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Some Aspects of Mechanical Test Methods for Advanced Composites

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ABSTRACT

This paper reviews research activities of some mechanical test methods for advanced composites which have been conducted in Fukuda laboratory, Tokyo University of Science. The subjects are (1) innovation and development of compression bending test, (2) mechanical-property evaluation of soft-core sandwich beam, and (3) loop test to measure the strength of monofilaments.

1. Introduction

Advanced composite materials are nowadays widely used in various engineering fields. Although new materials require new testing methods, most of test methods for advanced composites have been the imitation of metals or plastics.

The bending test is one of them. A three- or four-point bending is usually used to evaluate the bending strength and modulus of structural materials including advanced composites. However, as is well known, the bending strength of CFRP coupon is strongly affected by the stress concentration due to a hard loading device. The works of Whitney [1] and Cui and Wisnom [2] are some examples to have dealt with this stress concentration.

To compensate for this undesirable effect, the authors have hitherto demonstrated and proposed a compression bending test method for both flat coupons [3-6] and pipes [7-8], which is based on Euler buckling of a column. Applying "the elastica [9]," a methodology to calculate the bending modulus and strength has already been almost established. However, if the diameter of the pipe was relatively large, the Euler buckling could hardly occurred. Then we tried an eccentric compression bending [10] guided by Ref.[11]. We first review these subjects.

The second subject is to evaluate the mechanical properties of soft-core sandwich beams. Sandwich plates have long history of application to structural elements especially for aerospace use and tremendous research works have been carried out hitherto [12] and recently, a periodical journal for sandwich structures and materials was born [13]. In these researches, sandwiches of aluminum skin (face) and aluminum honeycomb core are of most interest and not a few standards [14] have been established to evaluate the mechanical properties of this kind of sandwiches. Recently CFRP skin/foamed core sandwiches have also been developed which are used in various fields including medical application mainly due to X-ray transmittability with sufficient bending rigidity. In such a case of relatively soft core, the existing test methods are not necessarily sufficient. For example, the deformation may not coincide with the classical beam theory

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due to the soft core.

In Chapter 3, we first report the bending rigidity of CFRP skin/foamed core sandwich beam [15]. The bending rigidity was strongly affected by the span and the test results did not meet with existing theoretical values. Then we proposed a method to correlate the experimental values with the theoretical values by using a kind of point collocation.

The above methodology of correlation is, however, somewhat artificial. In the calculation, the catalog value was used for the shearing modulus of the core, G_c , and this value is of most doubtful. The latter part of Chapter 3 is mainly focused on the evaluation of G_c[16].

The third topic of the present paper is a loop test to measure the strength of monofilaments. Although a tensile test is usually adopted to measure the strength of monofilaments, the monofilament often breaks at the root of chuck, which may lead more or less inaccurate measurement of the strength.

A so-called loop test is sometimes used to measure the strength or some other properties of monofilaments [17-20]. We also examined the applicability of the loop test to evaluate the strength of optical fiber and carbon monofilament [21, 22]. Chapter 4 first reviews these works in terms of Weibull distribution [23]. However, a so-called gage length is not necessarily clear in the loop test and the latter part of this Chapter is addressed to correlate the tensile test and the loop test taking into account a modified Weibull distribution.

2. Compression Bending Test

2.1 Scope and theoretical background

As was described in the Introduction, the compression bending test method was invented to remove undesirable effect of loading nose for 3- or 4-point bending. Since details of compression bending test method have already been reported elsewhere[3-6], only a brief summary is described here.

Figure 1 shows the half length of the present specimen the experimental methodology of which is based on the Euler buckling. The bending moment at the midspan A is

$$M_A = P\delta_A \tag{1}$$

where P is the applied load and δ_A is the midspan deflection. The bending stress (skin stress) at point A is, under linear elasticity condition,

$$\sigma_A = \frac{M_A t}{2I} \tag{2}$$

where I is the moment of inertia of section and t is the thickness. The bending strength is obtained by substituting the bending moment at failure in eq.(2).
The bending modulus is

$$E = \frac{M_A \rho_A}{I} \tag{3}$$

where ρ_A is the radius of curvature at point A.

According to the elastica [9] and succeeding formulation [4], the following equations are obtained:

$$\frac{\delta_A}{L} = \frac{2p}{K(p)} \tag{4}$$

$$\frac{\rho_A}{L} = \frac{1}{2pK(p)} \tag{5}$$

where $K(p)$ is the perfect elliptic integral of the first kind and $p = \sin\frac{\alpha}{2}$. Because δ_A and ρ_A are mutually related through a parameter p, ρ_A can be calculated by measuring δ_A.

There is another sophisticated way of calculating ρ_A or even δ_A. By further calculation [5] of the elastica,

$$\frac{\lambda}{L} = 4 - \frac{E(p)}{K(p)} \tag{6}$$

holds where λ is the crosshead movement and $E(p)$ is the perfect elliptic integral of the second kind. From equations (4)-(6) we can calculate both δ_A and ρ_A by measuring only λ.

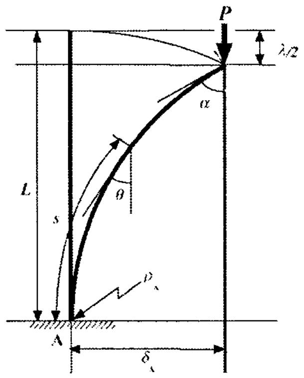

Fig. 1 The elastica.

2.2 Test results of flat coupon

In the first paper [3], the bending strength was evaluated, that is, by measuring δ_A at failure, the bending strength was calculated by eq.(2). Figure 2 compares the bending strength by means of the compression bending with that of 4-point bending of CFRP coupons where the alphabets U and Q represent unidirectional and quasi-isotropic, respectively, and the numerals 8 and 3 stand for T800 and T300 carbon fibers. The results show that for T300 composites, the bending strengths by both methods are almost the same whereas for T800 composites, the strength obtained by the compression bending was much higher than that of 4-point bending. Generally speaking, if we get higher strength, the test method is superior. In that sense, the compression bending test is suitable especially for high-performance composites such as T800 composites.

In the first paper [3], however, the bending modulus could not taken into account. Then we next tried to establish the methodology to get the bending modulus from the compression bending test In Reference [4], equations (4) and (5) were used to calculate whereas eq.(6) was adopted in [5]. Figure 3 is the result of bending modulus [4]; comparing with the 4-point bending, the present method (denoted as the elastica method) may be acceptable.

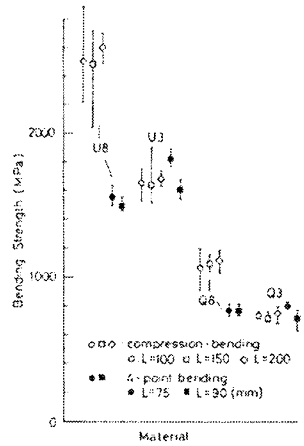

Fig. 2 Comparison of bending strength.

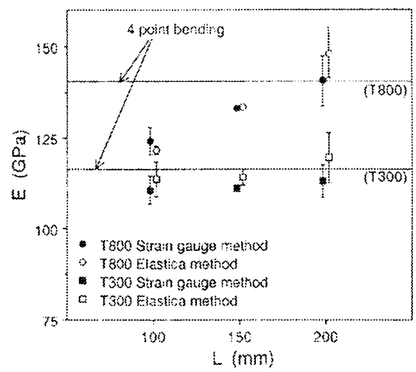

Fig. 3 Bending modulus.

2.3 Application to pipes

The above compression bending test was next applied to CFRP pipes [7-8]. Figure 4 [7] is the case for the pipes of the diameter of 5mm and the wall thickness of 0.3mm. Again the superiority of the present method was demonstrated because the measured strength was much higher than that of 3-point bending.

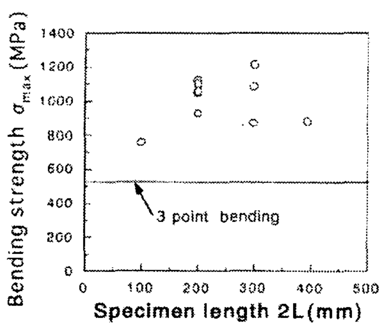

Fig. 4 Bending strength of pipe.

2.4 Eccentric compression bending [10]

Figure 5 schematically shows the eccentric compression bending. In this case, the maximum bending moment at the center of the pipe is [11]

$$M_{max} = P(e+\delta) \quad (7)$$

and this value should be used instead of eq.(1) for compression bending.

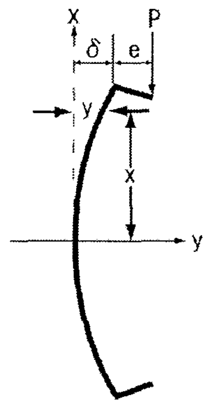

Fig. 5 Eccentric compression bending.

Figure 6 [10] is typical results of the bending strength versus eccentricity for the15mm-diameter pipes of thin-wall specimens (Type A). Almost constant strength was obtained.

If the ratio of the compressive stress to the bending stress is large, the test is no more a bending test. This point was also discussed and Fig.7 is the result for relatively thick-wall specimens (Type B). That is, comparing to the compression bending test of e = 0㎜, the ratio is small under eccentric compression bending. Thus a step forward to the compression bending was successfully realized.

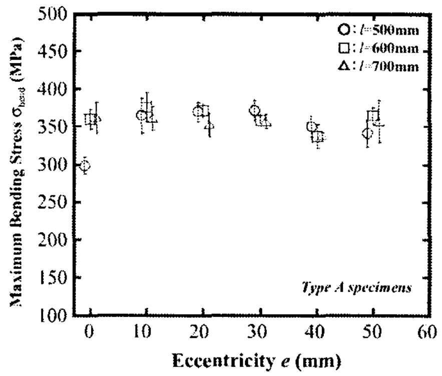

Fig. 6 Bending strength of pipe by means of eccentric compression bending.

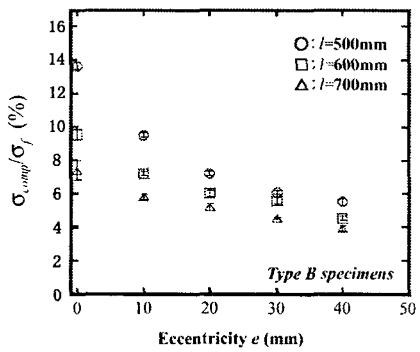

Fig. 7 Ratio of compressive stress to bending stress.

3. Sandwich Beam with Foamed Core

3.1 Bending rigidity

The bending rigidity *(EI)* can be measured experimentally by a three- or four-point bending test. In the case of the three-point bending,

$$EI_{exp} = \frac{PL^3}{48\delta} \tag{8}$$

holds where P is the applied load, L is the span, and δ is the midspan deflection. This equation is based on an elementary beam theory.

On the other hand, if we know the elastic constants of the constitutive materials, that is, if we know Young's modulus of the face material $(E)_f$ and the shearing modulus of the core $(G)_c$, the bending rigidity can be calculated. There are several levels for this procedure.

The simplest one is: if we assume that the applied load (moment) is carried by only the face material and that the role of core is only to keep two skins at a constant distance, the bending rigidity can be calculated, under Euler-Bernoulli's hypothesis, as

$$EI_c = \frac{E_f b t_f t_c^{\ 2}}{2} \tag{9}$$

where t_f and t_c are the thickness of the facing and core, respectively, and b is the specimen width. This corresponds to the case that the shearing modulus of the core is infinity nevertheless Young's modulus of the core is neglected.

In the case of a soft-core sandwich, shearing deformation of the core takes place. This leads the increase of the deflection, hence the decrease of the bending rigidity. The total deflection, δ_{total} , is the sum of the deflection due to bending, δ_b , and the deflection due to the shearing deformation of the core, δ_s , that is,

$$\delta_{total} = \delta_b + \delta_s \tag{10}$$

In the case of a three-point bending, these values can be calculated by

$$\delta_b = \frac{PL^3}{48EI_c} \tag{11}$$

$$\delta_s = \frac{PL}{4t_c b G_c} \tag{12}$$

where $(G)_c$ is the shearing modulus of the core. In this case, the bending rigidity, EI_m, is, referring to eq.(8),

$$EI_m = \frac{PL^3}{48\delta_{total}} \tag{13}$$

From eqs.(11)-(13),

$$EI_m = \frac{EI_c}{1+\alpha} \tag{14}$$

is derived where

$$\alpha = \frac{6E_f t_f t_c}{L^2 G_c} \tag{15}$$

Eq. (14) may be referred as a modified beam theory where the shearing deformation of core is considered, and the skin is assumed to share the bending moment whereas the role of core is to carry the shearing force. If we neglect the shearing deformation of core, $a = o$ holds and eq.(14) reduces to a composite beam theory, EI_c.

In eqs.(14) and (15), it becomes necessary to measure the shearing modulus of the core, $(G)_c$. There is a sophisticated way of calculating $(G)_c$ by combining the results of 3-point and 4-point bending tests of a sandwich coupon [24]. However, as far as our experiment was concerned, the scatter of the data by this method was fairly large; it is almost impossible to get reliable $(G)_c$ value using this method. An alternative way of measuring $(G)_c$ is described in Section 3.3.

3.2 Test results [15]

Several kinds of commercially available sandwich plates of CFRP-fabric skin and acrylic foam core were evaluated by means of a three-point bending to make sure their mechanical behaviors. The effects of the span and the radius of curvature of the loading nose on the bending modulus and strength were examined systematically.

Figure 8 shows the relation between the span, L, and the equivalent bending rigidity. Dots are experimental data and lines are (1) modified beam theory and (2) Kemmochi's derivation [25] referring to Hoff's energy approach [26]. For $(G)_c$, a catalog value of 27MPa [27] was used. According to this figure, experimental values are larger than the theoretical values although the tendency is the same. Although the main subject of Ref. [15] was to correlate the above experimental data to the theoretical values, details are not shown here due to the limitation of space.

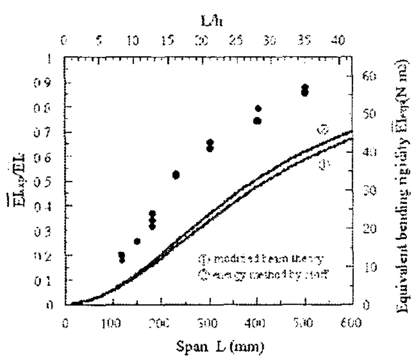

Fig. 8 Span vs. bending rigidity of sandwich beam.

3.3 Shearing modulus of foamed core [16]

Next we tried to measure the shearing modulus of core and Fig. 9 shows a schematic view of the present test specimen. This specimen consists of 4 pieces of core material and 4 facing materials which are arrayed in a symmetrical manner to eliminate the effect of eccentric load. Although this type of test is not authorized anywhere, this test is conducted at several organizations in Japan. By the way, a single-lap type specimen is at any rate inappropriate to measure $(G)_c$.

The effect of geometry of core material on the shearing modulus was examined by varying the core length (L_c) and the core thickness (t_c) and Fig. 10 is the final result in terms of L_c/t_c. These data seems to fall on one curve.

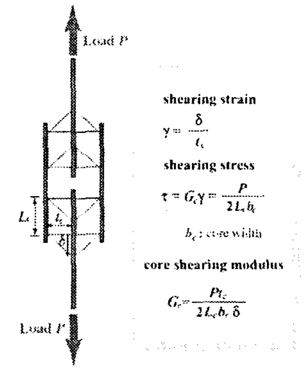

Fig. 9 Specimen configuration for measuring shearing modulus of core.

Then, we tried a three-dimensional linear FEM analysis where the core material was assumed to be isotropic and the input data for FEM analysis were $E_c = 91.9$ MPa and $\nu = 0.1$. E_c was measured previously from the tensile test whereas ν is the catalog value. The FEM values are also drawn in Fig. 10 and very interestingly, the $(G)_c$ value calculated by FEM also exhibits geometry dependence. With increasing L_c/t_c, the $(G)_c$ value calculated from the FEM analysis approached to the following theoretical value:

$$G_c = \frac{E_c}{2(1+\nu)} (=41.8 \text{ MPa}) \tag{16}$$

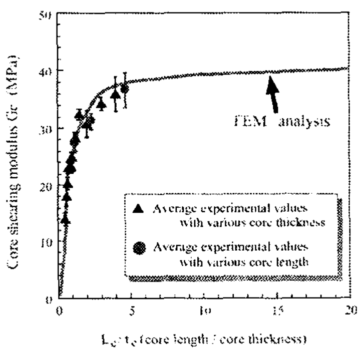

Fig. 10 Shearing modulus.

The above results suggest that the specimen geometry of large L_c/t_c ratio is desirable to get more reliable $(G)_c$ value. In other words, if we conduct the test using a moderate and reasonable size of specimen, some modification must be done by multiplying a correction factor. To this end, the shearing test should be done first using an appropriate size of specimen. Then, by the FEM analysis of the same geometry as the experiment, the material constants of core (E_c and ν) should be looked for so that the FEM result most likely fits to the experimental value.

4. Loop Test for Monofilaments

4.1 Theoretical background

The elastica is again used for the present loot test; Fig. 11 is the schematic view of the loop test. In addition to the equations of Chapter 2, the following equation becomes necessary:

$$\frac{X_\alpha}{l} = \frac{2E(p)}{K(p)} - 1 \qquad (17)$$

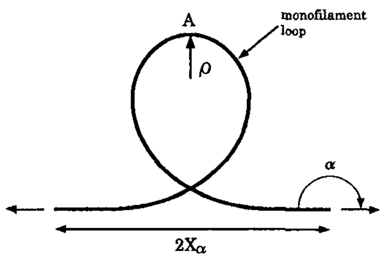

Fig. 11 Schematic view of loop test.

In the actual loop test, the angle α is very close to π and therefore, the approximation of $p \approx 1$ and $E(p) \approx 1$ holds with sufficient accuracy. Substituting these approximations into eqs.(5) and (17), we finally get

$$\rho_A = \frac{l - X_\alpha}{4} \qquad (18)$$

where $2l$ is the original length. By measuring X_a at failure, we can calculate the radius of curvature and hence the strength of monofilaments.

4.2 Test results [22]

Figure 12 is the results of the strength distribution of T300 carbon plotted on a Weibull probability sheet. The strength is likely to obey Weibull distribution with α (scale parameter) = 5.88 GPa and m (shape parameter) = 6.18. By the way, the average strength, μ, m is correlated with and m as follows:

$$\mu = \alpha \Gamma(1 + \frac{1}{m}) \qquad (19)$$

where Γ is the gamma function.

According to the previous study of the tensile test [28], the Weibull parameters at gage length of 25 mm were α=3.17 GPa and m=5.1. However, we can not define the gage length in the loop test and therefore, direct comparison of the loop test with the tensile test is rather difficult. Although we tried linear extraporation in Ref.[22], it seems not necessarily appropriate.

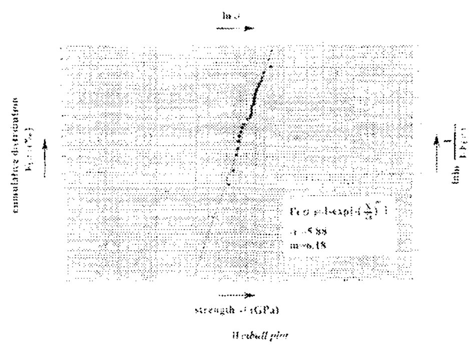

Fig. 12 Strength of T300 carbon monofilaments, Weibull plot.

4.3 Correlation between loop test and tensile test

If the strength of monofilaments obey Weibull distribution, the relation between log (average strength) and log (gage length) should be linear. But actual monofilaments do not necessarily meet with this relation. Then we tried to apply Phani's theory [29] which is expressed as

$$\overline{S} = S_L + \int_{S_L}^{S_u} \exp[-L \frac{(\frac{S - S_L}{S_{01}})^{m_1}}{(\frac{S_u - S}{S_{02}})^{m_2}}] dS \tag{20}$$

where $\overline{s}$ is the average strength, L is the gage length and S_u, S_L, S_{01}, S_{02}, m_1, m_2 are parameters to be determined by experiments.

In the experiment, E-glass monofilaments of 2 μ m-diameter were used and both tensile test and loop test were conducted. Figure 13 shows the strength versus gage length in the tensile test. From these data, the above parameters were determined and the solid line was drawn using eq.(20).

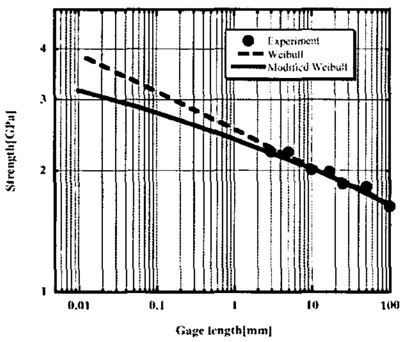

Fig. 13 Strength vs. gage length (E-glass monofilaments).

The average strength by the loop test was 3.28 GPa. During the loop test, we observed and recorded the location of fracture points. The fracture points were within 45 μ m from the top of the loop, point A of Fig.11. Although there is no guarantee that the value of 90 μ m corresponds to the gage length, this value may not far from real gage length.

The extrapolation of the tensile test to the gage length of 90 μ m is calculated to be 2.81 GPa by using eq.(20). The strength by means of loop test (3.28GPa) was larger than that of extrapolation (2.81GPa) from tensile test and this result suggests the superiority of the loop test.

5. Summary

In the present paper, three subjects related to mechanical test method were reviewed. They are (1) innovation and development of compression bending test, (2) mechanical-property evaluation of soft-core sandwich beam, and (3) loop test to measure the strength of monofilaments and the followings are the summary.

(1) Compression bending test and eccentric compression bending test was successfully applied to flat coupons and pipes made of CFRP.
(2) Mechanical properties of CFRP/formed core sandwich beams were evaluated. Notable finding is that the shearing modulus of core strongly depends on the specimen configuration.
(3) A loop test was tried to measure the strength of monofilaments used for advanced composites. Correlation between tensile test and loop test was also tried.

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Fukuda Laboratory Research Subjects

- compression bending of advanced composites (December 2001)
- Micromechanical strength of composites (April 2001)
- loop test of monofilament (July 2000)
- sandwich structures (December 2001)
- Thermal deformation of anti-symmetric laminates (March 1999)
- High temperature resistance of C/C composites (March 1999)
- Development and evaluation of smart materials (March 1999)
- Others
  durability (Jan. 2000), hybrid composites (March 1996), short fiber composites (March 1996), Damage and recycling of CFRTP (March 1996), epitaxial growth of crystal (not composite, March 1996)