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Some Considerations on the Basic Mechanical Properties of Carbon Fiber Mono-Filament

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Abstract

Some basic problems in measuring the strength characteristics of carbon fiber(CF) mono-filaments were studied. Tensile test was performed on PAN (polyacrylonitrile) type CF mono-filament test pieces with various test lengths. Determination of modulus of elasticity, relationship between fiber strength and cross-sectional area, and the test length dependence of strength were discussed. The results are as follows;

(1) The modulus of elasticity E, differs by 25% at the maximum depending on the load level where the modulus is determined. Excluding this effect, the higher strength fibers still tend to have a higher E value.

(2) In evaluating the tensile strength of fibers, it is desirable to use mean cross sectional areas than individual area of each fibers, because there is no clear relationship between the fiber strength and the fiber diameter.

(3) The mean strength, coefficient of variation and the Weibull modulus are all test length dependent. To estimate the critical strength, it is preferable to use two average strengths from different test lengths than using one average strength and the Weibull modulus for one test length. The estimated value, however, is higher than the actual critical strength in all methods.

1. Introduction

Carbon fiber (CF) is finding wide application as reinforcing fibers in composite materials as FRP and FRM because of its high specific strength and modulus of elasticity. In analysing and evaluating the strength of such composite materials, the most basic factors are the mechanical properties and the statistical feature of mono-filaments of CF.

There are many studies$^{1\sim4)}$ on the mechanical properties of CF and procedures of mechanical testing are established and standardized in JIS R7601 etc$^{5\sim7)}$. However, the difficulties in obtaining accurate strength parameters of mono-filament are often noted. Mechanical tests of CF requires special attention because the microstructure and the characteristics of CF are quite different from metals and other general materials. A microscopic fiber diameter and its scattering, highly brittle nature$^{8)}$, wide range of scattering in strength, and its test length dependence$^{4)}$ are the characteristic features of CF.

In this study, tensile tests were performed on the PAN type fiber mono-filaments according to JIS standards, and some basic problems in determining tensile strength and

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modulus of elasticity, and their dependence on test length are discussed.

2. Experiment

2.1 Test sample and specimens

The carbon fiber in this experiment is a high strength type polyacrylonitrile (PAN) fiber with a nominal diameter of 7 μm. The sample was supplied in 12000 fiber bundles, and mono-filament specimens from 0.5 mm to 50 mm length[4,5] were randomly removed for testing. Mechanical tests were performed according to JIS R7601. For 5-50 mm test lengths, fibers were attatched with an epoxy adhesive to a paper card with a window[2,5] (window card) as shown in Fig. 1. For tests of 0.5 mm specimens, a special steel jig shown in Fig. 2 was used to which the test fiber was attached directly by adhesive over a 0.5 mm slit.

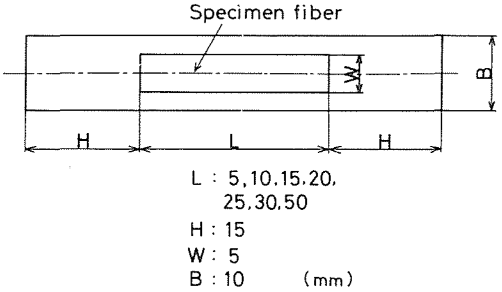

Fig. 1 Test specimen (Window card)

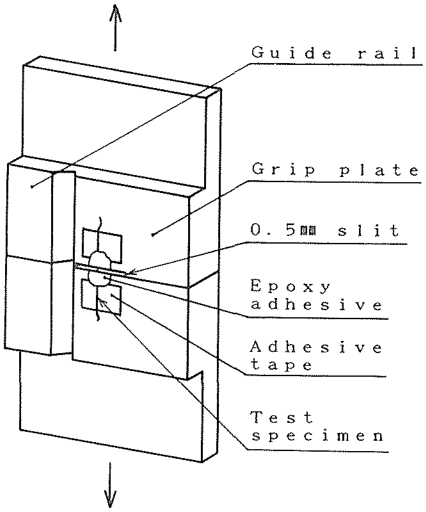

Fig. 2 Tensile jig for 0.5 mm specimens

2.2 Test devices

The test used a load cell type micro tensile test machine with a 2 kgf load cell, calibrated by 1-25 g micro weights. Elongation was measured by DTF extensometer. The load elongation curve was recorded on X-Y recorder with 40 g full load and 60-1500x magnification of the elongation. Cross head speed was between 0.5-2 mm per a minute according to the test length, so that the time from start to break was about 5-10 sec.

2.3 Measurement of fiber diameter

The fiber diameter was measured with a 700x magnification micro-photo taken together with a 10 μm microscale. The width of the fiber was determined by the microscale. Roundness of the fiber used in the experiment proved to be very high, and the measured width was considered as the diameter of the fiber. For 136 fibers, the average fiber diameter was 7.2 μm with a standard deviation of 0.65 μm, giving a 9% coefficient of variation.

3. Test results

3.1 Stress strain relations and modulus of elasticity

The characteristic load elongation curve is shown in Fig. 3. The load elongation relation appears as linear, but is actually slightly concave, and the tangent increases with the increase in load. In JIS, the modulus of elasticity, E, is determined by the following equation[5]

$$E = (\Delta P/\Delta L \times L/S)/(1-\Delta P/\Delta L \times K) \quad (1)$$

where L is the test length, ΔL is the elongation for the load range ΔP, S is cross sectional area of the fiber and K is the compliance factor that compensates for the deformation of the test system, including grips. The value of E is calculated at an arbitrary load between 20-60% of the fracture load with a load range of, ΔP, 20-30% of the fracture load. The K value is determined by plotting ΔL/ΔP for different L/S ratios, as an extrapolation to L/S=0. Fig. 4(1) is the ΔL/ΔP-L/S relation, here S was calculated from each fiber diameter, and the regression line gives the K value of 2.27 mm/kgf.

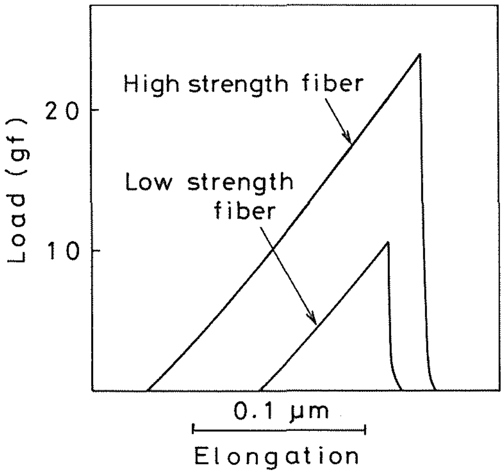

Fig. 3 Examples of load-elongation curve

In the JIS standard[5], it is permitted to used a constant average S value instead of an individual cross sectional area. Fig. 4(2) is a ΔL/ΔP=L/S diagram with constant S, but here, the regression line gives a negative K value, which is impossible.

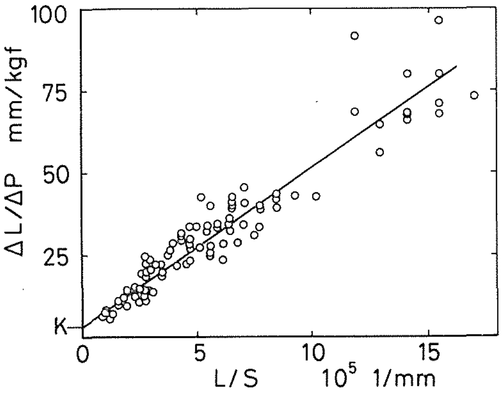

Fig. 4(1) Determination of K by individual S

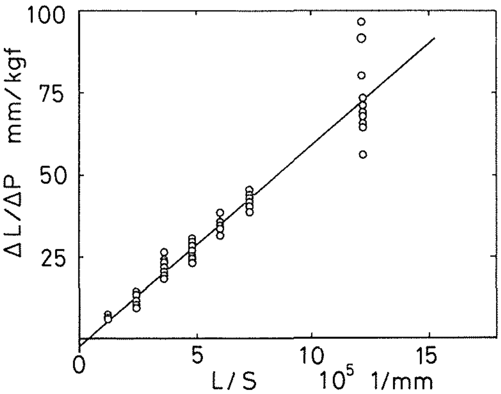

Fig. 4(2) Determination of K by average S

The value of E calculated for various test lengths is shown in Table 1. The specimens were classified into three strength grades, low, middle, and high. Each value in the table are the average of ten specimens. Table 1 indicates that fibers with higher strength have higher E values, in all test lengths. However, this requires some consideration of the load level where E is determined, because the load elongation curve is concave, and higher loads may give higher E values.

To determine this, E values were calculated at three different load levels, about 20%(W1, the low), 40%(W2, the middle) and 60%(W3, the high) of the fracture strength in 5 mm specimens. In 25 mm specimens, E values were calculated at loads that correspond to low(W1′) and middle (W2′) loads in 5 mm specimens as shown in Fig. 5.

Table 1 Elastic modulus in specimens with different strength

Test length(mm)	Strength grade	Mean Strength σm (Gpa)	Modulus of elasticity (Gpa)
5	low	2.97	271
	Middle	4.33	290
	High	5.65	350
25	Low	2.23	254
	Middle	3.39	253
	High	4.62	306
50	Low	1.89	216
	Middle	3.11	229
	High	4.25	248

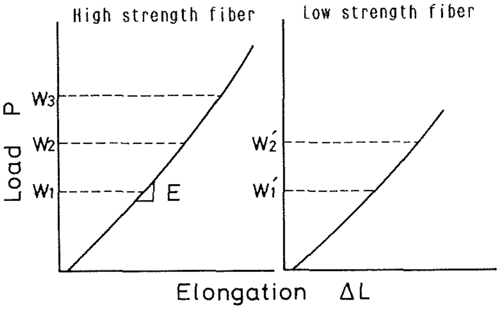

Fig. 5 Load levels to determine E

The E values are shown in Fig. 6, where the connected symbols represent the E values at different load levels expressed in terms of stress in the same specimen. It shows that E values increase with higher loads, in both test lengths. In 5 mm specimens, the E value at W2, and W3 are 1.5~16% (average 9%) and 9~31% (average 18%) higher than the value at W1. In 25 mm specimens, the E value at W2′ is 1.5~22% (average 9%) higher than at W1′ and the rate of increase is almost the same as in the 5 mm specimens.

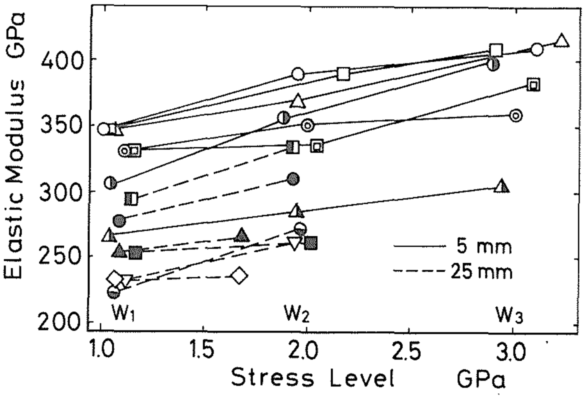

Fig. 6 Elastic modulus at different stress (load) levels

Table 2 Elastic modulus at different stress leves

Fiber type	σm (Gpa)	E (Gpa)
low strength	2.57	272
	2.64	248
	2.67	272
High strength	4.69	282
	4.79	310
	4.94	296

This shows that the high E value in high strength fibers is mainly due to a difference in stress level where E is determined.

Table 2 shows E values determined at the same stress in specimens with the same length, 25 mm, and different strengths. There is still a slight tendency for higher E value in high strength fibers, possibly bacause of the fine and rigid microstructure[8] in high strength fibers.

3.2 Tensile strength

The tensile strength of fiber is defined as $\sigma f = P\max/S$, where P max is the maximum load and S is the cross sectional area of the fiber.

Table 3 shows a comparison of strength with two methods, the uppers are the values with S calculated from the measured diameters, and the lowers are those with constant S calculated from the average diameter. In Table 3, SD is the standard deviation, CV is the coefficient of variation, and m is the Weibull modulus.

The two methods give almost the same average strength, but the coefficient of variation is larger and the Weibull modulus is smaller when determined by individual cross sectional areas.

Table 3 Comparison of strength with average and individual cross sectional area, S

L.(㎜)	n	σm (Gpa)	SD (Gpa)	CV (%)	m
5	18	4.08 (4.04)	0.700 (0.629)	17.2 (15.6)	5.76 (6.38)
15	16	3.28 (3.66)	1.046 (1.099)	31.9 (30.1)	3.02 (3.33)
25	17	3.51 (3.57)	0.901 (0.878)	25.7 (24.6)	3.62 (3.47)
50	14	3.53 (3.02)	0.743 (0.659)	20.3 (21.8)	4.61 (4.78)

n: Number of Samples

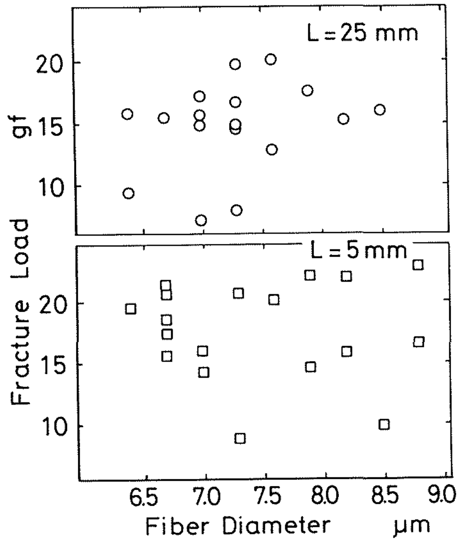

Fig. 7 Fracture load and the cross sectional area

In specimens from homogeneous solid materials, test pieces with larger diameters would have higher fracture loads. In this experiment, however, no relation was observed between the fracture load and the fiber diameter, as shown in Fig. 7. This suggests a difference in microstructure, possibly a coarse structure[8] with a low strength of large diameter fibers and a fine structure with high strength of small diameter fibers. This indicates that fracture stress calculated by individual fiber diameter is possibly not meaningful. In practical applications, the distribution of fracture loads of fibers is important, and the strength divided by individual fiber sections is not utilized. It appears advantageous to use strength values from average areas. To use individual areas only results in a large coefficient of variation and small Weibull modulus.

3.3 Test length dependence of strength

Table 4 shows the result of strength test for various fiber lengths. The number of specimen is around 110 for the 5-50 mm test length and 20 for the 0.5 mm length. The strength was calculated by the average fiber diameter, 7.2 μm. In 25 mm specimens, three results with extremely low strengths were omitted, the values including these three data are in parentheses.

Table 4 Strength at different test lengths

L.(㎜)	n	σm (Gpa)	SD (Gpa)	CV (%)	m
0.5	20	5.22	0.592	11.3	9.31
5	113	4.41	0.754	17.1	6.63
25	114 (117)	3.45 (3.38)	0.657 (0.770)	19.1 (22.7)	6.03 (3.81)
50	109	3.10	0.672	21.6	5.21

Fig. 8 is the strength distribution for each test length plotted on Weibull coordinates. The experimental data are approximated well by the two parameter Weibull distribution every test length.

In Fig. 8, the plot intersections with 50% probability line give the average strengths for each fiber length. The gradient of the plots gives the Weibull modulus, m.

Table 4 and Fig. 8 show that the value of m increases and that the average strength shifts to higher values with the decreasing test length. The average strength in 0.5 mm specimens is about 1.7 times the strength at 50 mm. The coefficient of variation, CV, decreases with the decreases of test lengths. The CV value in 0.5 mm specimens is about 60% of the value at 50 mm. In 0.5 mm specimens, m is about 1.8 times the value at 50 mm, while the increase of m is slow until lengths come down to 5 mm. This suggests that the scattering of fiber strengths decreases gently between 50 mm and 5 mm and shows an abrupt decreases between 5 mm and 0.5 mm.

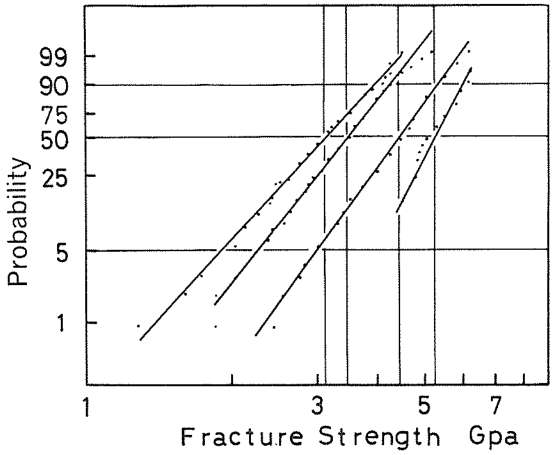

Fig. 8 Weibull plots of strength

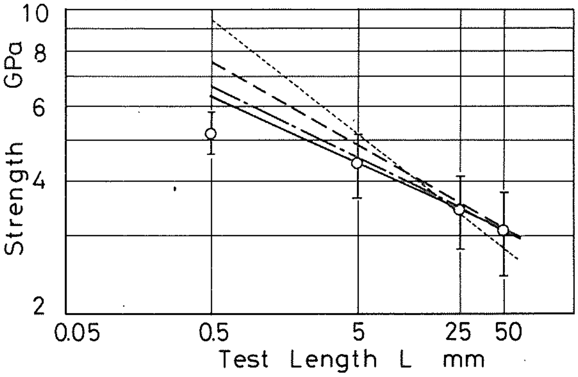

Fig. 9 Test length dependence of strength

Fig. 9 shows the relationship between the average strength and the test length. The open circles represent the average strength σ_m and the range of standard deviation is indicated. Fig. 9 clearly shows the size effect on the fiber strength. In estimating the strength of fiber reinforced composite, the strength of the fibers at a critical length σ_c, is required. The critical length, lc[9], is very short, about 30 times the fiber diameter and is usually below 0.5 mm. The critical strength σ_c is estimated from the results of lenger test lengths. In this experiment, the following three methods were applied:

(1) Extrapolating the regression line of the three average strengths from 5, 25 and 50 mm test lengths;

(2) Calculation from the average strength and Weibull modulus for the 50 mm test length, and;

(3) Method(2) with the values for the 25 mm test length.

In Fig. 9 the solid line is the result of (1), the broken line of (2), and the chain line is (3). The estimated strength at 0.5 mm is universally higher than the experiment. The value from 50 mm lengths deviates most from the experiment. The estimation by (1) and (3) give almost the same results but are still 20~25% higher than the experiment.

The dotted line in Fig. 9 is the estimate by the σ_m and m value at the 25 mm test length including the three low strength data that are omitted in method (3). The calculated σ_c at 0.5 mm is much higher than the value by (3). This supports that extremely low strength data should be omitted in estimating the critical strength from the results of σ_m and m values at one test length. It is preferable to use two or three average strength data from different test lengths.

The reason of high critical strength estimated by any of the procedures is that the Weibull modulus becomes large in short fiber length as indicated in Table 2. A large Weibull modulus in short fibers can be explained by two groups of flaws that governs the strength of fiber, large flaws with long intervals, and small flaws distributed homogeneously, as suggested by Phillips[4].

4. Conclusion

This is a report on tensile tests of carbon fibers with various test lengths from PAN performed to discuss basic problems of test method and the strength characteristics of carbon fiber mono-filament. Determination of E values, relationship between fiber strength and cross sectional area, and the test length dependence on strength were discussed. The results were as follows;

(1) Load elongation curves of carbon fibers are slightly concave and the modulus of elasticity, E, differs by 25% at the maximum depending on the load level where the modulus is determined. Mainly due to this, higher strength fibers have a higher E value.

(2) Excluding this effect, higher strength fibers still show higher E value.

(3) There was no clear correlation between the fiber strength and the fiber diameter. In evaluating the strength of carbon fibers, stress values divided by individual fiber diameters has no significant meaning. Strength using mean diameter is more useful.

(4) The coefficient of variation and Weibull modulus as well as the mean strength show the size effects. To estimate the critical strength, it is preferable to use two average strength values from different test lengths than using one average strength and the Weibull modulus at one test length. Extremely low strength data should always be omitted.

(5) The estimated value is higher than the actual critical strength in all cases.

Acknowledgement

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