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Improved testing method for the compressive strength of single fiber

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ABSTRACT

In this study, an improved method is developed to test the compressive strength of single fibers. Two improvements were carried out compared with the previous work, and they were composed of: (1) a skillful device for preparing the compression sample with the advantage of greatly saving time and highly efficiency; (2) an improved system for directly testing the single fiber's compressive strength with high accuracy and repeatability. More than fifteen qualified samples were successfully prepared within two hour compared with even only one sample in a day for the poor manipulation accuracy of previous work. Compressive strength of single fiber was tested based on four kinds of PAN-based carbon fibers. Experimental results from the new method show great agreement with the data published, which prove the designed method and improved device is more applicable for testing the compressive strength of single fiber in the optimization of cost and efficiency.

1. Introduction

Fiber-reinforced polymer composites (FRPC) are widely used in aerospace industry due to the excellent comprehensive technical performances such as low density, high specific modulus and strength. The compressive strength of a composite is significantly depended on the compressive performance of reinforcement consisting of single fiber. Compressive strength of single fibers is hard to obtain due to the difficulties of carrying out compressive tests. Many efforts have been undertake to theoretical prediction the compressive strength of single fiber [1–8]. The compressive strength of carbon fibers evaluated from the compressive strength of unidirectional fiber reinforced depends significantly on the properties of the matrix and the interface, since fracture modes vary with these properties, Furthermore, improper application of the rule of mixtures to give the strength of the reinforcing fibers adds uncertainty to the estimated values.

A number of efforts have been conducted to develop direct experimental methods to test the compressive strength of single fibers [9–19], for instance, bending beam, single fiber composite and recoil methods, which are obtained the compressive strength of single fiber by measuring the compression force acting on the single fiber and then calculated the compressive strength based on theoretical formula. Previous work [20] designed a direct system to test the compressive strength of single fiber. However, the manual processing in the sample preparation process increases the time cost and greatly hinders the widespread adoption of this method. Moreover, it still needs to some improvements especially in improving the efficiency of sample preparation and the experimental precision.

The first objective of the present article is to design a skillful device for preparing the validity compression sample with efficiently saving manipulating time. The second objective is to verify the reliability of the improved compression device in testing of compressive strength of single fiber.

2. Experimental

2.1. Materials

The compressive strength of four kinds of PAN-based carbon fibers studied in previous research [20–22] was tested in the present work. The physical properties of these fibers are presented in Table 1.

2.2. Theory of the experiment

2.2.1. Theoretical of the single fiber's compressive strength

Compressive strength for single fiber can be theoretical estimated based on cantilever beam pure bend theory [23,24]. Schematic of force analysis of cantilever beam is shown in Fig. 1a, in which the cantilever beam having a strain gauge was vertical to

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Table 1
Properties of PAN-based carbon fibers.

Fiber kinds	Tensile strength (GPa)	Tensile modulus (GPa)	Diameter (μm)
T300	3.53	235	7.01
T700	5.32	237	6.75
M40	4.46	377	4.97
M55	4.08	520	5.21

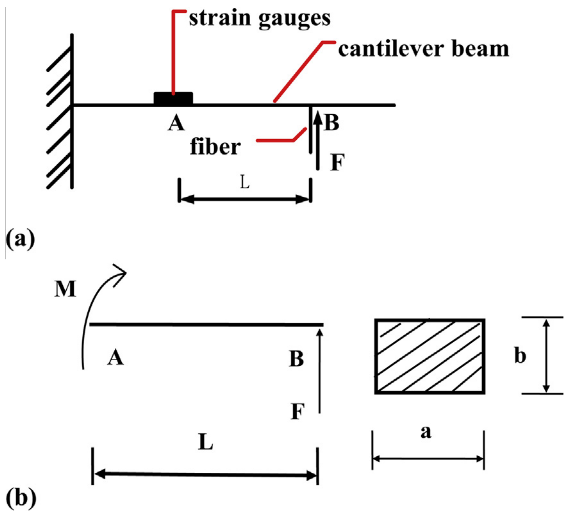

Fig. 1. Schematic of force analysis for cantilever.

the single fiber compression sample. Fig. 1b presents the top view of the experimental setup and cross section diagram of the cantilever beam, which is illustrated the compaction force applied on the cantilever beam from the compression sample.

With the assumption of quasi-static process in the compression process, the moment applied on cantilever beam from the compression sample can be calculated by

$$M = F \cdot L \tag{1}$$

where M is moment of section A; F is outer force; L is the length of force arm. Substitution of Hooke's law $\sigma = E_{beam}\varepsilon$ into the integral shape of formula (1), we could get

$$M = \int_A y\sigma dA = 2a\int_0^{\frac{b}{2}} y\sigma dy = 2aE_{beam}\varepsilon\int_0^{\frac{b}{2}} ydy = 1/4E_{beam}\varepsilon ab^2 \tag{2}$$

The outer force applied on the cantilever beam was calculated based on Hook's law, and then the compression reaction force acting on the single fiber from the cantilever beam reaction action was used to calculate the compressive strength of the compression sample.

It is worth pointing out that the hypothesis of vertical interaction between the compression sample and cantilever beam was adopted in the analysis process. The compressive strength of the single fiber will be compromised in the case of un-perpendicular between the sample and cantilever beam. The diagram of force analysis is shown in Fig. 2 and the mechanism is briefly discussed as follows.

Assuming compression sample has an angle of $\theta (0^\circ < \theta < 90^\circ)$ to the vertical direction of cantilever, and the force arm of the outer force between contact points and strain gauges is L. The reaction force of the cantilever beam applied on sample fiber will also has an angle of θ with vertical. According to the Pythagoras' theorem

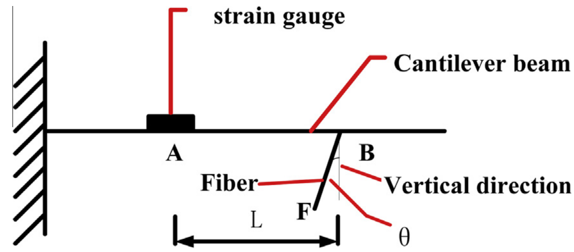

Fig. 2. Schematic of force analysis for cantilever at non-perfect interactions.

of vectors, the vertical component applied on cantilever is $F\cos\theta$, which decreases the experimental result of compression strength of sample. Moreover, the horizontal component force has an effect on resulting in buckling deformation, which will cause the same effect likewise too high length of sample. Hence, it can be seen clearly that the important of the vertical interaction of the sample and cantilever beam, which was successful overcame based on a visual monitoring the preparation process with electron microscope.

2.2.2. The length design of the single compression sample

The distance between the strain gauge and outer force direction is l. The inertia moment and elastic modulus of cantilever beam are I and E_{beam} respectively, and compression force of the cantilever beam is P, then critical buckling force P_{lj} can calculate as

$$P_{li} = \pi^2 E_{beam} I/(\mu l)^2 \tag{3}$$

where the length factor μ is determined by the boundary condition of the cantilever beam. The 'clamped-simple support' condition is adopted here [20], which gave $\mu = 0.7$. In this study, the compressive modulus of carbon fiber was assumed equal to the tensile modulus due to difficulty in obtaining the direct evaluation of modulus at very small force level. The critical stress for single fibers can be expressed as

$$\sigma_{lj} = P_{lj}/A = \pi^2 E_{beam} I/(\mu l)^2 A \tag{4}$$

Substitution radius of minimum cross-sectional inertia moment expressed as $r = \sqrt{I/A}$,

So we obtained the σ_{lj}

$$\sigma_{lj} = \pi^2 E_{beam}/(\mu l/r)^2 A = \pi^2 E_{beam}/\lambda^2 \tag{5}$$

Here $\lambda = \mu l/r$ is the soft coefficient of compressive column which characterizes the length effect, section figure and boundary condition to critical stress σ_{lj} and r is the radius of inertia moment. For example, the compressive strength of T300 carbon fiber (manufactured by *TORAY* Co. Ltd) is 1.8 GPa. Assume the cross section of the single fiber is ideal circle and the diameter d is equal to 7 μm. The section inertia can be expressed as $\lambda = \pi d^4/64$, and then the radius of minimum cross-sectional inertia moment can be calculated as

$$r = \sqrt{I/A} = d/4 = 1.75\ \mu\text{m} \tag{6}$$

The bending modulus of cantilever beam materials is 209 GPa, the λ can be calculated according to (5)

$$\lambda = \sqrt{\pi^2 E/\sigma_{lj}} = \sqrt{\pi^2 * 209/1.8} = 33.92 \tag{7}$$

Based on Euler's formula, the theoretical critical length of sample can calculate as

$$l = \lambda r/\mu = 33.92 \times 1.75/0.7 = 84.8\ \mu\text{m} \tag{8}$$

Hence the sample with fiber length only below 90 μm is recommended as effective one.