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Compressive strength determined for ultrahigh modulus fiber reinforced composites by $[90/0]_{ns}$ laminates

Mi Zhang[a], Xiaodong Wang[a], Weidong Li[b], Jie Yang[c], Zhidong Guan[a,*]

[a] School of Aeronautic Science and Engineering, Beihang University, Beijing 100191, China
[b] AVIC Composite Technology Center, Composite Corporation Ltd., Beijing 101300, China
[c] Beijing Institute of Electronic System Engineering, Beijing 100854, China

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ABSTRACT

Traditional ASTM D6641 standard is not suitable for ultrahigh modulus carbon fiber reinforced polymer (CFRP) composites under longitudinal compression due to the unacceptable failure mode of end crushing. Experiments and micro-mechanical finite element simulations are conducted for $[90/0]_{ns}$ laminates under compression to check if it is acceptable using results of $[90/0]_{ns}$ laminates to calculate longitudinal compressive strength. Experimental results show that failure modes in $[90/0]_{ns}$ laminates are acceptable. Fiber splitting, fiber breakage and kink band are found clearly in 0-degree lamina under SEM. Failure index distributions before peak load in simulation show that it is fiber failure in 0-degree lamina that causes the final failure which indicates that $[90/0]_{ns}$ laminates can be used to calculate compressive strength. Four different types of fibers with different modulus and $[0/90]_{ns}$ micro-mechanical model for ultrahigh modulus CFRP are also built for comparison. Results show that this method is also applicable for T800H CFRP composites, but not for T300 and T700 CFRP composites.

1. Introduction

With the development of ultrahigh modulus carbon fibers, ultrahigh modulus CFRP composites have been widely used, especially in aerospace field. Thus, compressive behavior of CFRP has received more and more attention as the diameter of fiber becomes much smaller. Usually, the compressive strength of CFRP composites is 60–70% of their tensile strength, and is therefore considered to be a design limiting parameter [1].

It is widely believed that kink band is a typical phenomenon for composites under longitudinal compression. The earliest study of kink band problem traces back to 1960, when Rosen [2] observed the microbuckling of fibers during the shrinkage of the resin as it was cooled from its curing process. He thought kink was governed by elastic fiber which was overturned by Argon [3] who thought kinking was governed by plastic buckling of the material. Then, further studies were conducted by Budiansky [4], Steif [5] and Jumahat [6]. They looked at the relationship between compressive strength and kink band angle, which is usually 10–30°. Besides, with the development of simulation technology, micromechanical models for compressive behavior were proposed by Hsu [7], Bai [8] and Pimenta [9].

When subjected to compression, CFRP composites exhibit different types of failure mechanisms, namely, kinking, matrix crack and delamination. These failure modes occur either separately or simultaneously depending on loading conditions [10]. Besides, with the development of ultrahigh modulus CFRP composites, longitudinal compression should be analyzed from different views due to the unacceptable failure modes under traditional standard.

Experiments [11,12] and micro-mechanical [13] models are conducted to analyze the features of CFRP cross-ply laminates under compression. X-ray computed tomography (CL) was used by Moffat [11] to observe damage in CFRP $[90/0]_s$ laminates. Different ply cracking in the surface plied of $[90/0]_s$ and $[0/90]_s$ CFRP laminates in two material systems were compared by Smith [12]. And it was suggested that the crack growth mechanisms were such that the 90-degree failure was essentially propagation-controlled and hence fracture mechanics-based modelling is appropriate. Besides, by using $[90/0]_s$ laminates, Arteiro [13] analyzed the effects of ply thickness on the transverse compressive strength at an *in situ* simulation. Prabhakar [14] investigated $[45/+45/90/0]_s$ laminates by using semi-homogenizing method in simulation, which overlooked the failure details of composite laminates.

With all this in mind, compressive tests were conducted for $[90/0]_{ns}$ ultrahigh modulus CFRP composite laminates in this paper. To explore

* Corresponding author.
E-mail address: zdguan@buaa.edu.cn (Z. Guan).

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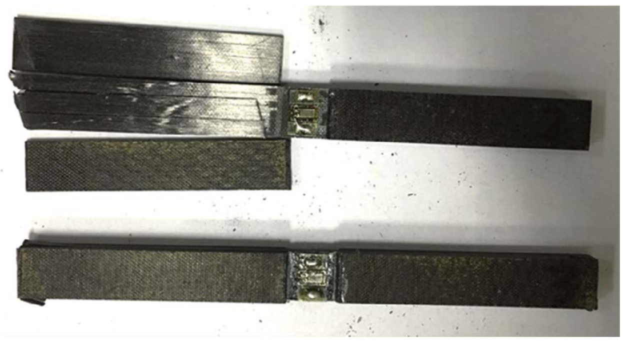

Fig. 1. Typical failure modes for M40J/epoxy under ASTM D6641.

failure details of the compressive process, a two-dimensional(2D) micro-mechanical model of ultrahigh modulus CFRP composites laminate is created with a layup of $[90/0]_s$, which is a representative of a bigger and macroscopical laminate. Each layer is built with discrete fiber and matrix to reveal the failure details of the laminates. Stochastic strength distribution for fibers and Drucker-Prager constitutive model for matrix are considered as well. Also, a comparison between the results of different fiber reinforced composites with different fiber modulus is presented with the aim of validating the applicability of Q/6S 3071-2016 [15] test standard. $[0/90]_s$ micro-mechanical model is conducted to compare with $[90/0]_s$ model to analyze the effects of surface ply on compressive behavior.

2. Experiments

At first, traditional test standard for compression – ASTM D6641 [16] is conducted for ultrahigh modulus CFRP composites with typical failure modes shown in Fig. 1. Actually, failure mode of end crushing like this is not valid for compression. Thus, other methods should be taken to measure the compressive strength for ultrahigh modulus CFRP composites.

A new test standard called Q/6S 3071-2016 has been proposed by Beijing Institute of Aeronautical Materials, which focus on T800 CFRP composites. It is suitable for strength and modulus of unidirectional (0-degree ply orientation) T800 carbon fiber reinforced composites. It was based on ASTM D6641 – Standard Test Method for Determining the Compressive Properties of Polymer Matrix Composite Laminates Using a Combined Loading Compression (CLC) Test Fixture. Q/6S 3071-2016 test standard stipulates the apparatus and supplies, sampling and test specimens, test conditioning, procedure, validation and calculation. The test fixture is the same with that in ASTM D6641. And the specimen configuration is shown in Fig. 2. In the new test standard, $[90/0]_{ns}$ specimen is used to test compressive strength, while $[0]_n$ specimen is used to measure compressive elastic modulus. And conversion coefficient should be introduced to convert compressive strength of orthogonal layer test sample to longitudinal compressive strength. The conversion coefficient k can be calculated as

$$k = \frac{2E_{11}}{E_{11} + E_{22}} \tag{1}$$

where E_{11} and E_{22} are modulus of longitudinal compression and transverse compression, respectively. As defined in Q/6S 3071-2016, longitudinal compressive strength can be calculated as

$$\sigma_c^{u0} = k\cdot\sigma_c^c \tag{2}$$

where σ_c^c is the strength of $[90/0]_{ns}$ laminates. Compression tests for $[90/0]_{8s}$ laminates of ultrahigh modulus CFRP composites were conducted in Beihang Structural Mechanics Laboratory, using WDW-200E electronic universal testing machine which is made by Jinan era-test-gold testing machine limited corporation. The manufacture of specimen and test methods were based on the test standard Q/6S 3071-2016.

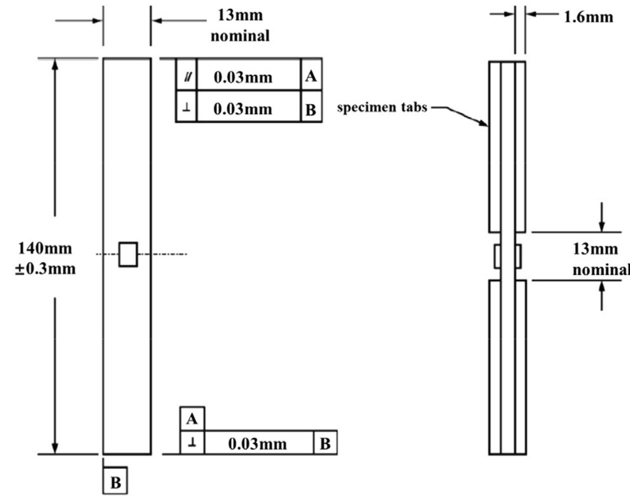

Fig. 2. Specimen configuration in Q/6S 3071-2016 test standard.

Engineering microscope was used to observe the failure details during the compressive tests. MA15 SEM scanning electron microscope (made by Carl Zeiss AG) is also used to observe after experiments. Final results are shown in Table1.

Digital image correlation (DIC) is also applied for observation during the experiments. As the test area for compression was small, the results were limited due to the light source. Longitudinal strain distribution and shear strain distribution at different times are shown in Fig. 3. It can be observed that the strain distribution is continuous along the thickness in spite of the different layers. Stress concentration can be found clearly at the end of the tabs.

Failure process was record by engineering microscope, which is shown in Fig. 4. The time between two adjacent images is 0.3 s. The integral typical failure mode of $[90/0]_{8s}$ laminate is shown in Fig. 4(d), with its magnified image shown in Fig. 5 and Fig. 6.

Images in Fig. 4 show that failure began at the end of tabs, and extended to the middle of the specimen. And it showed a rather rapid failure process. The time between (c) and (d) in Fig. 4 is 0.3 s, which indicates a sudden final failure under compressive load. However, it is believed that failure first occurred in the test area where specimen do not have the support of strengthen tabs, and then it spread to the internal area with strengthen tabs.

SEM images were taken after the test from two different view angles which are shown in Fig. 5 (view point A in Fig. 4) and Fig. 6 (view point B in Fig. 4). Images from the view point A show that fibers in 0-degree lamina tend to split and break. And the crack forms nearly 45° with the loading direction. Kink band can be found clearly in 0-degree lamina from view point B, which is the typical failure mode for longitudinal compression. And the width of the kink band w is about 40 μm according to the image scale in Fig. 6.

The final failure of the specimen was quite instantaneous which need more research. Thus, finite element simulation was conducted below to show the failure details of the process. Besides, the applicability of Q/6S 3071-2016 on ultrahigh modulus CFRP composites should be discussed through simulation below.

3. Discrete model for $[90/0]_s$ laminates

A two-dimentional (2D) micro-mechanical model for ultrahigh modulus CFRP composites laminate is created with a layup of $[90/0]_s$, which is shown in Fig. 7. The micro-laminate is a representative of a bigger and macroscopical laminate. Each layer is built with discrete fiber and matrix to reveal the failure details of the laminates. And fibers in 90-degree laminas is packed in stochastic distribution [17]. The fiber diameter and fiber volume fraction are 5 μm and 60%, respectively.