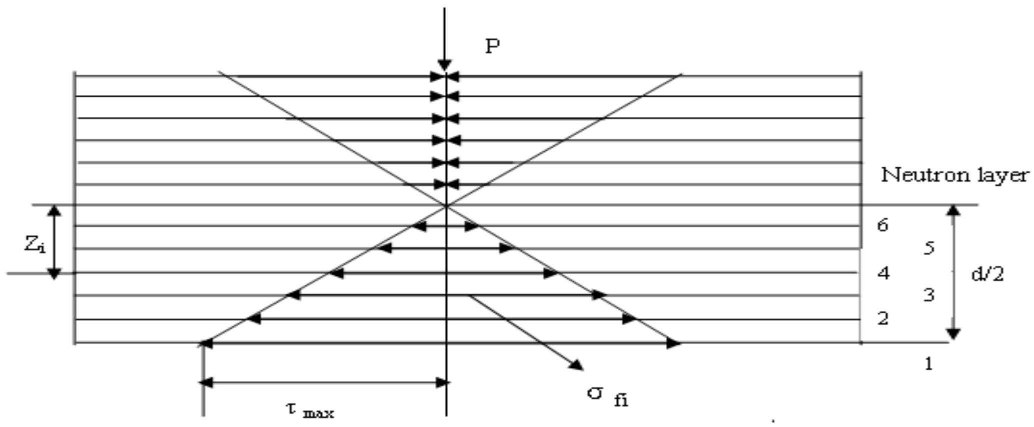

Figure 2: Interfacial stress distribution of unidirectional CF/epoxy composites.

The distance from neutron to the i^{th} layer is calculated by the following formula (3):

$$Z_i = (7-n_i)\, t \qquad (3)$$

Another equation can be obtained from Figure **2**,

$$Z_i/ (d/2) = \sigma_{fi}/(\sigma_f)_{max} \qquad (4)$$

Therefore, it can be deduced by the above formula that the interfacial stress of the i^{th} layer (σ_{fi}) should be followed by formula (5):

$$\sigma_{fi} = (\sigma_f)_{max} \cdot 2Z_i/d \qquad (5)$$

Combining formula (1) and formula (5), σ_{fi} can be simplified by formula (6):

$$\sigma_{fi} = 3PL(7-n_i)t /bd^3 \qquad (6)$$

Where t is the thickness of single layer (mm), Z_i is the distance from neutron to the i^{th} layer (mm), n is the number of layers (n=1~6)

The average stress of each layer is the mean value of stress in two adjacent ones, namely

$$\text{Average stress}=(\sigma_{fi}+\sigma_{fi+1})/2 \qquad (7)$$

For example, if the flexural strength of 0°-laminate is 1210 MPa, the interfacial stress and average stress can be obtained by the above formulas, which are shown in Table **2**.

Above theoretical calculations are carried out under the condition of no deformation or very small deformation and without obvious defect in laminates. In fact, some inevitable and artificial factors and different physicochemical property properties of each component can bring about various sensitivity of stress concentration. Plastic deformation (or partial plastic deformation) under load can occur, leading to the stress distribution of the laminates is similar to Figure **3**.

At least two conclusions can be deduced from the above analysis.

(1) When plastic deformation (or partial deformation) occurs, more and more parts of the unidirectional laminates reach the ultimate strength as much as possible.

(2) Although displacement of the unidirectional laminates is increased, load is not enhanced during the plastic deformation. Plastic deformation (or partial deformation) can not be deduced only by the flexural strength of laminates.

3.2. Assumptions of Fiber Accumulation Model

The kinds of unidirectional fiber accumulation model affect the mechanical properties of CF/epoxy composites to a great extent. In order to put forward

Table 2: Interfacial Stress and Average Stress of 0°-Laminate

Ordinal	1	2	3	4	5	6	Neutron layer
Interfacial stress /MPa	1210	1008	806.7	605.0	403.3	201.7	0
Average stress /MPa	1109	907.4	705.9	504.2	201.7	100.9	__

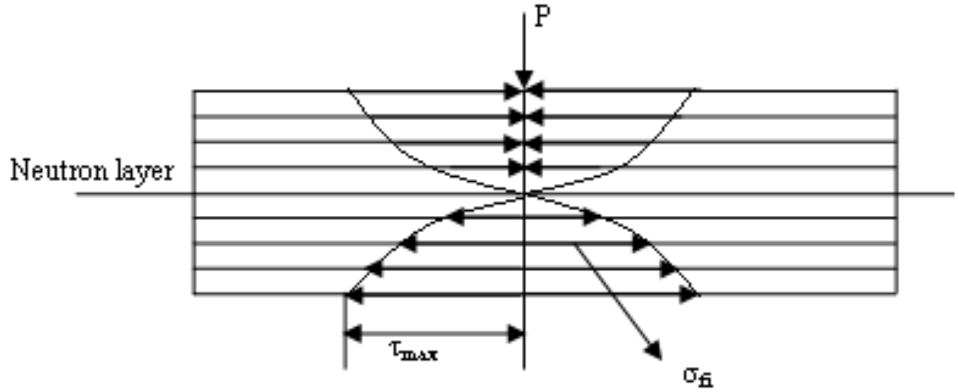

Figure 3: Interfacial stress distribution of plastic (or partial) deformation of unidirectional laminates under load.

fiber accumulation model, the following assumptions of fiber properties have been made: (1) the shape of transverse section of fiber is circular relatively, and the diameter is uniform. (2) after impregnating treatment, the fiber does not disperse.

We propose three kinds of fiber accumulation models as shown in Figure **4**, in which circles and ellipses represent fibers. Model I is loose packing of fibers, which contains too much epoxy resin between fibers and relatively reduces fiber content. In that case, the reinforcing effects of fibers can not fully play significant role in the CF/epoxy composites. Model II is close packing, which increases the contact area between the fiber and resin and is beneficial to enhancement of the flexural strength. Model III, one of the most common ways, has very strong flexural strength. It is due to the large contact area between the fibers. And fiber content increases will reduce the degree of stress concentration on the end of crack tip. In addition, resistance is enhanced with the growth of the crack length [13-14]. However, fiber content in model III can not be too high. For circular cross section, the maximum theoretical value of V_f is 90.7%. At the same time, when the fiber content is too high, it is impossible for wetting fiber bundles well, leading to matrix poorly combined with fiber, which will reduce the flexural strength of the composite materials [15]. So selecting appropriate process parameters for impregnates is crucial to manufacturing high performance composites.

3.3. Flexural Fracture Failure Mode of UD-CFRP

3.3.1. Fracture Surface Morphology of UD-CFRP and Mechanism Analysis

The SEM photographs shown in Figure **5** are fracture surface morphologies of UD-CFRP. Figure **5a** is for unmodified epoxy resin composites, and Figure **5b** is for epoxy resin composites modified by phenolic resin. As shown in Figure **5a**, serious lamination and a significant gap between layers appear. A lot of fibers are pulled out and a small amount of residual resin is on the surface of them. The fracture failure mode is typical non cumulative brittle fracture and the partial fiber fracture leads to the complete damage of the composites quickly. In Figure **5b**, the fracture surface is smooth and the fibers that are pulled out are bonded with the resins tightly. This failure mode is cumulative fracture that both fibers and resins play an important role in bearing load. This is helpful to obtain higher flexural strength. In Figure **5a**, the main failure mechanisms are the fiber pullout and lamination between the fibers and matrix. The following resin fracture caused by them is the main reason for the destruction of the composite. While in Figure **5b**, reinforced fiber and resin matrix are jointly to resist external load, which reflects the ability of the whole

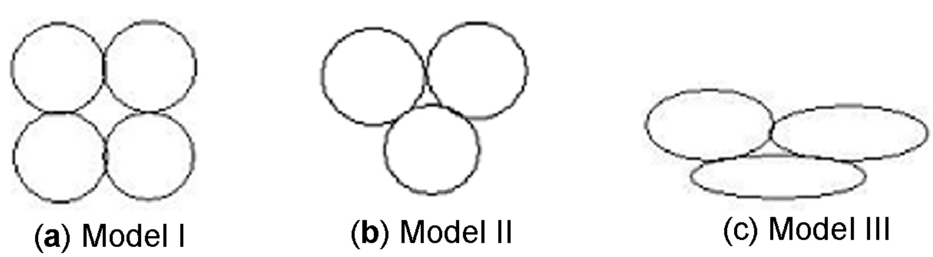

Figure 4: Schematic representation of fiber packing modes.

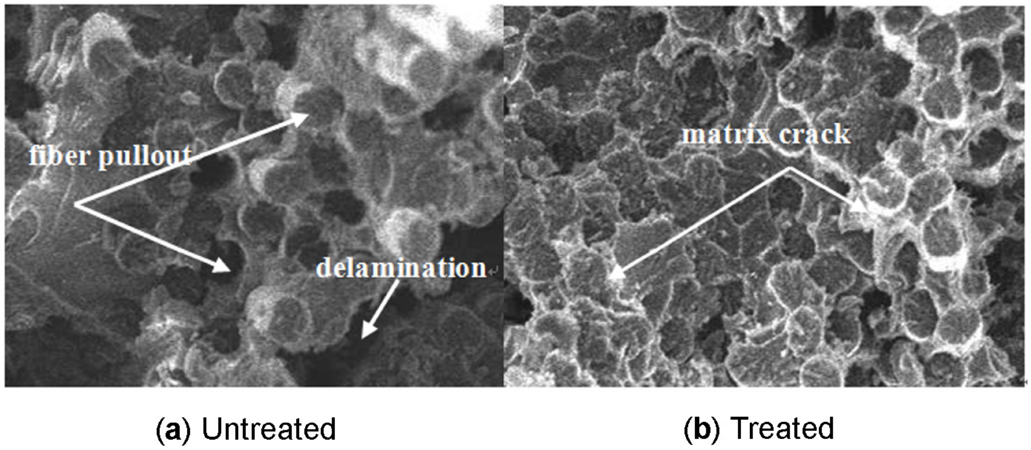

Figure 5: SEM photographs of transverse section of unidirectional CF/epoxy composites under shear load.

composite laminate to resist the load. Thus bending strength also have been greatly improved accordingly. When suffering loads, UD-CFRP mainly has three different fracture models, i.e. fiber pullout, matrix crack and delamination of fibers and matrix, which are marked in Figure **5**.

3.3.2. The Load - Displacement Curve Analysis of UD-CFRP

The typical load - displacement curve for the UD-CFRP is depicted in Figure **6**. As shown in Figure **6**, load-displacement of untreated sample presents a perfect linear relationship before maximum load, but the curve drops rapidly beyond the maximum point, which is the typical brittle fracture. Compared with the untreated sample, the treated sample is obviously different. After the maximum load, the load-displacement curve at the descent stage displays several distinct humps, suggesting that there exist multiple-step failures made. The load distributed over a large portion of the composites creates more crack surfaces, reflecting a noncatastrophic failure mode and plastic deformation.

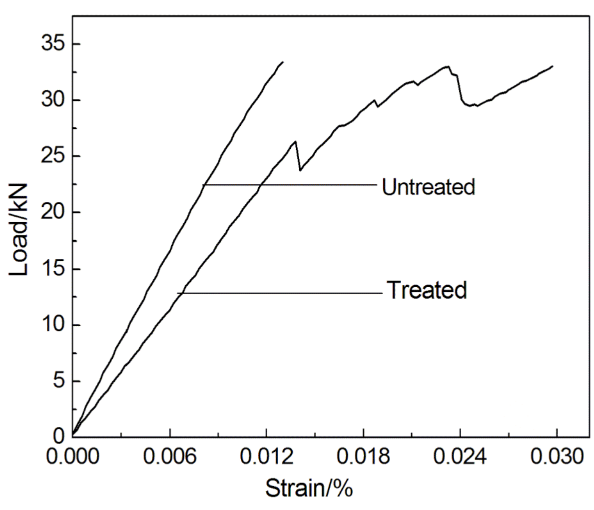

Figure 6: Load-displacement curve of unidirectional CF/epoxy composites.

From the above analysis, on the one hand, the obvious humps at the descent stage demonstrates that more and more parts of the unidirectional laminates reach the ultimate strength and bear a large load. This fully complies with the two conclusions of 3.1.2 section, also showing the assumptions of flexural strength is valid. In addition, the area below the load-displacement curve in the treated sample is larger than that of the untreated sample, which illustrates that the amount of work required to break a specimen is increased. The larger break elongation and higher work both confirm the higher damage tolerance of the composites. Three reasons for this phenomenon are as follows. First, the phenolic resin is a polymer with good toughness and high modulus thermoplastic, and will inhibit or bridge the further expansion of crack, absorbing much energy. Second, soft segment of the phenolic resin is also capable of absorbing the stress suffered by the specimen [16]. Besides, phenolic resin will also participate in the curing reaction of epoxy resin to form ether bond, which will improve the plastic deformation of composites.

4. CONCLUSION

In the study, the flexural strength and failure modes of unidirectional CF/epoxy composites was theoretically analyzed and calculated. The simplified schematic diagram of the stress form of unidirectional composites was proposed, and the equations of bending stress distribution in each layer were presented from analyzing the test of UD-CFRP under load. Three different patterns of fiber accumulation for determining the reasonable technology parameters are very significant in preparing impregnates. Three different failure modes were analyzed by SEM, and the load-displacement curve of unidirectional CF/epoxy composites verifies that the addition of phenolic resin will improve the plastic deformation of composites.

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