EFFECTS OF MICRO-DEFECTS ON THE MECHANICAL PROPERTIES OF CBCFS CARBON-BONDED CARBON FIBER COMPOSITES

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ABSTRACT

Carbon-bonded carbon fiber composites (CBCFs) consisted of chopped carbon fibers and the phenolic resin. The random carbon fiber bonded together with the carbonized phenolic resin and formed the fiber network material with an excellent thermal protective property. As the material forming process inevitably leads to defects within the material, evaluation on the effects of the defects on the mechanical and thermal properties is very necessary. In this paper, the effects of micro-defect on the mechanical properties of CBCFs are investigated by numerical simulation based on a 3D random fiber network model. Two typical defects, broken fiber and broken bonding joints are considered in the simulation. Broken fibers are realized by randomly removing fiber segment between two bonding joints in a perfect model, and failure at the bonding joints is realized by the randomly removing the bonding materials. The numerical simulation results show that the mechanical properties of the CBCFs are more sensitive to the connection failure than the broken fiber. In CBCFs material, fiber is divided into several fiber segments by the bonding joints. The load is transmitted through the bonding joints between the fibers. When one of the fiber segments is broken, the remaining fiber segments still have a load carrying capacity. If bonding joints between fibers fail, the stress in the fiber network is redistributed, and the force path is remarkably changed. In addition, the mechanical properties of fiber are better than those of bonding material which caused more bonding joints come into breakage.

1 INTRODUCTION

Carbon-bonded carbon fiber composites (CBCFs) have a wide range of potential applications in the development of thermal insulation in new spacecraft shuttles [1-3], for their lightweight structure, ultra-low thermal conductivity and excellent thermal insulation performance. The random chopped carbon fibers bonded together at the intersections by discrete regions of the pyrolytic carbon derived from phenolic resin. After the pyrolysis process, micro-cracks or defects occur within the material due to mismatched internal thermo-physical properties. It has been shown that the properties of porous materials are sensitive to defects generated either from material processing or during in-service life. For instance, only 1% of defects (fractured cell edges) can reduce the hydrostatic strength of 2D honeycombs by 90% [4]. Thus, the evaluation on the effects of the defects on the mechanical and thermal properties is very necessary.

Internal microstructure of CBCFs is a typical kind of random fiber network. In the theoretical study, Gibson and Ashby [5] found a relationship between the relative density and mechanical properties of the porous solids, while the relationship was not enough to characterize the mechanical properties of the material with random defects in the network. In addition, a few theories [6-8] based on the affined assumption have been established to analyse the mechanical properties of fiber network. While, lots of research found that the nonaffined deformation is more actual for the fiber network [9], especially for the influence of defect will exacerbate the nonaffined deformation. Compared to the theoretical methods, FEM provided a more direct approach for understanding the relationship between the microstructure and mechanical properties based on the detailed microscopic model. In this paper, a finite element model is established to characterize the microstructure of the material based on the SEM observation of CBCFs. Two types of defect, broken fibers and broken bonding joints are explored in the numerical model. The uniaxial compression behaviour of the CBCFs is simulated based on this model, and analysed the effects of micro-defect on the mechanical properties of CBCFs. In section 2, 3D random fiber network models with above defect are established. The effects of micro-defects are discussed in section 3.

2 METHOD

According the observation in experiments, the carbon fibers are assumed to be straight cylinder with uniform diameter (D) and length (L). More details of the progress are described as follows: The fiber orientation is determined by two Euler angles α and β, which reflect the fiber distributions in 3D space, as shown in Fig. 1. Here, uniform random distribution is adopted to describe the distribution of Euler angles β, and Gaussian distribution was adopted for Euler angles α, which is in good agreement with the experimental observation of fiber distribution. The Euler angles were expressed as follow:

$$\alpha \sim \mathrm{N}\left(0,\varphi^2\right), \beta \sim U\left(0,2\pi\right) \tag{1}$$

where N and U represent the Gaussian distribution and uniform distribution, respectively.

The vector of fiber axis in the 3D space, as illustrated in Fig. 1, could be expressed as:

$$\vec{L}_i = \left(L\cos\alpha\cos\beta - x_i^M, L\cos\alpha\sin\beta - y_i^M, L\sin\alpha - z_i^M\right) \tag{2}$$

where x_i^M , y_i^M and z_i^M are the coordinate values of the center point M_i in the fiber i.

Therefore, the fiber is considered as the aggregation of points:

$$C_i = \left\{ K_i^r \left| \overrightarrow{OK_i^r} = \overrightarrow{OM_i} + \lambda \frac{\vec{L}_i}{\left|\vec{L}_i\right|} + \vec{r},\ \lambda \in \left(-\frac{L}{2},\frac{L}{2}\right) \text{ and } \left|\vec{r}\right| \in \left(-\frac{D}{2},\frac{D}{2}\right) \right. \right\} \tag{3}$$

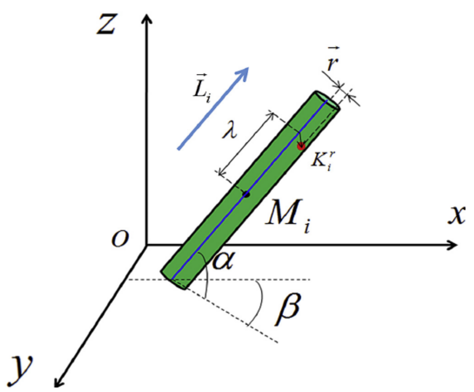

Figure 1: The description of a fiber in 3D coordinate system.

Based on the description of the position of a fiber in the domain, a 3D random fiber network model is established, as shown in Fig. 2. Two typical defects, broken fiber and broken bonding joints are considered in the model. Broken fibers are realized by randomly removing fiber segment between two bonding joints in a perfect model (Fig. 3(a)), and failure at the bonding joints is realized in the modelling by the randomly removing the bonds (Fig. 3(b)). In the 3D model, each fiber is simulated by Timoshenko beam element with shear effect included. The bonding materials are also simulated by beam element for matching freedom. In addition, the periodic boundary conditions are applied to the RVE model Mesh sensitivity analysis is conducted to ensure numerical convergence. Finally, 6 meshes are assigned for each fiber. The maximum principal stress criterion is employed for both the fiber and bonding materials, and the onset and propagation of damage are implemented with stiffness reduction method.

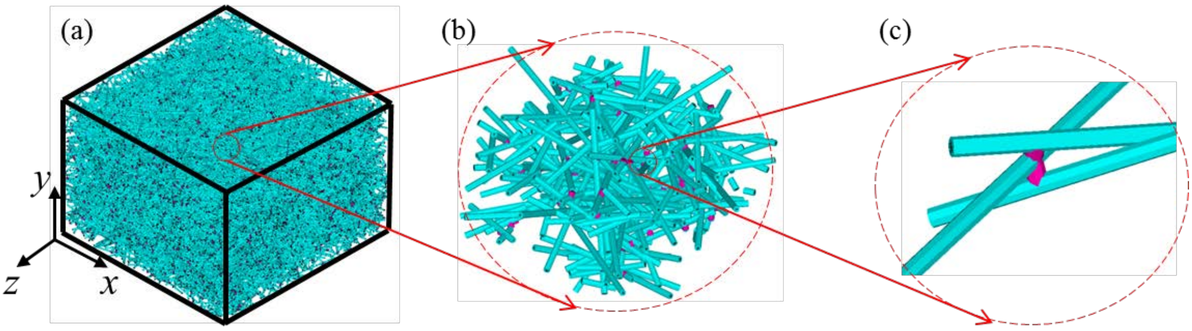

Figure 2: A geometrical model of random fiber network. (a) the RVE model, (b) the close-up view of the network, (c) the enlarged picture of the bonded fibers, with fibers coloured in cyan and the bonding material in red.

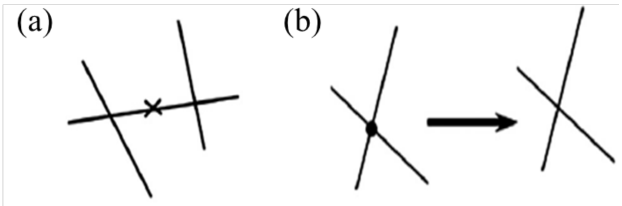

Figure 3: Two types of defect in CBCFs: (a) broken fibers, (b) separation of fiber joints

3 RESULTS AND DISCUSSION

The numerical model is established to simulate the compression behaviours of the CBCFs. The details for the geometrical parameters and material information are list in Table 1. Considering the computational convergence, a loading step of 0.15% strain increment is adopted to ensure a stable calculation.

Table 1 Geometric parameters and mechanical properties of CBCFs

Fiber diameter	9.0 μm	Fiber Poisson's ratio	0.26
Fiber length	800 μm	Fiber strength	3.5 GPa
Relative density	0.14	Bonding elastic modulus	4.65 GPa
Fiber elastic modulus	230 GPa	Bonding strength	0.2 GPa

3.1 Sample capacity

Before the calculation, 25 random fiber network models with defect were established in order to obtain the capability of the model. The critical sample capacity is determined by monitoring the convergent relative error of mean value (REMV) and relative standard deviation (RSD):

$$REMV = \frac{|M_{n+1} - M_n|}{M_{n+1}} \times 100\% \ , \ M_n = \frac{\sum_{i=1}^{n} Q_i}{n}$$
$$RSD = \frac{D_n}{M_n} \ , \ D_n = \sqrt{\frac{\sum_{i=1}^{n} (Q_i - M_n)^2}{n}} \tag{4}$$

where Q_i is the value obtained from numerical sample i, M_n and D_n are the mean values and standard deviations calculated with n samples, respectively.

As presented in Fig.4 (a), the REMVs are all below 0.5% when sample capacity exceeds 12, and the convergent RSDs obtained stable after sample capacity exceeds 20 (Seen in Fig. 4 (b)). Consequently, the sample capability of defect model is 20 and the follow calculation results are the average of the 20 samples.

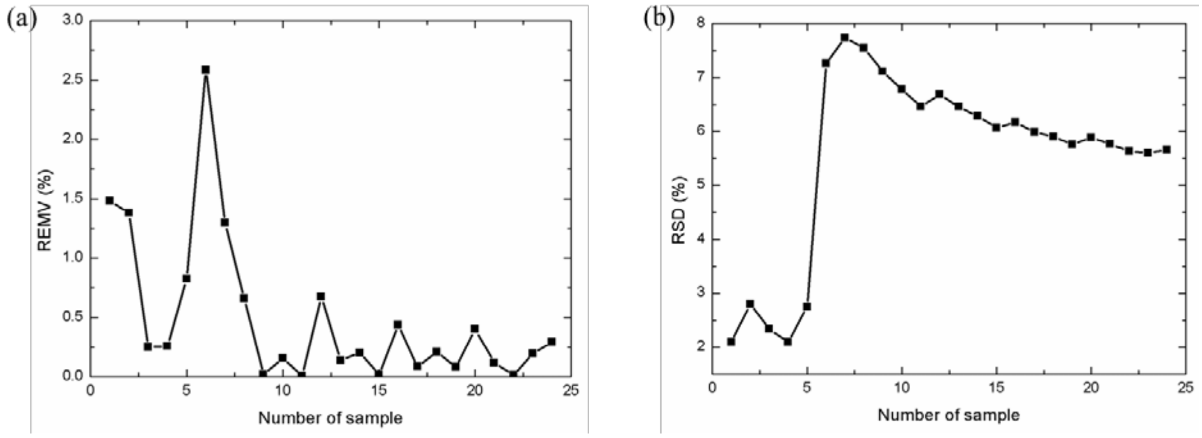

Figure 4: The convergence of the (a) REMVs and (b) RSDs of the effective mechanical properties.

3.2 Effect of micro-defect

Fig. 5 gives the relationship between percentage of defect and elastic modulus, which is shown that elastic modulus decreased with the increment of two types of defect both for in-plane and out-of-plane direction. As illustrated in Fig. 5(a), in-plane elastic modulus rapidly declines with the increase of fiber defects, while it slowly declines with the increase of bonding defect. Comparison between the two type defects, the fiber defect is more serious than bonding defect for in-plane properties of CBCFs, especially the percentage of defect is below 2%. As for the out-of-plane modulus in Fig. 5(b), at the percentage of bonding defect is 10%, the out-of-plane modulus reduce by 25% compared to the modulus of perfect model, which is more than the declination of in-plane modulus. It is also reflected the bonding materials have an effect on the out-of-plane loading transfer. This result mainly attributes to the internal microstructure of CBCFs for the anisotropic in-plane and out-of-plane direction. Fibers almost distribute within in-plane direction and connected by the bonding material both in layer and out of layer, which can be macroscopically treated as lamellar structure of fiber sheet and bonding sheet. Obviously, the mechanical property of fiber sheet is much better than bonding sheet. Thus, during the in-plane compression, loading is mainly carried by fiber sheet. Fiber defect can sharply decrease the in-plane properties. While, under the out-of-plane compression the bonding sheets and the fiber sheets are paralleled to carry the load. Thus, the bonding joints have the effect on out-of-plane mechanical properties.

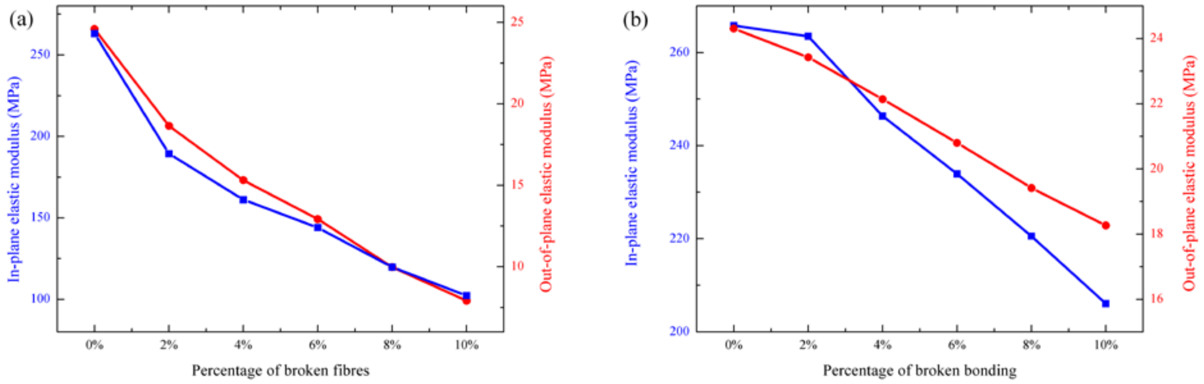

Figure 5: Effect of defect on mechanical properties of CBCFs: (a) broken fibers, (b) separation of fiber joints. (Percentage 0% standards a perfect model with porosity is 86%)

The typical in-plane microstructure of fiber boned fiber is to explain the deformation in microscope. In Fig. 6, the random fibers distributed in-plane direction, which we called fiber sheet or a layer. The layer stacked in out-of-plane direction through the bonding joints between the layers. The fiber ($\overline{AE}$) is divided into several fiber segments ($\overline{AB} \sim \overline{DE}$) by the bonding joints. The out-of-plane load is transmitted through the bonding sheets between the fiber sheets. If one of the segments is deleted, the remaining fiber still has a load carrying capacity through other loading transfer path. Unfortunately, the capacity declines due to the weak mechanical properties of bonding materials. Thus, the bonding defect is more important for the out-of-plane deformation.

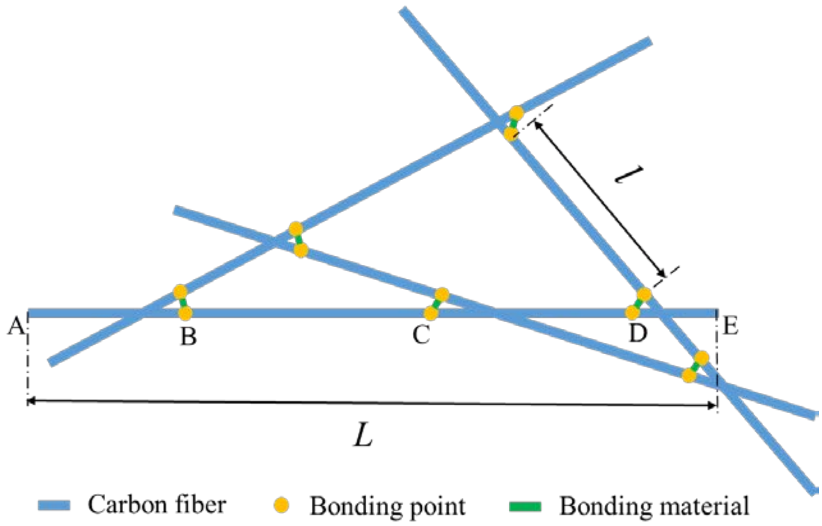

Figure 6: Illustration of fiber bonded fiber microstructure in-plane direction.

The compression strength of fiber defect model, bonding defect model and perfect model is given in Fig. 7. Compared to the perfect model, fiber defects lead to a decrease within the in-plane strength by 22.45%, which is more serious than the declination by the bonding defect. However, bonding defect for out-of-plane strength is more critical than fiber defect.

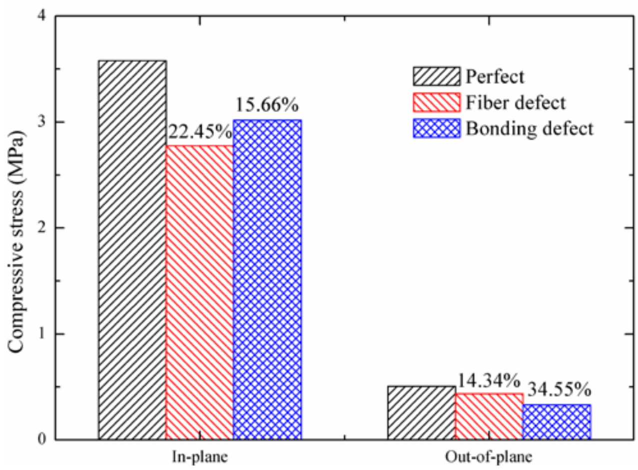

Figure 7 Two types of defect in CBCFs: (a) broken fibers, (b) separation of fiber joints

For compressive strength, if bonding joints between fibers are deleted, the stress in the fiber network is also redistributed. In addition, the mechanical properties of fiber are better than those of bonding material, if one of bonding material firstly came into breakage, the loading redistributed on the other bonding materials along this fiber will increase, which caused more bond materials come into breakage. Thus, the effect of bonding material defect is more significant for out-of-plane mechanical properties

CONCLUSION

In this paper, based on our 3D random fiber network model, the effect of two typical defects, broken fiber defect and broken bonding joints defect on the compression behaviours of CBCFs are investigated. The numerical simulation results show that CBCFs has obvious layered characteristics. In-plane mechanical properties of the CBCFs are more sensitive to the broken fiber. And out-of-plane properties of the CBCFs are more sensitive to the bonding material.

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