Carbon 116 (2017) 398–408

Contents lists available at ScienceDirect

Carbon

journal homepage: www.elsevier.com/locate/carbon

Compression behaviors of carbon-bonded carbon fiber composites: Experimental and numerical investigations

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ARTICLE INFO

Article history:
Received 31 October 2016
Received in revised form
18 January 2017
Accepted 5 February 2017
Available online 6 February 2017

Keywords:
Carbon-bonded carbon fiber composites (CBCFs)
Compressive behavior
Mechanical properties
Finite element method (FEM)
Unloading-reloading test

ABSTRACT

Carbon-bonded carbon fiber composites (CBCFs) were widely used as thermal insulation materials due to their light weight and ultra-low thermal conductivity. The CBCFs with density of about 0.256 g/cm^3 were tested in compression with the modulus and strength evaluated. The in-plane and out-of-plane tests revealed obvious anisotropic behavior of the material, which could be attributed to the fibers distribution. The unloading-reloading tests showed more evidence for the difference of the mechanical behaviors between in-plane and out-of-plane. In addition, we presented a finite element model to predict the mechanical properties of the CBCFs, and the deformation mechanisms as well. The numerical results showed the compressive modulus and strength increased with density following exponential functions. Moreover, the effects of fiber length and the fiber orientation on the mechanical properties were also discussed numerically. The results of this paper are helpful for the design and optimization of these materials for potential applications.

1. Introduction

Carbon-bonded carbon fiber composites (CBCFs) consist of chopped carbon fibers bonded together at the intersections by discrete regions of the pyrolytic carbon derived from phenolic resin, with the densities as low as 0.1–0.5 g/cm^3 and the porosity up to 70–90% [1,2]. Consequently, CBCFs have a wide range of potential applications in the development of thermal insulation in new spacecraft shuttles [3–5], for their lightweight structure, ultra-low thermal conductivity and excellent thermal insulation performance. To a great extent, the thermal insulation performance of CBCFs depended on the internal microstructure of materials [6,7]. For example, thermal insulation effect of CBCFs can be reduced by the destruction of the microstructure [8]. Therefore, it is important to understand the mechanical properties of CBCFs, which is a prerequisite for the best function of these materials.

The mechanical properties of CBCFs could be enhanced by increasing fibers, which was at the expense of thermal insulation performance and light-weight for the price [9,10]. Moreover, the bonding strength between the fibers was enhanced with chemical vapor infiltration (CVI) [11] or chemical vapor deposition (CVD) [12]. Recently, lots of researchers tried to tune the mechanical properties of CBCFs by the addition of Si [13,14], Zr [15,16] or Zr-Ti [17] and to improve oxidation corrosion resistance of CBCFs as well. Also, the nanowires [18–20] were added into the coating to improve interface cohesion between carbon fibers. Experiments also revealed the influence factors of material performance, including manufacturing process parameters and structural parameters [21–23]. Therefore, establishment of the relationships between microstructure and mechanical properties is essential to prepare and optimize these materials for engineering applications.

In the theoretical study, Gibson and Ashby [24] found a relationship between the relative density and mechanical properties of the porous solids, but the relationship was not enough to characterize the mechanical properties of the material with high porosity complex network. Hence, a few theories [25–28] based on the affined assumption have been established. Picu et al. [27] employed the relative density and a characteristic length scale to predict the mechanical properties and reflect the transition of fiber deformation. Therefore, the geometrical parameters of the fibers could not

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http://dx.doi.org/10.1016/j.carbon.2017.02.012
0008-6223/

be neglected in the prediction of the mechanical behaviors of CBCFs.

Finite element method (FEM) was widely applied to investigate the mechanical properties of material with the complex internal structure [29,30]. Compared to the theoretical methods, FEM provided a more direct approach for understanding the relationship between the microstructure and mechanical properties in detail. FEM was employed to investigate the 2D fiber network such as nonwoven fabrics [31], paper material [32,33] and metal fiber-sintered sheets (FSs) [34]. Due to the complex microstructure, the simulation of 3D fiber network was more challenging. Markti and Clyne [35] established the 3D geometrical model through the X-ray tomography and predicted the elastic constants of transversely isotropic metal FSs. Isaksson et al. [36] proposed a 3D fiber model with hybrid particle element and analyzed the deformation and fracture mode. In addition, Liu et al. [37–39] established a 3D random fiber network model to predict the mechanical behavior of ceramic insulation tile, with good agreement with the experiment results.

The aim of this paper was to investigate the uniaxial compression mechanical properties of CBCFs with experiments and to establish an effective numerical method, which was applicable to study the relationship between the microstructure and mechanical properties of CBCFs. This paper was organized as follow: firstly, the modulus and strength of CBCFs were evaluated and deformation mechanisms of CBCFs in compression were analyzed using various experimental techniques. Next, a 3D geometrical model was presented for the CBCFs based on our previous work [37–39], which was applied to predict the mechanical properties and deformation of CBCFs. Finally, the influence of the relative density, fiber length, and fiber orientation angle on the mechanical properties were discussed systematically.

2. Experimental procedures

2.1. Materials

CBCFs were composed of two kinds of materials: rayon-based carbon fibers produced by Institute of Coal Chemistry Chinese Academy of Sciences (Shanxi, China) and the pyrolytic carbon derived from phenolic resin. Carbon fibers were first cut into short segments with averaging length (L) of about 0.8 mm and diameter (D) of about 9 μm, and were dispersed in water with the dispersant such as polyacrylamide. Then the phenolic resin solution diluted by addition of ethanol into this chopped fiber slurry. After 60 min mechanical stirring, a homogeneous distribution slurry could be obtained. The slurry was then poured into a mould with vacuum pressure and keeping the shape and size of composites constant. The water in the composites was removed with a drying process. After that, the random fibrous body was sintered in a furnace (High multi-5000, Fijidempa Co. Ltd., Osaka, Japan) with temperature of approximately 1200 °C for 2 h in argon atmosphere. During the sintering process, the randomly orientated fibers were bonded together by the solidification and carbonization of phenolic resin, and an ultra-high porous fiber network was finally formed (Fig. 1(a)).

2.2. Compression testing

The uniaxial compression test was implemented to study the compressive mechanical behaviors of the CBCFs, with using a Universal Test Machine (MTS 880, MTS System Corporation, USA). 7 specimens were adopted for the experimental test in each direction with the dimensions of specimens is 20 mm × 20 mm × 20 mm [37], which is coincided with Ref. [1] and is helpful to reduce the data dispersion. The normal direction of the X-Y plane was defined as the out-of-plane direction, and the plane perpendicular to Z axis was considered as the in-plane (Fig. 1(b)). The specimens were stored in the dryer to avoid absorbing moisture before the experiments, and the density of the specimens is measured as 0.2559 ± 0.008 g/cm^3. The loading speed in all the experiments was set to 0.5 mm/min. To understand the deformation mechanisms of the CBCFs under compressive loading, a scanning electric microscope (SEM) (JSM-6010, JEOL) was used to characterize the microstructures of the CBCFs. In order to explore the mechanical deformation, additional tests were carried out with the specimens subjected to successive unloading–reloading cycles. The specimens unload and reload in each 3% loading increment. The loading speed was 0.5 mm/min which was the same as the static loading, and the unloading speed was 1.2 mm/min.

3. Numerical implementation

In addition, to understand the deformation mechanisms, including damage propagation and fracture of CBCFs, the FEM method was employed to simulate the mechanical behaviors of the CBCFs. According the observation in experiments, the carbon fibers were assumed to be straight cylinder with uniform diameters and lengths. More details of the simulation were described as follows.

3.1. Mathematical description of the fiber position

The fiber orientation was determined by two Euler angles α and β, which reflect the different distributions in two directions, as shown in Fig. 2. Here, uniform random distribution was adopted to describe the distribution of fibers in the in-plane direction [1,2], and Gaussian distribution was adopted for those of out-of-plane direction [37,38], which were in good agreement with the experimental observation [1,2]. The Euler angles were expressed as follow:

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

where N and U represented the Gaussian distribution and uniform distribution, respectively. Here standard deviation ϕ was determined to be about 21.5°, according to the experiments [37,38].

The vector of fiber axis in the 3D space, as illustrated in Fig. 2, could be expressed as:

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

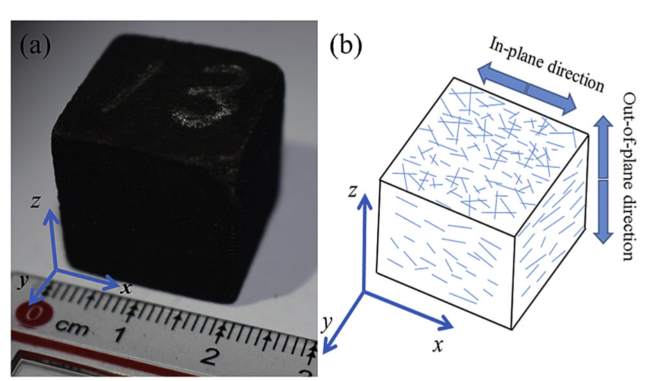

Fig. 1. (a) Image of the typical specimen of CBCFs. (b) Schematic of CBCFs specimen, the in-plane and out-of-plane direction is given by the arrows. (A colour version of this figure can be viewed online.)