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A loop test to measure the strength of monofilaments used for advanced composites

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Abstract—This paper presents a methodology to measure the strength of monofilaments which are commonly used for fiber-reinforced composite materials. A so-called loop test is adopted for the present test. Because the loop test has some disadvantages in the measurement of the strength of monofilaments, we combined it with the elastica, by which combination the bending strength of monofilaments can be obtained. This method was successfully applied to a carbon fiber. During these tests it has been made clear that this method can be used to evaluate the strength of monofilaments. Some statistical discussion was also conducted.

Keywords: Strength of monofilaments; loop test; the elastica; carbon fiber.

1. INTRODUCTION

Composite materials are nowadays used in various engineering fields because of their high stiffness- and/or strength-to-density ratios. Since most of the load in composite materials is carried by the fibers, it becomes necessary to measure the strength of these fibers (monofilaments). Although a tensile test is usually adopted to measure the strength of monofilaments, the monofilament often breaks at the root of the chuck, which may lead to more or less inaccurate measurement of the strength.

A so-called loop test is sometimes used to measure the strength or some other properties [1–4]. Sinclair [1] first proposed the loop test and he succeeded in measuring both the strength and Young's modulus of glass fibers of diameter 10–20 μm. His theory is based on the large deformation with linear elastic material properties. Wiliams *et al.* [2] adopted Sinclair's method to measure the strength of carbon fibers. The work of Fidan *et al.* [3] also belongs to this category, although their primary concern is to observe kink band formation or failure mode, rather than

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the strength. Further, Kitano *et al.* [4] dealt with the strength of monofilaments by means of the loop test where the strength is defined in a special way.

In the previous paper [5], we also examined the applicability of the loop test to evaluate the strength of optical fiber and carbon monofilament. As was described there and will be discussed later, the loop test itself is not necessarily convenient to measure the strength of monofilaments. Therefore, we combined the loop test with the elastica theory [6] to overcome the difficulties encountered. By combining them, the measurement of the bending strength became technically possible. In the previous paper, however, the result was not really satisfactory, probably due to an inferior testing device; also, some error might have occurred during the test.

Then we again designed a refined device to reduce undesirable error and, using this new device, the loop tests of carbon monofilaments were conducted. Some refinements of the theory were also carried out.

2. PRINCIPLE OF PRESENT METHOD

A brief summary of our idea for measuring the strength is first given, although it has already been reported elsewhere [4]. Figure 1 schematically shows the procedure of the loop test. By pulling both ends of the monofilament, the radius of curvature of the loop, ρ, decreases and eventually the filament breaks due to bending. Under the assumption of linear elasticity, the skin strain, ε, and the skin stress, σ, at point A of Fig. 1 are calculated as

$$\varepsilon = \frac{D}{2}\rho, \tag{1}$$

$$\sigma = E\varepsilon, \tag{2}$$

where D and E are the diameter and Young's modulus of the monofilament, respectively. Therefore, if we measure the radius of curvature at failure as well as D and E, we can calculate the bending strength.

The loop test is usually carried out on a microscope and photographs are taken at intervals to measure the radius of curvature, ρ. However, it is rather difficult to take a photograph at or just before the failure, because the failure of the monofilament usually takes place suddenly without any signal. This is a major disadvantage of the loop test.

To compensate for the above shortcoming, we tried to combine the loop test with the elastica theory [6]. Figure 2 shows the elastica deformation where one end is clamped and the other loading end is free. If the angle α at the free end exceeds $\pi/2$ and close to π, it is the case of our present concern, although Fig. 2 shows only one-half of our experimental set-up.

The fundamental equation of bending is [6], referring to Fig. 2,

$$EI\frac{d\theta}{ds} = -Py, \tag{3}$$

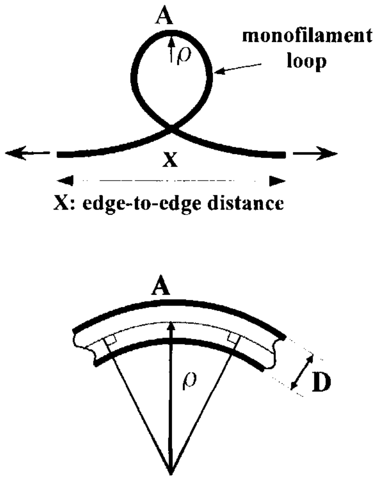


Figure 1. Scheme of loop test.

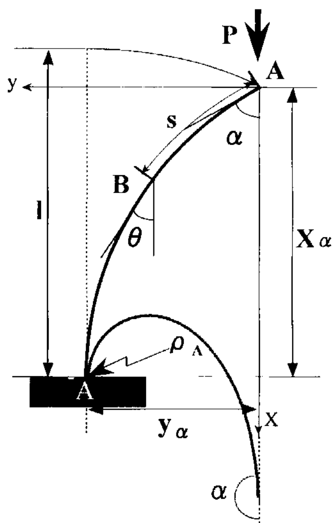


Figure 2. The elastica.

where I is the moment of inertia of the cross section, P is the applied load, and θ, s, and y are defined in Fig. 2. After some calculation, this equation ends up with

$$X_\alpha = \frac{2E(p)}{k - l}, \tag{4}$$

and

$$\rho_{\mathrm{A}} = \frac{1}{2kp}, \tag{5}$$

where

$$k = \sqrt{P/EI}, \quad p = \sin\frac{\alpha}{2}, \tag{6}$$

and

$$E(p) = \int_0^{\pi/2} \sqrt{1 - p^2 \sin^2\phi}\, \mathrm{d}\phi. \tag{7}$$

$E(p)$ is known as the complete elliptic integral of the second kind. The length of the bar, l, can be expressed as

$$l = \frac{K(p)}{k}, \tag{8}$$

where $K(p)$ is the complete elliptic integral of the first kind, defined as follows:

$$K(p) = \int_0^{\pi/2} \frac{\mathrm{d}\phi}{\sqrt{1 - p^2 \sin^2\phi}}. \tag{9}$$

From equations (4), (5), and (8),

$$\frac{\rho_A}{l} = \frac{1}{2pK(p)}, \tag{10}$$

and

$$\frac{X_\alpha}{l} = \frac{2E(p)}{K(p)} - 1 \tag{11}$$

are obtained. These equations include only p, or in other words, only the angle α. Thus, if we measure the edge-to-edge distance, X, of Fig. 1, the radius of curvature, ρ, can be calculated with the aid of the parameter α. Details of the derivation of the above equations, except for equation (5), are described in [6].

In the actual loop test, the angle α is very close to π and, therefore, the approximation of $p \fallingdotseq 1$ and $E(p) \fallingdotseq 1$ holds with sufficient accuracy. Substituting these approximations into equations (10) and (11), we finally get

$$\rho_A = \frac{(X_\alpha + l)}{4}. \tag{12}$$

This is much simpler than equations (10) and (11). Note that X_α in equation (12) is negative referring to Fig. 2 and the edge-to-edge distance of Fig. 1 is

$$X = -2X_\alpha. \tag{13}$$

Since Fig. 2 shows one-half of our experiment, the value of $2(X_\alpha + l)$ is the reduction of the edge-to-edge distance from the original length, $2l$. Therefore, equation (12) coincides with equation (1) of Sinclair [1], that is,

$$L = 8R_\mathrm{m}, \tag{14}$$

where L is the horizontal distance in Sinclair's terminology and R_m is the minimum radius of curvature.

Sinclair [1] measured both L and the applied load, T, to calculate the strength as well as Young's modulus. However, according to our preliminary study, the applied load was too small to measure in a precise manner. Therefore, as an alternative, we used equations (1) and (2) instead of measuring the load.

3. EXPERIMENTAL

Torayca T300 carbon filaments were tested here where D and E were measured by our separate experiments [7]. They are: $E = 230$ GPa and $D = 7$ μm.

Figure 3 is a hand-made testing machine which should be mounted on an optical microscope. By rotating the drive lever manually, one crosshead slowly moves to the right and simultaneously, the other crosshead, to the left by the same amount. In the previous device [5], there was only one crosshead and it moved in only one direction. Using the previous device of one-way movement might have led to some distortion of the shape of the loop, which therefore might have caused quite large scattering of data in the previous paper [5]. The new device solved this problem and, as a result, the shape of the loop became symmetric. The crosshead movement was measured with a scaled microscope.

It is necessary to make a loop, the shape of which is close to the deformation predicted by the elastica theory. In addition, it must be associated with a practicable experimental method. In the previous paper [5], we tried three ways of making a loop, shown in Fig. 4, which were tested for an optical fiber the diameter of which was 125 μm, very much thicker than carbon fibers, 7 μm. The method (a) was unsatisfactory because the shape of the loop was far from that predicted by the elastica. The methods (b) and (c) were acceptable for the optical fiber, but there was

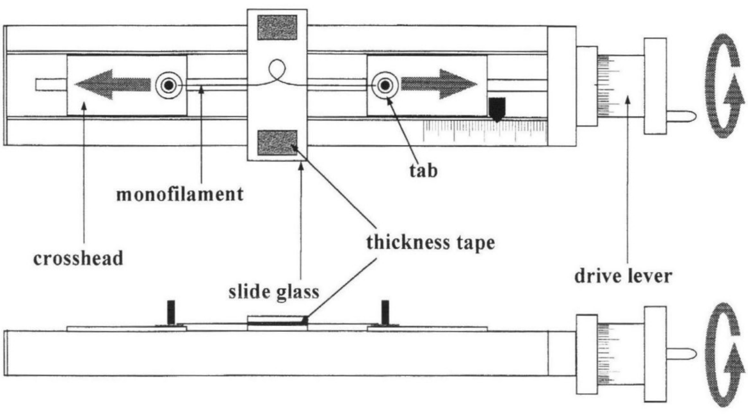


Figure 3. Loop test device.

no ring small enough that was suitable for carbon filaments. Finally we chose the method of Fig. 4c, that is, a looped monofilament which was sandwiched with a pair of slide glass.

If a slide glass is directly placed on a looped carbon fiber, the deformation of the fiber will be affected by the friction between the carbon fiber and the glass plate. We need at least 14 μm of spacing between two glass plates to make sure smooth movement at the crossing point of the monofilament. On the other hand, if the spacing is too large, the deformation will become three dimensional; this may become a source of error. After some trials, we finally inserted a pair of 20 μm thickness tapes to maintain the necessary space, as shown in Fig. 5a. Fidan *et al.* [3] used some kind of oil between the cover slide and the microscope slide to maintain the looped shape. Although we also tried the same method, we could not get reliable results, which is why we used the thickness tape.

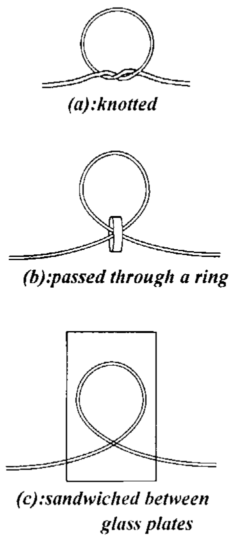


Figure 4. Three ways of keeping a loop shape [5].

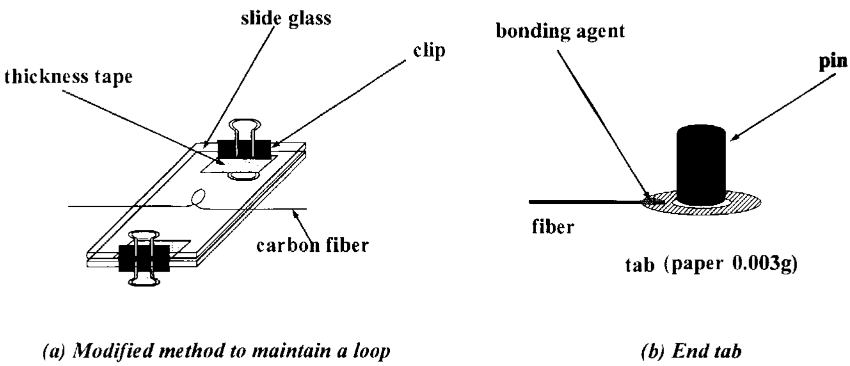


Figure 5. Detail of mounting a fiber.

Both ends of a fiber should be rotation free. After some trials, the fiber ends were finally glued on a pair of circular paper sheets (tabs) of mass of about 3 mg (see Fig. 5b). Each tab had a hole and it was mounted on the testing machine through a pin, as shown in Fig. 3.

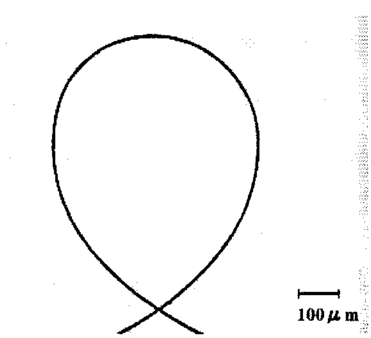
Photographs were taken at intervals during the test to compare the radius of curvature with that calculated by the elastica.

4. RESULTS AND DISCUSSION

Figure 6 is an example of the shape of a carbon monofilament during the test. Our optical microscope is connected to a personal computer and these types of pictures were saved in the computer to calculate later the radius of curvature.

Figure 7 demonstrates an example of the comparison between experiment and theory of one monofilament. The ordinate is the skin stress calculated from equation (2) where ρ is either (a) measured from photograph (experiment) or (b) calculated from equation (12) (elastica theory). The abscissa was arranged in terms of $X/l-2$ where X is the edge-to-edge distance of Fig. 1 and l is half of the original length. In the present case, pictures were taken three times during the test (dots in Fig. 7). Good agreement between experiment and elastica theory was realized. One point to be noted is that the experimental value from the figure is missing at the final point A of Fig. 7 where the fiber break took place. What we want to know is the bending stress at point A (bending strength) whereas we cannot 'measure' it by means of a photograph because the fracture occurs suddenly. The elastica theory successfully compensates for it.

Figure 8 summarizes all experimental results from a total of 28 specimens although we cannot identify all of them because many data are overlapping. Considering that the mechanical properties of each monofilament show some amount of scatter, the result of Fig. 8 seems acceptable, although this discussion is rather qualitative.



Shape of carbon monofilament during the test

Figure 6. Photograph of a looped shape.

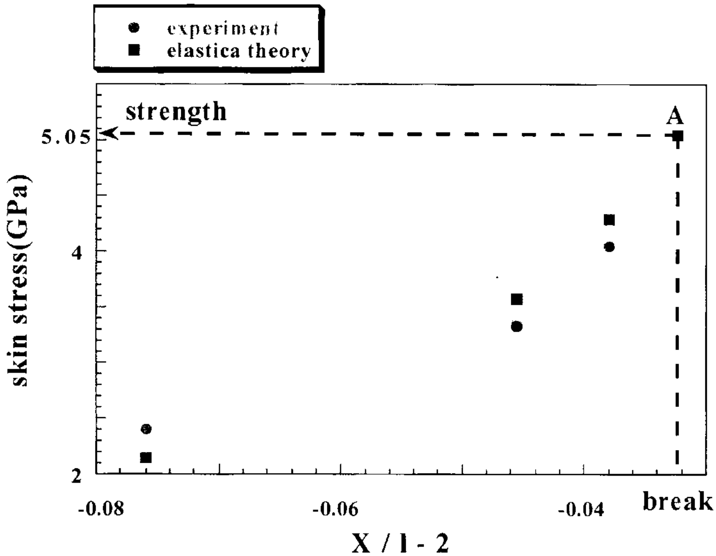


Figure 7. Comparison of skin stress between experiment and theory (example).

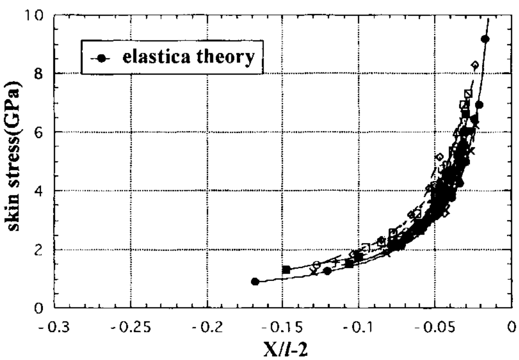


Figure 8. Comparison of skin stress between experiment and theory (all data).

The strengths thus obtained were next plotted on a Weibull probability sheet (Fig. 9). The strength is likely to obey Weibull distribution with α (scale parameter) $= 5.88$ GPa and m (shape parameter) $= 6.18$. The average strength, μ, is correlated with α and m as follows:

$$\mu = \alpha\Gamma(1 + 1/m), \tag{15}$$

where Γ is the gamma function. In the range of $1 < x < 2$, the value of $\Gamma(x)$ is a little smaller than unity, $0.88 < \Gamma(x) < 1$. Then we can briefly understand that α represents the strength.

Let us now discuss quantitatively the above values. The catalog value of the strength of T300 carbon fiber is around 3.5 GPa and our data is significantly higher

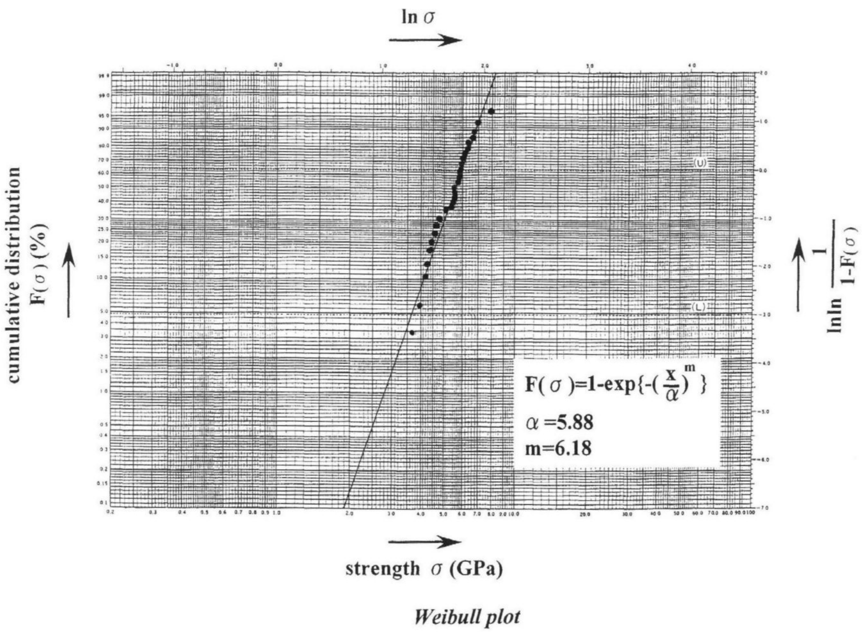


Figure 9. Weibull plot of the strength.

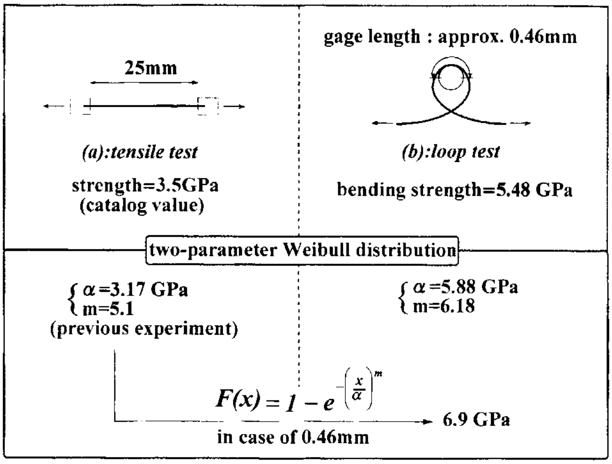


Figure 10. Comparison between tensile test and loop test.

than that. As was also discussed in [1] and [2], this may be due to the difference of the gage length; shorter fiber is stronger.

Figure 10 shows, in advance, the story of the following discussion to grasp the idea of the data reduction. According to the previous study of the tensile test [7], the Weibull parameters at gage length of 25 mm were $\alpha = 3.17$ GPa and $m = 5.1$.

In the loop test, unfortunately, we cannot exactly define the gage length. If we assume the circumferential length of a semi-circle with the radius ρ_A at failure to be the gage length, it is 0.46 mm in average. Using two-parameter Weibull distribution and the tensile test data for 25 mm, we get $\alpha = 6.9$ GPa for 0.46 mm length. The reason of the difference between the loop-test data ($\alpha = 5.88$ GPa) and the extrapolated value from tensile test ($\alpha = 6.9$ GPa) is not clear at present. The shape parameter of the present loop test ($m = 6.18$) is larger than that of tensile test ($m = 5.1$). This may suggest indirectly the superiority of the present method because large m corresponds to small scatter.

The present method is still being developed: there are several points to be overcome. First, the present method is based on the assumption of linear elasticity. It is well known that the stress–strain relation of carbon fibers exhibits nonlinearity; Young's modulus increases as the tensile strain increases. If the degree of nonlinearity is small, the present method may be used with sufficient accuracy. If the fiber has high material nonlinearity, the present theory itself should be modified. To this end, a numerical analysis such as a finite element analysis would be necessary. Ultimately, if this nonlinear analysis is completed, further discussion will become possible. That is, if the fiber exhibits nonlinear stress–strain relation, the shape of the loop will deviate from the ideal shape predicted by the elastica. Therefore, by precisely measuring the shape of the loop, it should be possible to make clear the degree of nonlinearity.

The second point to be discussed further is that the elastic modulus should be measured separately by some other methods. This is inevitable if we do not measure the applied load during the test.

Third, the gage length in the loop test is ambiguous. This may be the most serious problem for the loop test. The failure does not necessarily take place at the maximum stress. If there is a weak point in the loop, the fiber may break there even if the maximum stress is not generated at that point; the failure point should be discussed in a statistical manner. Concerning this, we have a prospect to make clear the gage length in the loop test by conducting computer simulation such as a Monte Carlo simulation, although this subject is left for future discussion.

5. CONCLUSIONS

In the present paper we have tried to develop a methodology to measure the strength of monofilaments by combining a so-called loop test and the elastica theory. The result showed that the present method can become an alternative of the tensile test, although there still remain some points to be overcome.

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