PREDICTION OF TENSILE STRENGTH OF UNIDIRECTIONAL CARBON FIBER/EPOXY COMPOSITES USING THE FRAGMENTATION TEST

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Abstract

The fiber breakage behavior of unidirectional polyacrylonitrile (PAN)-based carbon fiber/epoxy composite material was estimated, taking into account stress concentration in the adjacent fibers resulting from matrix cracking around fiber breakages. Analysis of the breakage behavior of adjacent fibers in double-fiber fragmentation tests showed that the results of simulation conducted using a spring element model and taking into account the stress concentration on the fiber surface corresponded well with experimental results. In addition to considering the stress concentration, it is essential to employ a bimodal Weibull distribution, which is a narrow strength distribution in the high strength-region, to explain the behavior observed in double-fiber fragmentation tests. When carbon fiber with no treatment and no sizing agent was used, matrix cracking around fiber breakages did not occur, and the tensile strength of unidirectional carbon fiber/epoxy composites was improved. These findings suggest that there is considerable potential for improving the tensile strength of composites by suppressing stress concentration on the fiber surface.

1. Introduction

In comparison to other materials, carbon fiber-reinforced plastic (CFRP) composites are relatively lightweight and high in tensile strength and tensile modulus. The use of CFRP composites in sporting goods and in materials used in aerospace and industrial applications has grown considerably. In recent years, as interest in global environmental problems has grown, the use of CFRP composites in the aerospace industry has grown because of the need to improve the fuel efficiency of airplanes to meet growing demand. In airplanes, the characteristics in the fiber axis direction of CFRP composites is important because the characteristics are directly linked to weight savings, and it is therefore important to understand the tensile strength of unidirectional CFRP composites.

Many studies predicting the strength of unidirectional carbon fiber/epoxy composites have been reported in the literature [1-4]. These studies have noted that estimating the fiber strength statistics and the constitutive law of the matrix and using a full three-dimensional (3-D) numerical model are important in predicting composite tensile strength. The tensile strength distribution of PAN-based carbon fibers is known to be one of the factors that controls the tensile strength of CFRP composites. A number of studies have proposed statistical approaches to describing the tensile strength distribution of carbon fiber [5-8]. In a recent study, it was found that the bimodal Weibull distribution model was well suited to describing experimentally obtained data for fibers over a wide range of gauge lengths in

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both single-fiber tensile tests and single-fiber composite fragmentation tests [9]. In addition, the tensile strengths of unidirectional carbon fiber/epoxy composites predicted on the basis of a bimodal Weibull distribution were found to be in better agreement with experimental data than tensile strengths predicted on the basis of a unimodal Weibull distribution.

In this paper, the fiber breakage behavior of a unidirectional PAN-based carbon fiber/epoxy composite material was estimated, taking into account the stress concentration in the adjacent fibers resulting from matrix cracking around fiber breakages. We conducted double-fiber fragmentation tests in which two carbon fibers were arranged parallel to the load axis to estimate the stress concentration in the adjacent fiber. In a subsequent analysis of adjacent fiber breakage in double-fiber fragmentation tests, the results of a simulation conducted using a spring element model and taking into account the stress concentration in the fiber surface were found to correspond well to the experimental results. We also examined the influence that the tensile strength of a unidirectional PAN-based carbon fiber/epoxy composite has on matrix cracking around fiber breakages.

2. Experiments

2.1. Materials

TORAYCA™ T800S carbon fibers (Toray Industries, Inc.), which are high-strength polyacrylonitrile (PAN)-based carbon fibers, were used in this study. Table 1 summarizes the physical and mechanical properties of the T800S carbon fibers. We determined the tensile strength distribution of the carbon fibers using both a single-fiber tensile (SFT) test and a single-fiber composite (SFC) test. We employed a bimodal Weibull distribution, given by the following equation, to describe the tensile strength distribution:

$$F(\sigma) = 1 - \exp\left\{ -\frac{L}{L_0}\left(\frac{\sigma}{\sigma_{01}}\right)^{m_1} - \frac{L}{L_0}\left(\frac{\sigma}{\sigma_{02}}\right)^{m_2} \right\} \tag{1}$$

where $F(\sigma)$ is the probability of failure of a fiber, L_0 is a representative length (L_0 = 10 mm), σ is the fracture stress at the gauge length L, σ_{01} and σ_{02} are the Weibull scale parameters, and m_1 and m_2 are the Weibull shape parameters. Table 2 shows the bimodal Weibull parameters of the T800S fibers [9]. As in the previous study mentioned [9], we considered the weakest-link theory, not with respect to the effective volume but with respect to the surface area, because almost all fibers were broken by flaws present on the fiber surface.

Table 1. Physical and mechanical properties of TORAYCA ™ T800S.

Bundle strength	GPa	5.9
Tensile modulus	GPa	294
Density	g/cm^3	1.8
Diameter	μm	5.4

Table 2. Weibull parameters of T800S.

σ_{01}	GPa	6.9
m_1	-	4.1
σ_{01}	GPa	8.3
m_2	-	13

2.2. Double-fiber fragmentation tests

Diglycidyl ether of bisphenol A (DGEBA) and the curing agent diethylenetriamine (DTA) were used to form a matrix with a weight ratio of DGEBA to DTA of 100/10. All of the samples prepared were cured at 50°C for 5 h. Table 3 shows the material properties and the stress–strain curve of the matrix. Each specimen was fabricated such that two carbon fibers were aligned parallel to the load axis at an inter-fiber spacing of 2–5 μm and located at a depth of 50–80 μm from the surface of the specimen. No special equipment was used for this purpose. The depth of each fiber was measured using an optical microscope after curing of the specimens. The matrix beam was deformed in a four-point bending manner, and the strain was monitored using a strain gauge attached to the top surface. The strain was increased in increments of 0.1%, and for each strain increment, the number of fibers that broke within the central part of the beam (10 mm in length) was counted using a polarized optical microscope. Any fiber breaks outside the central 10-mm-long zone were ignored to prevent the effects of a strain gradient arising from the four-point bending of the beam. The number of fiber breaks in each of 20 SFC test specimens was determined. The strain applied to each single fiber, ε_f, was calculated using equation (2):

$$\varepsilon_f = \varepsilon_c \times \frac{2.0}{\kappa} \times \left(\frac{D - 2d}{D} \right) - \varepsilon_r \tag{2}$$

where ε_c is the composite strain, κ is the gauge factor, D is the thickness of the beam, d is the depth at which the individual fibers were placed, and ε_r is the residual compressive strain. The residual compressive strain was 0.14%, as determined from the thermal expansion coefficient of the matrix resin. Matrix crack was observed by field emission scanning electron microscopy (FE-SEM, S-4800 Hitachi High-Tech Fielding Corporation, Japan) at an acceleration voltage of 5 kV.

Table 3. Material properties of the matrix.

Matrix initial modulus	GPa	3.9
Matrix modulus after yielding	MPa	57
Matrix yield stress	MPa	77
Matrix shear modulus	GPa	1.4

2.3. Tensile tests of unidirectional CF/epoxy composites

The tensile strength of resin-impregnated bundles of these fibers (i.e., the so-called bundle strength) was determined in accordance with the method suggested by the JISR 7608 standard (2007): "Carbon fibre—Determination of tensile properties of resin-impregnated yarn." The composites (bundles of epoxy resin-impregnated carbon fibers) whose strengths were to be measured were prepared by impregnating the carbon fibers with DGEBA and the curing agent DTA at a weight ratio of DGEBA to DTA of 100/10. All the samples were cured at 50°C for 5 h. Table 3 summarizes the material properties and the stress–strain curve of the formed matrix. The volume fraction of the carbon fibers in the composites was controlled to be approximately 50%. The bundle strength is defined as the actual strength divided by the volume fraction of the fibers.

3. Numerical Simulation

In this study, a Monte Carlo simulation was conducted using the spring element model (SEM) depicted in Fig. 3. The SEM consisted of longitudinal and transverse elements in a 3-D hexagonal arrangement. The longitudinal spring element represents the fibers, while the transverse shear element represents the matrix. [3, 4] We utilized a bimodal Weibull distribution to describe the tensile strength distribution (Table 2). The simulated model was composed of two fibers, and the simulation was

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performed under displacement control. The model was 3 mm in length and divided into 500 segments. The node mesh in the horizontal plane was 50 × 50 and consisted of two adjacent fibers in the center and the rest of the matrix. We took into account the stress concentration in the adjacent fibers resulting from matrix cracking around fiber breakages. We defined the stress concentration factor α as shown in equation (3):

$$\alpha = 1 + \alpha_0 \times (1 - \frac{x}{l}) \tag{3}$$

where α_0 is the stress concentration factor for the element in the same plane as the fiber breakage, x is the longitudinal direction of the fiber breakage, and l is the stress recovery length. The average stress applied to the fiber did not change, and it was assumed that the stress applied to the fiber surface was increased. We checked that this model agreed with the stress distribution around a fiber break given by the shear-lag model [10].

4. Results and discussion

To examine the stress concentration factor in the adjacent fibers precisely, we utilized double-fiber fragmentation tests. Figure 1 depicts the birefringence patterns around double fibers breaks at a strain of 3.4%. We found that almost all fiber breakages occurred next to each other and that the fracture probability increased around the fiber breakages. Figure 2 shows a scanning electron microscope image of the double fibers. This image suggests that the fracture probability next to the fiber breakages increased as a result of matrix cracking around fiber breakages.

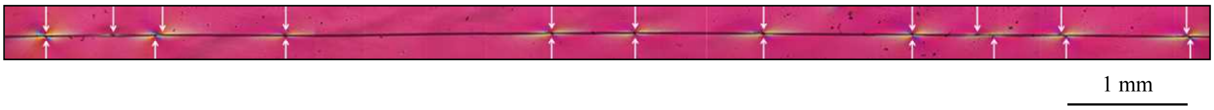

Figure 1. Birefringence patterns around double-fiber breaks at a strain of 3.4%.

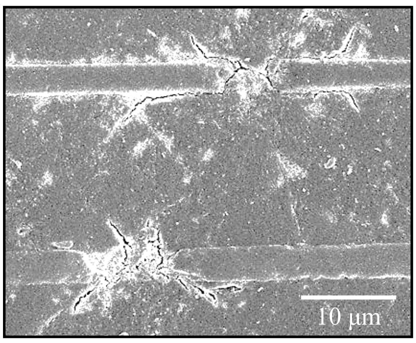

Figure 2. Scanning electron microscope image of double fibers and matrix cracks.

Figure 3 shows the average breakage behavior of the adjacent fiber in the double-fiber fragmentation tests and the simulation results obtained using the SEM, taking into consideration the stress concentration factor on the fiber surface. Analysis of the breakage behavior showed that the simulation results obtained by considering the stress concentration on the fiber surface to be 2.0 corresponded well with the experimental results. Figures 4 and 5 shows the fiber break behaviors at 3.5% predicted using the SEM. We employed a bimodal Weibull model to describe the experimental data for the fiber breakage behavior. We found that it is essential to employ a bimodal Weibull distribution, which is a narrow strength distribution in the high-strength region, to explain the experimental behavior observed

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in the double-fiber fragmentation tests.

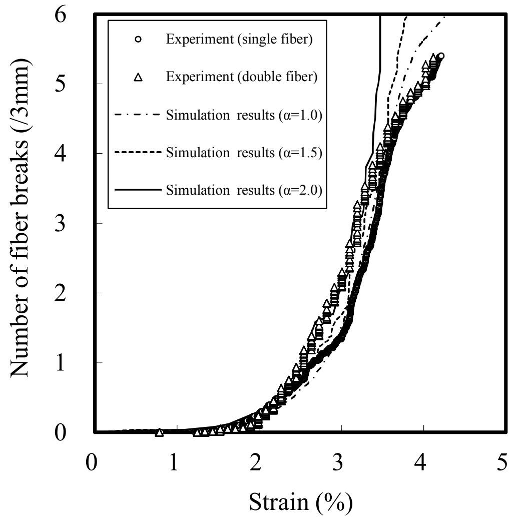

Figure 3. Number of fiber breaks versus the strain measured during the SFC tests.

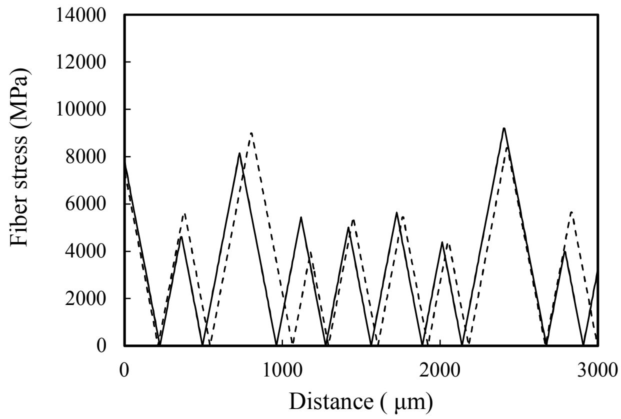

Figure 4. Fiber break behaviors at 3.5% predicted using the SEM (bimodal Weibull distribution).

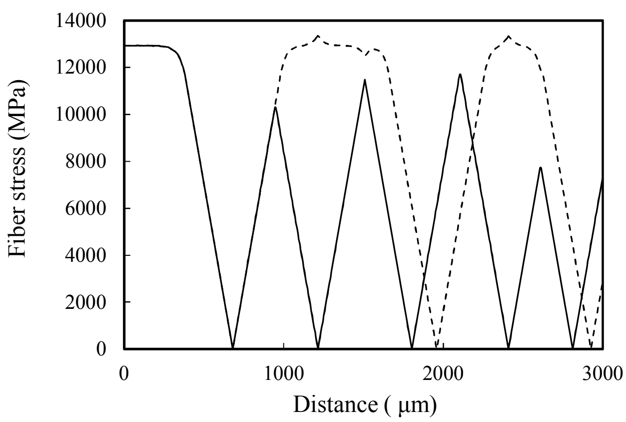

Figure 5. Fiber breaks behaviors at 3.5% predicted using the SEM (unimodal Weibull distribution).

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Figure 6 shows a scanning electron microscope image of the fiber break using no treatment and no sizing agent. Figure 7 shows the tensile strength of unidirectional carbon fiber/epoxy composites. We found that matrix cracking did not occur around fiber breakages and that the tensile strengths of unidirectional carbon fiber/epoxy composites were improved when we utilized a carbon fiber with no treatment and no sizing agent. This suggests that there is considerable potential for improving the tensile strength of composites by suppressing stress concentration on the fiber surface.

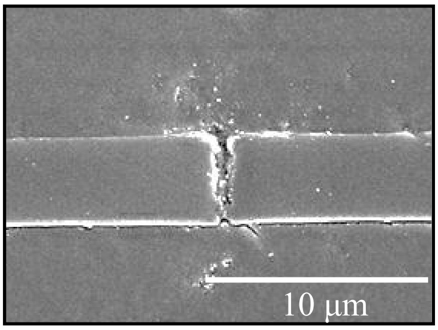
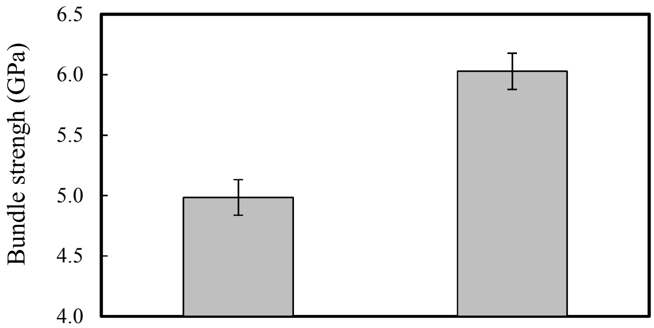


Figure 6. Scanning electron microscope image of fibers and matrix cracks.
(no treatment and no sizing agent)



Surface treatment	Yes	No
Sizing agent	Yes	No

Figure 7. The tensile strength of unidirectional carbon fiber/epoxy composites.

5. Conclusions

We investigated the fiber breakage behavior of unidirectional PAN-based carbon fiber-reinforced epoxy matrix composites, estimated by taking into account the stress concentration in the adjacent fibers that results from matrix cracking around fiber breakages.

(1) To examine the stress concentration factor in the adjacent fibers precisely, we utilized double-fiber fragmentation tests. We confirmed that fiber breakages increased.

(2) Analysis of the breakage behavior of the adjacent fiber in double-fiber fragmentation tests showed that the results of simulation conducted using SEM and considering the stress concentration on the fiber surface to be 2.0 corresponded well with experimental results. In addition to considering the stress concentration, it is essential to employ a bimodal Weibull distribution, which is a narrow strength distribution in the high-strength region, to explain the experimental behavior observed in the double-fiber fragmentation tests.

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(3) We found that matrix cracking around fiber breakages did not occur and that the tensile strengths of unidirectional carbon fiber/epoxy composites improved when we utilized a carbon fiber with no treatment and no sizing agent. This suggests that there is considerable potential for improving the tensile strength of composites by suppressing the stress concentration on the fiber surface.

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