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Fatigue of high strength fiber caused by repeated axial compression

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Abstract—We report a method for measuring the axial compression characteristic of high strength fibers. This is a technique for loading compression force on a fiber by winding it on a plastic rod at an angle of 45 degrees. The fiber was fixed to the rod with an adhesive. The aramid fiber, the carbon fiber, and the E-glass fiber were examined in this research. The relation between the compression fatigue and strength of the fiber became clear by this technique.

Keywords: Carbon fiber; Kevlar; single fiber; compression; fatigue; twist; superposition.

1. INTRODUCTION

Previously, we measured the axial compression characteristics of high strength, high modulus fibers. Two techniques were developed. Firstly, we measured the properties of a high packing density micro composite [1] (1990–1995), and secondly we axially compressed single fibers [2, 3] (1995–1996). In this paper we report a method of measuring the axial compression characteristics of fibers using torsion. The advantage of this technique is that it is very easy to measure the axial compression fatigue of a fiber. The measurement of the elastic modulus and the yield strength is possible in both the micro composite and the single fiber compression method tests. However, the fatigue measurement was difficult, because of crushing at the composite edge in the composite method, or the falling of the single fiber in the single fiber method. In contrast, using the method described in this paper, it is easy to observe the change in elastic modulus during compression fatigue of a fiber. We report the measured result on high strength fibers.

2. EXPERIMENT

2.1. The principle of the measurement

The deformation γ (shear strain) by torsion in the stress skin (twist angle θ) is given in equation (1).

$$\gamma = \frac{\theta R}{L}, \tag{1}$$

where L is the cylinder length, and R is the cylinder radius.

In particular, the strain in the 45° direction is given by equations (2) and (3),

$$\varepsilon_1 = \frac{1}{2}\gamma \quad \text{(Tensile)}, \tag{2}$$

$$\varepsilon_2 = -\frac{1}{2}\gamma \quad \text{(Compressive)}. \tag{3}$$

When equation (3) is substituted into equation (1), and using diameter D instead of radius R, equation (4) is obtained

$$\varepsilon_2 = -\frac{\theta D}{4L}. \tag{4}$$

The torsion torque T of the cylinder is given by

$$T = GI_P \cdot \frac{\theta}{L}, \tag{5}$$

where G is the shear modulus and I_P is a shape factor. I_P is equal to $(\pi D^4)/32$ for a cylinder, so we have

$$T = G\frac{\pi}{32}D^4 \cdot \frac{\theta}{L}. \tag{6}$$

Consider the case in which a fiber is wound around this cylinder at a 45° angle (Fig. 3a). The compressive strain ε_2 which is added to the fiber is given by equation (3). The compression energy u_c added to the fiber corresponds to the area

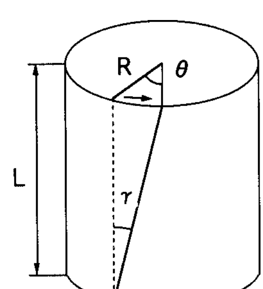

Figure 1. Relation between twist angle and shear strain of the round bar.

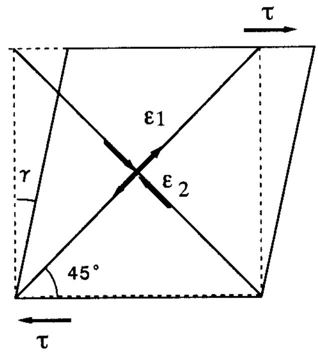

Figure 2. Shear strain on surface of round bar.

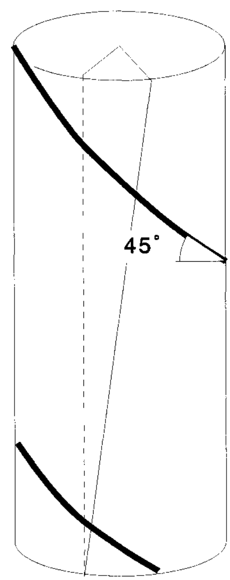

Figure 3a. Wrapping of fiber around surface of round bar.

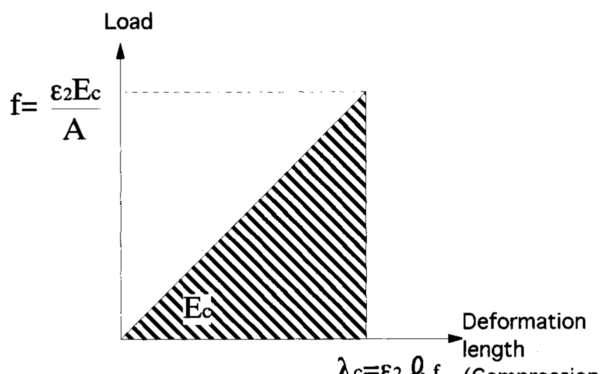

Figure 3b. Relation between compressive strain and stress loaded to fiber.

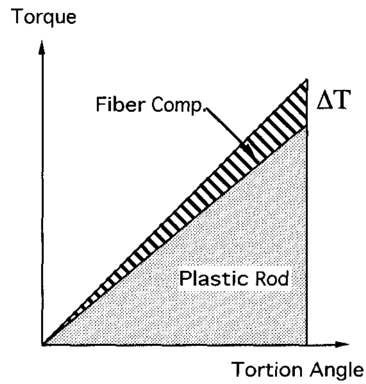

Figure 4. Relation between twist angle and torque of the round bar which wound the fiber.

under the load–elongation curve of the fiber (equation (7) and Fig. 3b).

$$u_c = \frac{1}{2} \cdot \lambda \cdot f. \tag{7}$$

Let ℓ_f and A denote the length and cross-sectional area of the fiber. When equations (8) are substituted into equation (7), we obtain equation (9)

$$f = \sigma \cdot A, \quad \sigma = \varepsilon_c \cdot E_c, \quad \ell_f = \sqrt{2}L, \quad \lambda = \varepsilon_c \cdot \ell_f, \tag{8}$$

$$u_c = \frac{1}{2} \cdot \frac{\gamma}{2}\sqrt{2}L \cdot \frac{\gamma}{2}E_c A = \frac{\sqrt{2}}{8}\gamma^2 AL. \tag{9}$$

Figure 4 shows the twist energy of the cylindrical composite consisting of the rod and the fibers wrapped around it. The gray area is the twist energy of only the round rod. The area filled with diagonal lines represents the increase due to the presence of the helically wrapped fibers. The fibers are assumed to be wrapped in a single layer. The increase in the energy due to the increase of the torque (ΔT) of the cylindrical composite resulting from the winding of the fiber is denoted by u_t. The increase in compression energy of the fiber is u_c. The energy increase from the increase in the torque u_t can be considered to be equal to u_c (equation (11)). Hence we can derive equation (12), which gives us the axial compression modulus of the single fiber, E_c.

$$u_t = \frac{1}{2}\Delta T \cdot \theta, \tag{10}$$

$$u_c = u_t, \tag{11}$$

$$E_c = \frac{4L}{\sqrt{2}R^2\theta A} \cdot \Delta T. \tag{12}$$

2.2. Sample

The cylindrical rod used as the base unit was made from acrylic or polycarbonate resin. The rod had a diameter of 3 mm. A bundle of fibers (aramid fiber ‘Kevlar’, carbon fiber ‘T-300’ and E-glass fiber) was spirally wound onto the cylindrical rod at

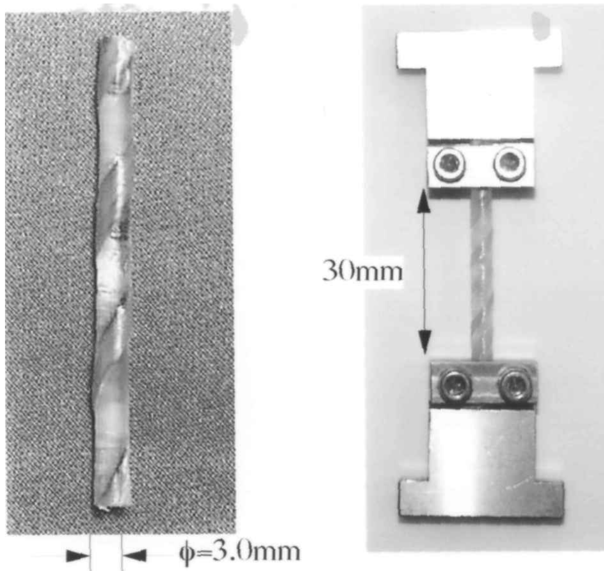

Figure 5. The cylindrical rod sample.

an angle of 45°, and then fixed to the rod by a cyanoacrylate adhesive. The adhesion between the fiber bundle and the rod was good; there was no peeling at this interface. After bonding to the rod, the sample was aged for 24 hours at room temperature. The gauge length of the torsion tester was 30 mm. A test sample is shown in Fig. 5. This technique is to twist the cylindrical rod which wound the fiber, and it applies the compressive force to the fiber. It is necessary that rod and fiber have perfectly contact with each other through adhesion. Compression modulus of the fiber is calculated from the torque difference (ΔT) of *rod* and *rod* + *fiber*, as shown in equation (12). Though this technique is also one of the composite methods, it is called the torsion method. The torque was equal to the rod, even if the resin were applied to cylindrical rod and this rod did not generate strength degradation by the fatigue in the strain range of the experiment.

2.3. Measurement

Figure 6 shows the high load and high performance torsion tester that was used (Kato Tech Ltd.). The maximum twist angle was ±80°. The sample was fixed in a chuck, and then attached to the tester. The relationship between torque and twist angle was recorded on a X–Y recorder or on a personal computer.

3. RESULT AND DISCUSSION

The suitability of the linear elastic range in torsion of the plastic cylinder was confirmed by a preliminary experiment. The twist measurement of the cylinder was

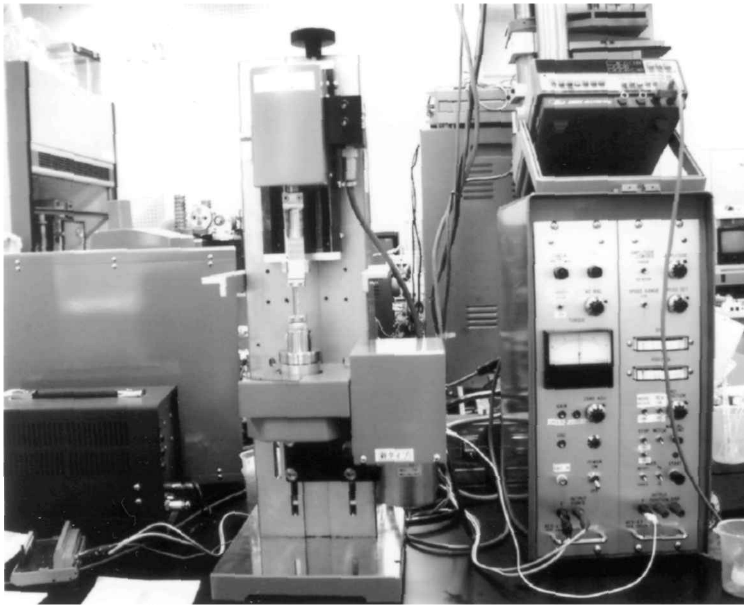

Figure 6. The high perfomance torsion tester (Kato Tech Ltd.)

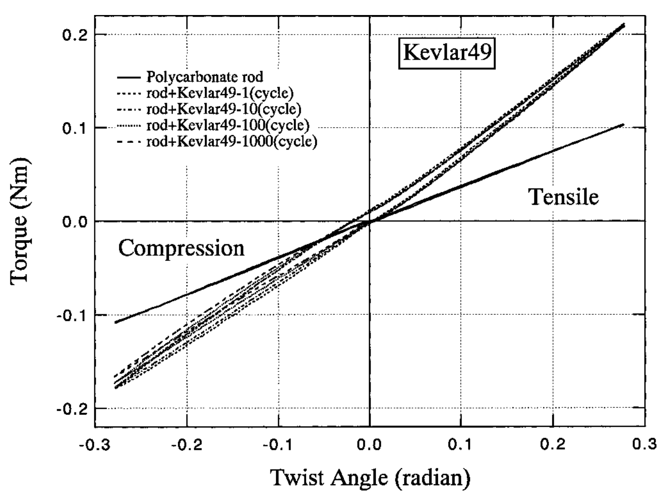

Figure 7. Relationship between torque and twist angle of rod for Kevlar49.

carried out in the linear range. The plastic cylinder did not show a decrease after repeated twisting. Figure 7 (Kevlar29) and Fig. 8 (T-300) show the relationship between the twist angle and the torque of both the cylinder and the fiber–cylinder composite. In this case, the round bar was twisted in both the right and left directions. A compressive force is applied to the fiber when the round bar, to which the fiber is bonded, is twisted to the right. Tensile force is applied when twisted to

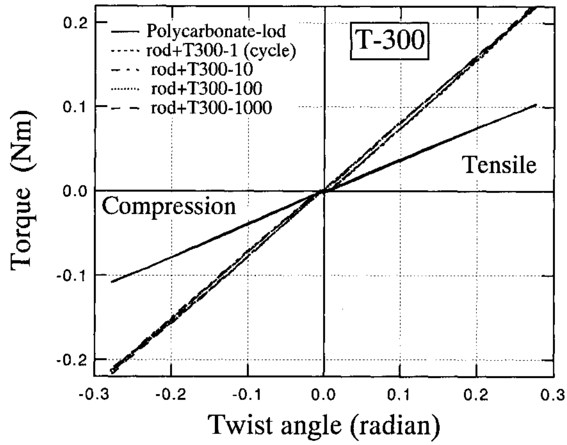

Figure 8. Relationship between torque and twist angle of rod for T-300.

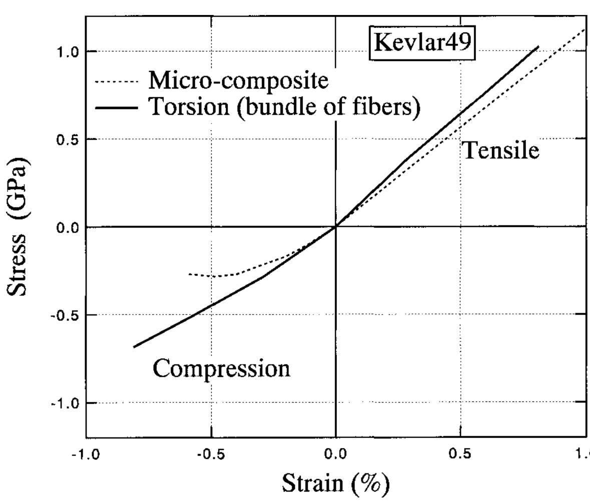

Figure 9. Longitudinal properties of aramid fiber (Kevlar49) covering the whole compression and extension region.

the left. Compression force and tensile force are alternately applied to the fiber as the round bar is repeatedly twisted to the right and to the left.

The glass fiber was used to verify that the experiment matched the theory. The compression modulus of glass fiber measured by the torsion compression was 81 GPa, which almost corresponds to 84.5 GPa which is the value of its tensile modulus. Because the relation between compressive strain and compression modulus is obtained from equations (1), (3), and (12), the compressive stress is given by the multiplication of the strain and modulus. The result is shown in Figs 9 and 10. It is understood that compression moduli of the aramid and carbon fibers are smaller their tensile moduli. However, the lowering of the elastic modulus by composite collapse as observed in the Kevlar micro composite was not generated.

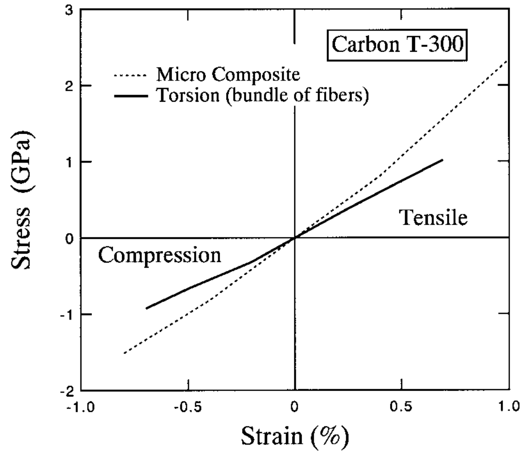

Figure 10. Longitudinal property of carbon fiber (T-300).

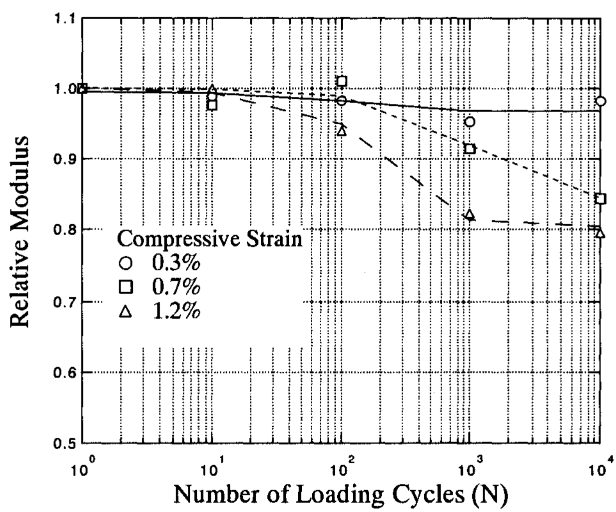

Figure 11. Strain dependence of the compressive modulus for Kevlar49.

Therefore, the fiber axial direction compression modulus measurement was easy using this technique.

Figure 11 shows the relationship between the frequency of the compression fatigue and the change in modulus of elasticity of the Kevlar fiber. It was observed that, for the cylinder wrapped by Kevlar, the modulus decreased due to compression torsional fatigue. The compression yield strain of the Kevlar fiber is 0.5% according to our composite method. Modulus does not decrease when compressive strain is 0.3%. When the compression fatigue strain exceeded 0.5%, we observed that the modulus began to decrease. It is thought that modulus decreases as the twist cycle increases when the compression fatigue strain exceeds 0.5%. However, a decrease in modulus of the fiber was not observed after tensile torsional fatigue. Figure 12

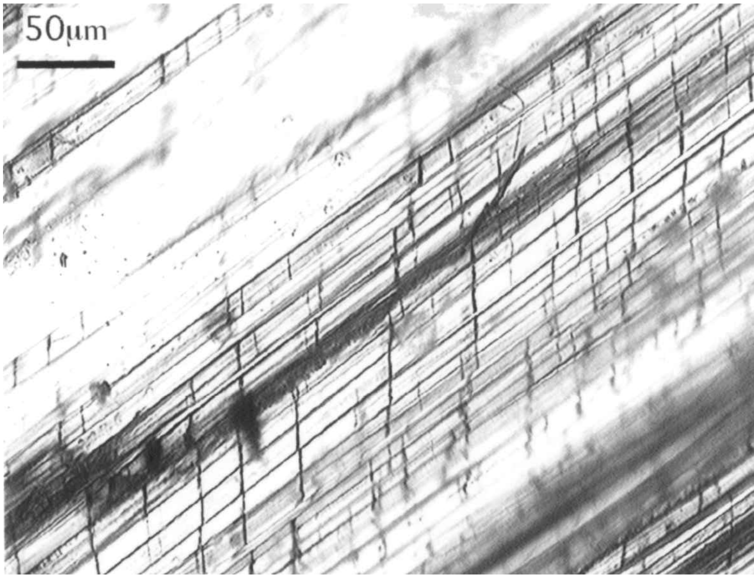

Figure 12. Photograph of after 1000 cycles compression fatigue of Kevlar49.

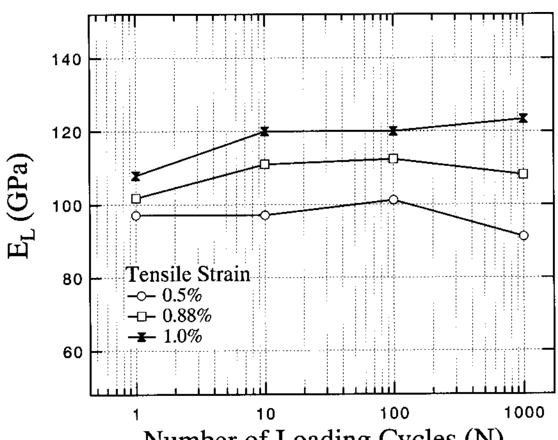

Figure 13. Kevlar49 tensile fatigue.

is a photograph of the Kevlar fibers taken after 1000 compression fatigue cycles. Many kink bands can be seen on the surface of the Kevlar fibers.

Figure 13 shows the change in the modulus when repetitive fiber tensile strains of 0.5%, 0.88%, and 1.0% were used. The tensile modulus of Kevlar single fiber increases a little as a result of tensile fatigue.

It is important to predict the lowering of the elastic modulus by long-term fatigue. Previously, a superposition rule was established between fatigue frequency and strain in the single fiber torsional fatigue test [4], that is, the fatigue was found to be a function of the product of frequency and strain. However, in this experiment,

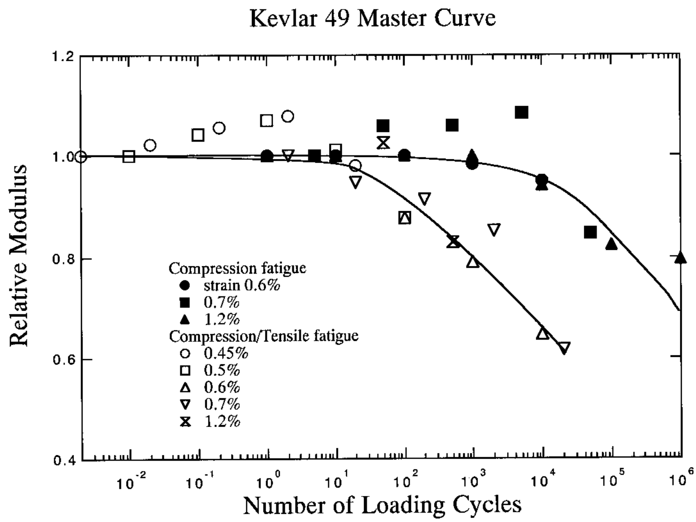

Figure 14. Superposition curves of the compression fatigue. Solid line/filled mark shows the compression torsion. Dotted line/open mark shows the compression/tensile torsion.

when both the compression force and tensile force fatigues were loaded to the fiber, it was obtained that the decrease in modulus quickened compared with only the compression force (Fig. 14). Modulus decreases even twice as fast as the fatigue only of compression. This reason is being examined now. Perhaps, it may be that the amount of the total strain loaded to the fiber is related to the fatigue.

4. CONCLUSIONS

(1) This compression test in which the compression force was loaded to the fiber by wrapping the fiber around the round bar at the angle of 45 degrees is easier than the micro composite method.

(2) This examination method can load large compressive strain, and this technique is excellent for compression fatigue examination of the fiber.

(3) The equivalent conversion rule is established on the Kevlar fiber between repeated time and compression strain.

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