Optimal Layer Thickness during the Design of Carbon Fiber Composite under Bending Loading

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Abstract. Carbon fiber resin composite materials are widely used in manufacturing and industrial production due to their many performances better than that of traditional materials. However, how to use the limited carbon fiber resin composite material to design the product with the excellent bearing capacity and relatively low processing cost still needs to be explored. The layer thickness is an important parameter during the design of carbon fiber composite. Large layer thickness between carbon fiber layer and resin layer could lead to poor mechanical properties. Small layer thickness could improve the bearing capacity but accompany with the high cost of production. Optimal layer thickness can balance the mechanical properties and production costs. Here, Abaqus software was employed to establish the finite element models with the same size but different number of layers, by dividing the mesh and finding the ultimate bearing capacity of each model, the relationship between the model layer and the ultimate loading force was obtained. Based on the calculated results, the optimal design scheme of carbon fiber resin composite materials was proposed.

1. Introduction
The outstanding properties of carbon fiber composite materials, e.g., high specific strength and modulus [1, 2], small density, high temperature performance [3,4], good anti-vibration performance, wear resistance [5] and damage safety performance [6], have made it a multi-functional special engineering material with increasing demand. As a kind of advanced material, carbon fiber composites are playing an increasingly important role in other traditional or emerging industrial fields, such as automobile engineering and new energy engineering [7-9]. As composite materials, the design parameters have a great effect on the mechanical properties. The addition of Ni into carbon fibre can have the excellent cycling performance [10]. Ultimate strength of carbon fibre composite was improved by nano-enhanced interface between carbon fibre and resin fibre [11]. Batabyal et al. evaluated the effect of the mechanical properties of glass fibre and carbon fibre on the mechanical responses of carbon fibre composite [12]. Krishna et al. analyzed the effect of composition addition of polycarbonate on the tensile, interlaminar and flexural properties of hybrid composites [13]. The compressive response of 3D nonwoven carbon fibre composite was investigated by means of finite element method [14]. Recently, by means of COMSOL software, a finite element model was developed to simulate the dynamic mechanical behaviours of carbon fibre composite [15]. From the perspective of engineering, the layer thickness is a special parameter to balance mechanical properties and production costs of carbon fiber resin materials. The effect of layer thickness on the mechanical properties of carbon fibre composite has not been revealed. In this paper, numerical simulation was used to quickly and efficiently obtain the ultimate bearing capacity of carbon fibre composite. Based on the calculated results, the effect of layer thickness on the bearing capacity of carbon fibre composite was analyzed. The optimal layer thickness was proposed by a series of simulations. This
will help engineers and industrial departments combine a certain amount of carbon fiber resin composite materials with production costs to produce workpieces or equipment that meet the relevant ultimate load-bearing capacity requirements.

2. The Establishment of Finite Element Model

2.1 Numerical Assumptions
In this paper, Abaqus finite element analysis software was used to analyze the mechanical properties of carbon fiber resin composite materials. First, build five 2D deformable rectangular models with a length of 0.8 meters and a width of 0.006 meters, and then successively mesh the five models in a bounded manner. Use the seed edge to select the top and bottom of the five rectangular models and divide it into 100 elements with no bias. Actually, the layer number of five models are 2, 4, 6, 12, 24 respectively, but for effective analysis, the left and right sides of the five rectangular models are all divided into 24 elements (layers) with no bias, so the entire rectangular model is divided into 2400 meshes. Each mesh of the three rectangular models has a length of 0.008m and width of 0.00025m. This provides a method for analyzing the stress and strain of each small element (figure 1).

The analysis object of this experiment is carbon fiber resin composite material, so it is necessary to create the material properties of five 2D models: Create T700 carbon fiber material and set its isotropic density value as 1700kg/m$^3$, carbon fiber material has isotropic elasticity, so the value of Young's modulus as 230GPa and the Poisson's ratio as 0.2. Similarly, the 4211 epoxy resin material was created and its isotropic density was set to 1000kg/m$^3$. Resin material also has isotropic elasticity, so the value of Young's modulus was 4.5GPa and the Poisson's ratio as 0.2. Thus, the two material types analyzed in the experiment were determined. Since the quality and availability of materials must be guaranteed in the process of industrial production, the cross-sectional properties of carbon fiber materials and resin materials in the finite element model are homogeneous and solid.

2.2. Finite Element Model
At this time, the created cross-section properties of carbon fiber and resin are assigned to the rectangular model which is divided into meshes. The goal is that the carbon fiber material and resin material account for 50% respectively in the model, the five models have the same overall thickness but different number of layers of carbon fiber and resin. And the cross arrangement of carbon fiber layer and resin layer is designed. After assembly, the model of carbon fiber resin composite was created. At the same time, the freedom of displacement and rotation of the model should be limited. Limit the degrees of freedom of the lower left corner node of the model in the X-axis and Y-axis directions, and the lower right corner node of the model only in the Y-axis direction (figure 1).
3. Numerical Results

The loading force was applied to the carbon fiber resin composite model at a suitable position. In this experiment, the 25th meshes at the left and right ends of the model were selected, that is, the 0.2m points were the application points of the loading force. The initial loading force is set to 1000N, the direction is vertical down and the type is static concentrated force. This completes the procedure preceding the stress analysis. After setting the load force, the stress data of each part of the model is calculated by Abaqus cloud diagram, and the result can be queried and displayed. In order to calculate the bearing capacity, the loading force was continued to be increased until the mesh ed materials was destroyed first. Figure 2 illustrates the relationship between loading force and stress in the 12-layer model.

At this time, the middle column of the model is analyzed. The first step is to find the element that produces the largest stress in each material. When the loading force is 1000N, the stress on each mesh is far less than the failure strength of the carbon fiber material 5133MPa and the failure strength of the epoxy resin material 36.6MPa. However, by querying and observing the stress values of each mesh in cloud maps, we can find the mesh with the largest stress in the same material. The results show that in the 12-layer models, the stress produced by the meshes No.29 and No.72 in the lowest layer is the...
largest instead of the middle mesh No.50 (figure 2); That is to say, with the increase of loading force, these meshes must be the first to be destroyed. In order to determine the ultimate loading force, this experiment will gradually increase the loading force by twice, until the stress generated by the above meshes exceeds the failure strength of the corresponding material to a certain extent.

![Stress comparison between the 29th and 50th elements.](image)

**Figure 2.** Stress comparison between the 29th and 50th elements.

4. Discussion
With the increasing loading force, the stresses in carbon fiber and resin layer increase. If the stress on any part of the carbon fiber or resin material exceeds the corresponding failure strength, the carbon fiber composite will fail. In order to find out the critical load that leads to the failure of carbon fiber resin materials, five different values of loads, 2000N, 4000N, 8000N, 16000N and 32000N, were tested respectively. The results show that when the loading force is 16000N, the stress produced by No.29 mesh of 12-layer model is far less than the failure strength of corresponding materials. However, when the loading force is doubled to 32000N, the stress produced by these meshes exceeds the material failure strength, so the critical loading forces of the 12-layer model must be between 16000N and 32000N.

At this time, larger loading force of more than 16000N was imposed on carbon fiber composite to calculate its bearing capacity. By observing the stress generated by each mesh on the cloud image under these loading forces, we can judge whether it exceeds the destruction strength of the material. Until the stress generated by the No.29 mesh is close to the failure strength of the resin material, increasing the load value by small amount. Finally the critical load value is determined to be 26783.88N. Using the similar method to simulate other models with different layers, the results show that the loading forces of 2-layer model, 4-layer model, 6-layer model and 24-layer model increase to 6093.49N, 19492.71N, 23370.53N and 28151.14N respectively, the stress generated in the above mesh just exceeds the failure strength of the epoxy resin material by 36.6MPa. These are stress distribution cloud images of the part first reaching the failure strength under their respective critical loading forces in the 2D model (figure 3).
Under the same overall size, when the 2D model of carbon fiber resin composite includes two layers (one layer of carbon fiber and one layer of resin), the ultimate bearing capacity of the model is far less than that of four layers, six layers, twelve layers and twenty-four layers. Figures 4 and 5 show the ultimate bearing capacity varying with the number of layer and the thickness of each layer respectively. As the thickness of the layer decreases and the number of layers increases, the bearing capacity will first greatly increase. But as this trend goes further, the degree of increase in bearing capacity becomes smaller and smaller. Combined with figure 4 and figure 5, it is obvious that there is an optimal layer thickness, i.e., decreasing the layer thickness almost could not improve the ultimate bearing capacity of carbon fiber composite. In engineering, increasing layer number and decreasing layer thickness could result in the difficulty of engineering production, which induces the huge cost of production.
5. Summary

In this paper, the mechanical properties of carbon fiber resin composite materials are analyzed by Abaqus modeling and simulation system. The following conclusions can be drawn, which provide some ideas for the current and future applications of carbon fiber resin composite materials in engineering.

(1) The ultimate bearing capacity of carbon fiber composite increases greatly with the decreasing layer thickness and approaches to a stable value when the layer thickness is less than a certain value, i.e., the optimal layer thickness is obtained.

(2) Compared with the carbon fiber layer, the stress produced by the resin layer is more likely to exceed the failure strength, that is, the lowest resin layer must be the first to be damaged.

(3) The lowest resin material parts closest to the loading force are destroyed first.
(4) When the loading force is constant, in the same material layer, the stress generated by the part closer to the middle is smaller; the stress generated closer to the two sides is greater.

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7. Reference
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