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Effect of Braid Angle on Crushing Performance of Double-Layer Carbon Fiber Composite Pipe

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Abstract

Three-dimensional braided composite materials have the advantages of high specific strength and good specific rigidity, they are widely used in various fields. With the help of the full-scale macrostructure model finite element analysis method to pre-test the mechanical properties of the axial compression, the simulation can observe the failure process, stress distribution and propagation form of the pipe, and study its failure mechanism. Then verify the correctness of the simulation through experiments. The conclusion is that the compressive performance of the material changes with the change in the braid angle. A smaller braiding angle can bear a larger load, but its material failure process is relatively rapid, and the load drop increases as the braiding angle decreases.

Keywords: Carbon fiber, epoxy resin, numerical simulation, axial crush

1. Introduction

The three-dimensional braided composite material is a textile structural material which is woven into a three-dimensional monolithic fabric by a braid technique and then composited with a matrix (resin, metal, etc.). Compared with laminated composites, it overcomes the shortcomings of low interlayer strength and easy delamination after being stressed. Because of its high specific strength and excellent mechanical properties, it is widely used in aviation, aerospace, military and civil fields (Wu Ly, 2008; CHEN Lei, ZHAO Man & WANG Zhutang, 2020; SRIVVAS P D & CHAROO M S., 2019; Zhang D, Zheng X T, Sun Y, et al, 2015). Since the domestic research on carbon fiber and epoxy resin started late, the research on the mechanical properties of composite material specimens is mainly concentrated in the laboratories of various universities and the research departments of enterprises. With the widespread application of CF/RP composites and the introduction of simulation software, some university students have also conducted a more detailed analysis of the mechanical properties and failure principles of three-dimensional braided composites (Wu X, Zhang Q, Zhang W, et al, 2016; Zhou H, Pan Z, Gideon R K, et al, 2016; Zhou H, Zhang W, Liu T, et al, 2015). However, in most studies, simulation and experiment cannot be organically combined, the reinforcement properties of fibers in composite materials are not described too much, simulation is limited to the mesoscale, and the prediction of the mechanical properties of materials lacks macro-scale demonstration (Tan H C, Qin W Y, et al, 2021; GONG Y., 2010). While foreign arguments and technologies are relatively mature, related scholars have obtained the main factors affecting the mechanical properties of braided composites through research, including braided yarn types, braiding angles, and material geometry (mainly concentrated in round tubes and square tubes). And factors such as the number of braided layers, but the main focus of the study is the energy absorption factor in the material failure process, and most of them are to establish a full-scale meso model or related mechanical experiments to study the failure process and failure mechanism of composite materials (Maragoni L, Modenato G, Rossi N D, et al, 2020; Gideon R K, Zhou H, Li Y, et al, 2016; Priem C, Othman R, Rozycki P, et a1, 2014; Sturm R & Heieck F., 2015).

In this paper, the three-dimensional woven composite model is constructed by three-dimensional drawing software, and then the finite element simulation software ABAQUS is used to mesh the model and simulate the quasi-static crushing performance. By comparing the simulation results with the experimental results, to analyze the quasi-static axial crushing performance of the composites with different braid angles, and then make recommendations for the optimization of the braided structure.

2. Building the Finite Element Model

2.1 The Basic Assumption

In order to simplify the model and reduce the amount of calculation in numerical simulation, refer to the literature (Feng G Y, Cao H J. et al, 2017; Li Y Y, Gan X H, Gu B H, et al, 2016), this paper makes the following settings when building the composite structure model:

a) The fiber bundle model is the basis for establishing a macroscopic model and simulation analysis. After the reinforcing fiber and the resin matrix are solidified to form a composite pipe, the resin is filled into the gap between the fiber tows. Therefore, it is assumed that the fiber bundle is a one-way plate containing a carbon fiber tow and a resin.

b) The composite of fiber and resin is carried out under ideal conditions. It is assumed that the bonding property is good, the interior of the matrix is intact, and there are no defects such as cracks, voids and agglomeration inside.

c) The reinforcing fiber and the matrix are in a good bonding state, and the gap between the outer layer fiber and the inner layer fiber is filled with the resin.

2.2 Building the Geometric Model

In order to make the modeling of the braided yarn more realistic, to further study the mechanical behavior of the braided composite tube in the axial crushing process, the simulation model established in this paper is based on the yarn scale. The fiber of the composite pipe is woven by a circular knitting machine. A total of five models were created for this model, namely 30°/30°, 30°/60°, 45°/45°, 60°/30° and 60°/60°.

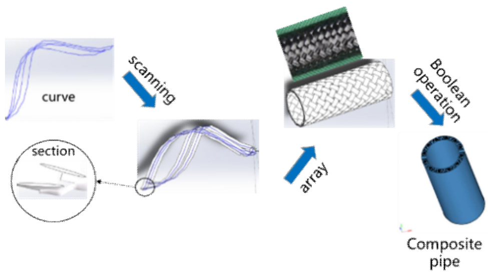


Figure 1. Geometric Modeling Process

2.3 Finite Element Model

The model is shown in figure 2, and the number of grids is shown in Table 1. Both boundary conditions and load conditions are established in the load module of ABAQUS. At the upper end of the above definition, the main node applies a displacement constraint to constrain the six displacements of the node; at the upper end of the above definition, the main node applies a displacement in the Z direction, and the size is 20 mm.

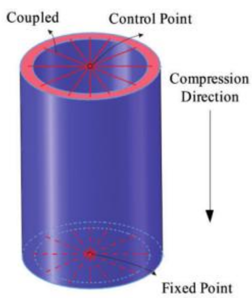


Figure 2. Structure connection, boundary and load conditions

Table 1. Dividing the grid

Braid angle	fiber		resin		Total number of grids
	Grid type	Number of grids	Grid type	Number of grids	
30/30	C3D8R	100837	C3D4	203721	304558
30/60	C3D8R	124215	C3D4	223264	347479
45/45	C3D8R	146234	C3D4	243426	389660
60/30	C3D8R	153557	C3D4	254512	408069
60/60	C3D8R	173421	C3D4	273214	446635

3. Experiment

3.1 Composite Preparation

In this paper, the forming process of the three-dimensional braided composite round tube adopts VARTM forming technology, and its working principle is: under the action of the vacuum pump, the resin is pressed into the mold through the draft tube by vacuum negative pressure, and the resin is infiltrated into the fiber. When the resin enters the resin collector through the outlet pipe, it takes a while to ensure that the resin can be combined with the braided structure. The molding process is shown in figure 3.

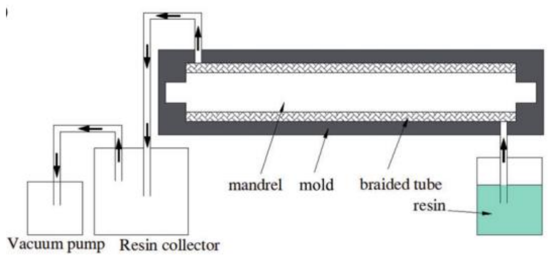


Figure 3. Schematic diagram of sample preparation

3.2 Composite Testing

In this experiment, according to the ASTM D695-10 standard, a universal testing machine with a working limit of 100KN was selected. As shown in figure 4, the sample was placed between two circular indenters. Prior to the start of the test, the indenters were kept parallel to each other and held until the end of the test. The head displacement determines the compression displacement. The sample was compressed axially by 20 mm and the compression speed was 2 mm/min. The force displacement curve of the crush test was automatically obtained by the data acquisition system.

Figure 4. Axial compression process

4. Results and Discussion

Through the axial crushing experiment, the corresponding load-displacement curve is obtained. Figure 5 is the comparison of experimental data and simulation data of five kinds of braid angle combinations. Figure 6 is the comparison of experimental and simulated compression process. Numerical simulations are calculated under ideal conditions, so the upward trend of the simulated curve is smoother than the experimental curve. From the overall point of view, the curves of each angle combination are linearly rising first, and after reaching the maximum load, the curve begins to decrease, and finally tends to be gentle. From figure 6, the failure process of the five kinds of braid angle combinations is similar, most of them are easy to produce stress concentration at the end, and the end is subjected to a large load. Therefore, the damage is at the top or bottom, and the damage is also caused by the different knitting angles. From the data curve, the maximum load and displacement of each combination of braid angles are also different. The maximum load of 30°/30° braid angle is the largest among the five, followed by 30°/60°, 45°/45° and the 60°/30° braid angle combination, while the 60°/60° braid angle has the smallest maximum load, but the displacement to the maximum load is opposite to the above sequence. This shows that within a certain range, the smaller the angle, the larger the maximum load, the shorter the displacement to the maximum load, and the previous stress analysis shows that the outer fiber is subjected to the main load, therefore, in the comparison between 30°/60° and 60°/60° braid angle, the former has a larger load and a smaller displacement. Comparing the descending stages of the five kinds of pipe fittings, it can be concluded that the pipe load of 30°/30° braided angle has the largest drop, and the pipe of 60°/60° braided angle has the smallest drop. This is because the braid angle is different, so five kinds the fiber volume of the pipe is also different, and the fiber is in the tension state during the failure process, and the tensile modulus of the carbon fiber is high, and the tensile strength is strong, so the post load drop degree is greatly different, although 60°/60°. The braided angle is subjected to the smallest maximum load, but can still withstand large loads after material failure.

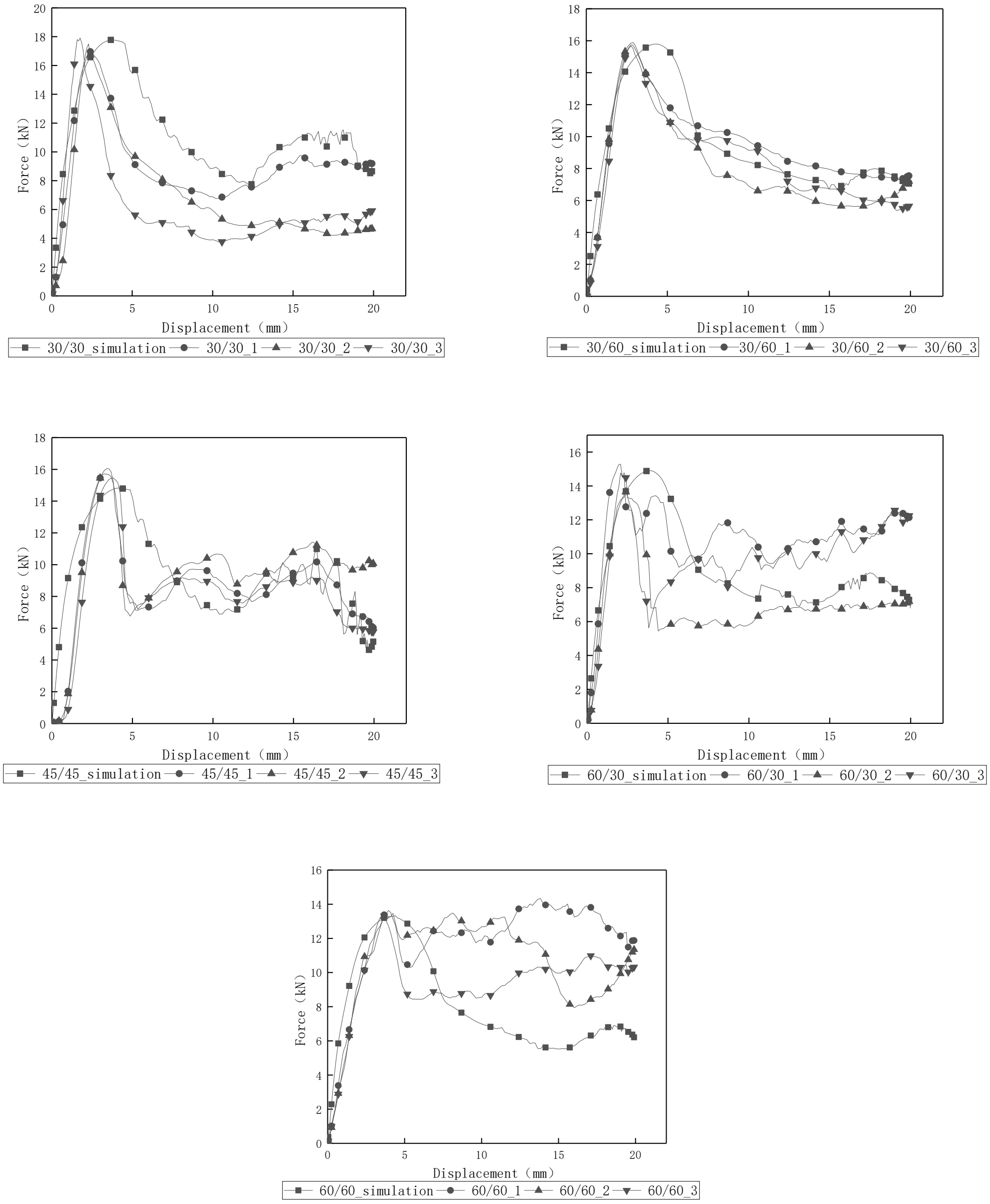


Figure 5. Load-displacement data for five different angle combinations

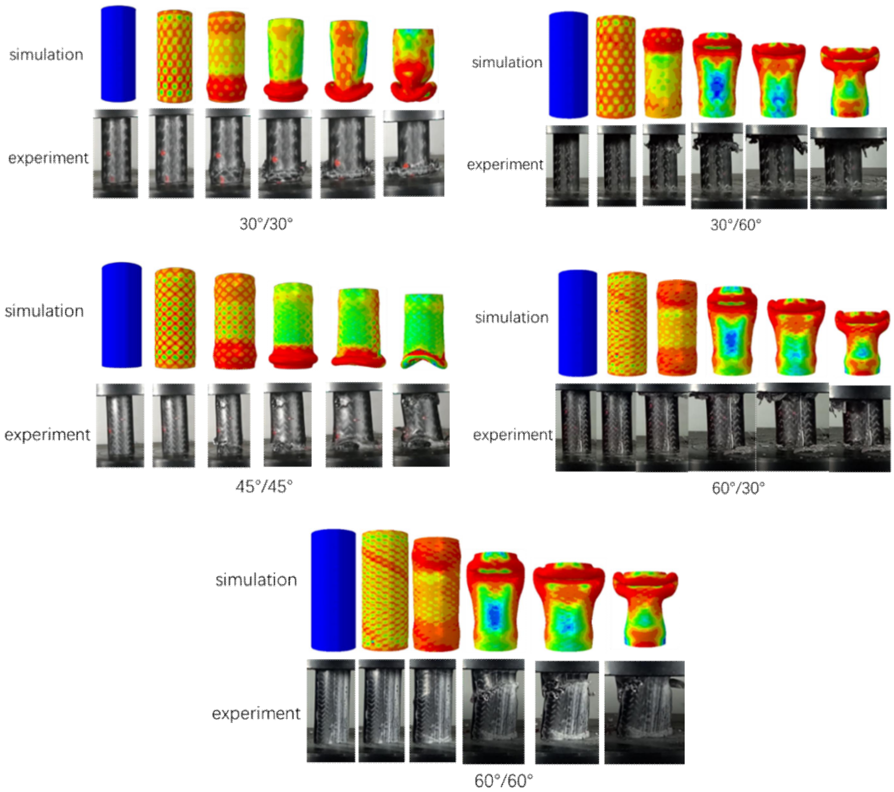
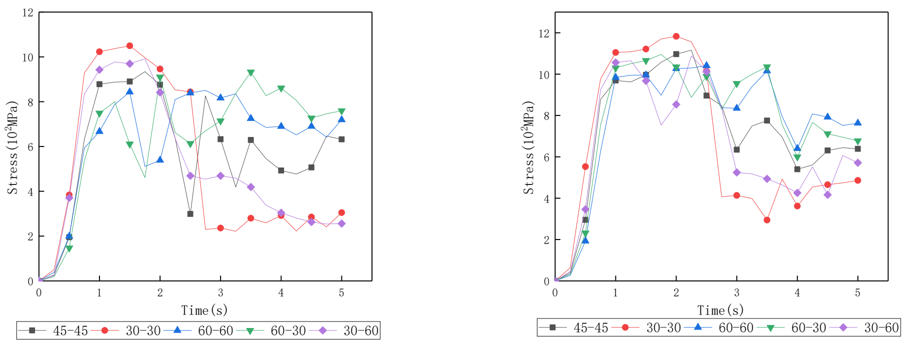


Figure 6. Comparison of axial crushing of five different angle combinations

In order to analyze the failure mechanism of the composite pipe fitting from the stress level, the stress-time curves were extracted from the inner and outer fiber stress concentration parts of the five pipe fittings, as shown in figure 7. It can be seen from the figure that the smaller the braid angle, the greater the stress on the fiber, and the maximum stress of the outer layer fiber is higher than that of the inner layer fiber. When the material is damaged, the equivalent stress of the fiber will drop. The smaller the braid angle, the larger the drop value.



(a) inner layer (b) outer layer

Figure 7. Stress analysis of fiber stress concentration

5. Conclusion

The classical laminate theory is based on Kirchhoff-Love's assumption that the straight line method assumes that the normal length remains constant and the z-direction stress is negligible. Only the in-plane stress can be calculated, and the three-dimensional braided composite structural model based on the finite element analysis method can obtain the stress distribution of the internal structure of the material, which has important theoretical significance and practical value for the performance strength analysis and prediction of the composite.

Through the research work of this paper, the conclusions obtained are as follows:

(1) By comparing the simulation and test data, it can be concluded that within a certain range, the smaller the braiding angle of the fiber, the greater the force that the pipe can withstand, and the fastest rise, while the load

decreases the most after the failure, and decreases. The fastest time. From the stress level, the influence of the braid angle on the composite material is analyzed. The smaller the braid angle, the greater the stress on the fiber. When the material is damaged, the equivalent stress of the fiber will drop. The smaller the braid angle, the lower the drop value. Large, the curve fluctuates more.

(2) Due to the high cost of sample preparation, the finite element software is not very skilled, and because the simulation is too idealized, the initial stage of the load-displacement curve is smoother than the experiment, and the experimental curve is not enough, and the individual angle simulation is nearly the same. In the future, other failure parameters can be added to the finite element analysis to bring the simulation closer to the experimental results.

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