Fiber Fragmentation by Twin-Fiber Bending Beam

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SUMMARY: In the present study, an epoxy beam embedded with two single carbon fibers was made to study the fiber fragmentation behaviour in composites. The bending of the beam provides tensile or compressive loads of the same magnitude to each fiber. The transparent epoxy matrix allowed "on-line" inspection of the fibre during the bend test using a microscope. Birefringent patterns were obtained to reflect the stress state at different regions along the fibre, in particular, at or near fibre breakage regions. It was found that under a given bending stress, the fiber fragment under compression is shorter than that under tension, due to the fact that the compressive strength is lower than the tensile strength of carbon fibers. Interfacial shear strength was calculated with Kelly-Tyson's model for the fiber under compression and was found to be smaller than that under tension. The inversion of Poisson's ration effect was suggested to be the main reason for the difference, with the support from the different birefringent patterns obtained.

KEYWORDS: twin-fibre, single fibre, fragmentation, residual stress, tension and compression, birefringent patterns.

INTRODUCTION

The fiber fragmentation test is widely used to obtain both the fiber strength and the strength of the fiber/matrix interface. Although numerous composite scientists accept the test method, the obtained results on single fiber composites are not exactly the same as those in real composites because of the interaction between the fibers in real composites. However, it is almost impossible to measure directly the interfacial strength in real composites. In order to solve the problem, some attempts were made by using multi-fiber micro-composites which contains single layer of fibers [1-3]. The inter-distance between fibers was varied to examine the interaction influences on fiber fragmentation. The results so obtained are closer to bulk composites than single fiber composites. Up till now, much attention was paid on fiber fragmentation by tension. However, the materials data on the compressive strength of single fiber is scarce as standard tensile testing equipment and methods cannot be used. By loading the single fiber specimen in tension with the fiber perpendicular to the loading axis, the compressive strength of fibers was measured successfully. This transverse tensile test uses the Poisson's ratio effect to induce a compressive strain in the fiber resulting in the fragmentation phenomenon [4]. Another attempt to determine the compressive strength was carried out by using thermal stress to develop fiber fragmentation [5].

The main objective of this study is, by using four-point bending test, to compare the fiber fragmentation by tension with that by compression. In the same beam containing two fibers situated near the top and bottom respectively, the fiber fragmentation can take place simultaneously by tension and compression.

EXPERIMENTAL DETAILS

Two carbon fibers of type T300 were placed in parallel into a Teflon mould. Two ends of each fiber were stuck on external sides of the mould to prevent it from becoming loose. The liquid epoxy was then poured into the mould. Curing was carried out at 120 °C for two hours, followed by natural cooling at room temperature. Beams were cut from the composite plate formed by the mould so that each beam contains two fibers as shown in Fig. 1. Bending tests were performed using a motor-driven testing stage with a polarized light microscope. The loading rate is about 0.3mm/min. A region of 15mm long along the beam length was identified as the observation zone for the fragmentation procedure. Classical beam theories were used to calculate the beam stress.

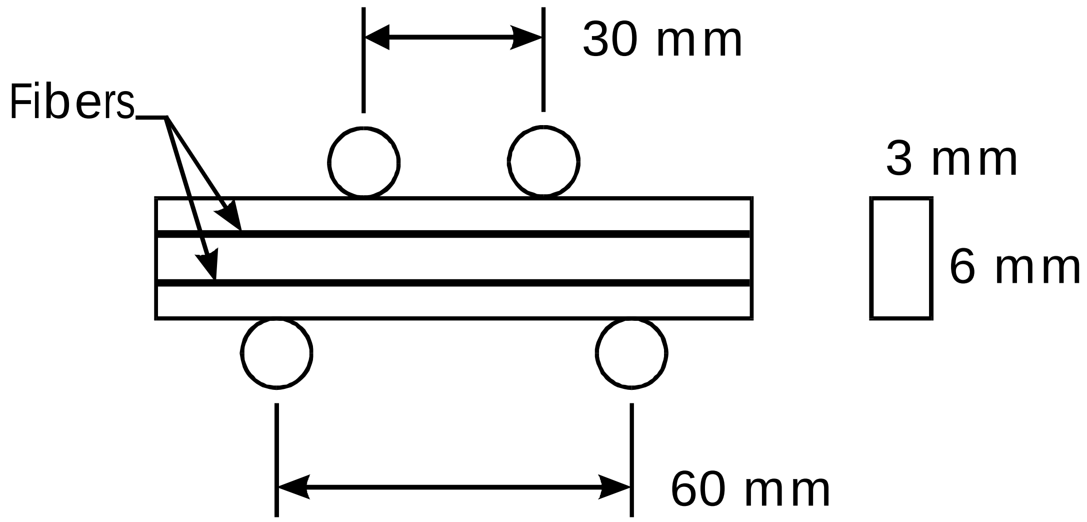


Fig. 1 Beam geometries and fiber position

THEORY

Fiber Fragmentation by Tensile Tests

In general, fiber fragmentation tests are carried out by monotonically loading a single fiber embedded specimen in the direction of fiber axis. Since the fiber failure strain is lower than that of the ductile matrix, the fiber will fracture into small fragments within the matrix. As higher and higher tensile strain is applied, the fragmentation process continues until the interfacial stress is no longer capable of inducing further rupture of the fiber fragments. The variables measured in the tests are the length of the fragments and the applied strain (or stress). The fiber tensile strength and the interfacial shear strength can be obtained from the above variables using Weibull statistics and the Kelly-Tyson model. The stress transfer on the fiber/matrix interface is analyzed based on the force balance of a fragment between the axial tensile stress and the interfacial shear stress. The Kelly-Tyson's equation gives the interfacial shear strength τ_t,

$$\tau_t = \frac{\sigma_{fu} d}{2L_c} \tag{1}$$

where σ_{fu} is the tensile strength of the fiber at critical length L_c, and d is the fiber diameter. Eqn (1) is commonly used to study the interfacial shear strength if L_c is measured by experience and σ_{fu} calculated by extrapolation of σ–L curves.

Fiber Fragmentation by Compressive Tests

Weilbull statistics are still valuable for the fiber fragmentation by compressive loading. As the axial stiffness of the carbon fiber in compression and tension are considered to be similar, the difference between tensile modulus and the compressive one is not significant. However, the compressive strength is considerably lower than the associated tensile strength. Besides, the compressive stress-strain profile is different from that of the tensile one. The compressive stress on a fiber can be transferred perfectly across the break from one fiber fragment to the other due to the fact that the fragments are still in contact with each other. It is evident that a critical fragment length, as defined by the tensile load transfer model, does not exist in a compressive system. According to the compressive profile, Wood *et al*. [5] proposed a mathematical representation of the interfacial shear strength, τ_c, based also on the force balance,

$$\tau_c = \frac{\sigma_{fc} d}{2L_c} \tag{2}$$

Eqn (2) is very similar to Eqn (1) for tensile fragmentation save that in this compressive scenario the critical length is the original length of the fiber ($L_c = L_1$). σ_{fc} is the fiber stress at the point where the interfacial stress are insufficient to induce further fragmentation.

Thermal Stress

Owing to the different thermal expansion coefficients between carbon fiber and epoxy, the thermal stress will be induced in both matrix and fiber. As the thermal expansion coefficient of a carbon fiber is small in comparison to that of the matrix, for the case of a micro-composite where the fiber volume fraction is near zero, the thermal stress equation in a one-dimensional model is

$$\sigma_f^{th} = \left(\alpha_m - \alpha_f\right)\left(T - T_{ref}\right)E_f \tag{3}$$

α_m and α_f are thermal expansion coefficients of the matrix and the fiber respectively, T is the ambient temperature, T_{ref} is the reference temperature at which the material solidifies upon cooling. By using the parameters in Table 1, the thermal residual stress is calculated to be 140MPa.

Table 1: Materials parameters used in this study

	E(GPa)	$\alpha(\mu K^{-1})$	T_g (°C)
Carbon fiber	300	0.5	
epoxy	3	6.0	107

While, the stress on the fiber in the longitudinal direction is given in Eqn (4) :

$$\sigma_f = \sigma_m \frac{E_f}{E_m} + \sigma_f^{th} \tag{4}$$

where $\sigma_m = \sigma_{beam} \frac{2y}{h}$, with h being the beam height. In our case, y = 2.03 for the fiber under tension, and 2.25 for the fiber under compression. In fact, σ_m is the beam stress at the level of the fiber position. On the beam section, the stress varies almost linearly with the beam height. Therefore stress distribution is not same as a tensile specimen. However, in order to simplify the problem, the tensile and compressive stress applied to the fiber-matrix representative volume is considered to be uniform. The representative volume is composed of a fiber and a layer of matrix around the fiber just as a single fiber micro-composite specimen. The external stress applied to the representative volume is taken as σ_m.

RESULTS AND DISCUSSION

Fig. 2 shows the variation of the fragment length as a function of beam stress. Two key features can be identified for a given stress level: the fragment lengths are not uniform, which is certainly caused by the microstructures of the fibers (such as micro-defects), and the fiber fragments under tension are longer than those under compression. These seem to have corresponded well with the view that the compressive strength of carbon fiber is lower than tensile strength.

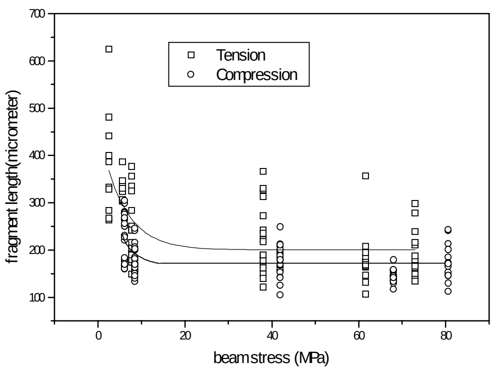


Fig. 2: Fragment length versus beam stress

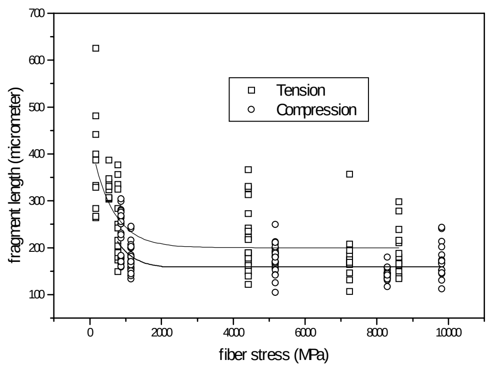


Fig. 3: Fragment length versus fiber stress

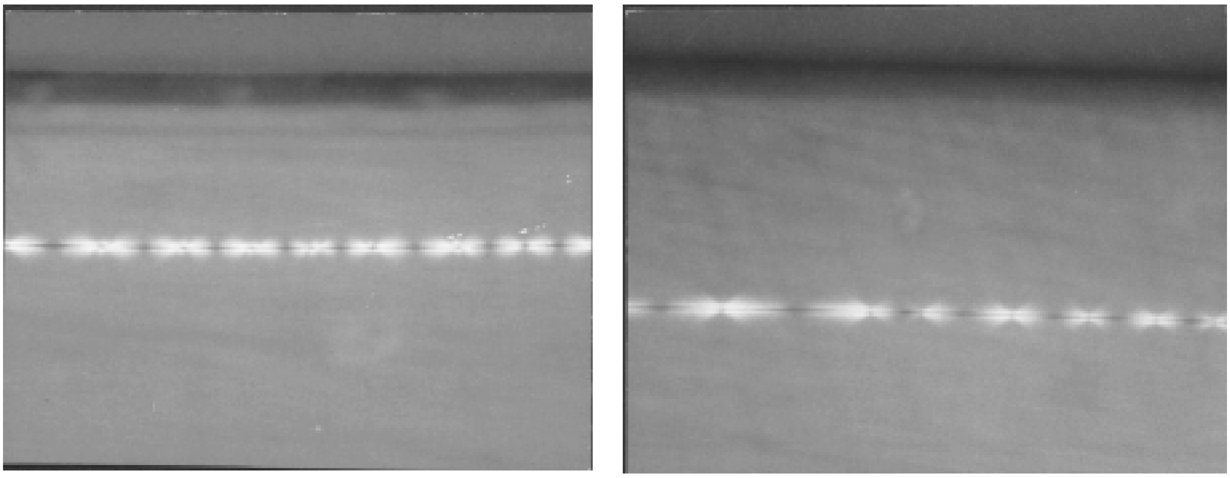
The fragment length data and the associated fiber stresses, according to Eqn (4), are plotted in Fig. 3. Tensile modulus is used, as compressive modulus is unknown for a single fiber. It can be seen in Fig. 3 that the fiber fragment length becomes constant when the fiber stress reaches a critical value of 3.0 GPa for the fiber under tension and 2.0 GPa for that under compression. After the critical stress, the fragment cannot be broken further. By substituting the critical stress and corresponding fragment lengths into Eqn (1), we obtained the interfacial shear strength as listed in Table 2.

Table 2: Critical fiber stress, fragment length and interfacial shear strength

fiber loaded by	σ_{fu} and σ_{fc}(GPa)	L_c (μm)	τ_t and τ_c (MPa)
tension	3.0	215	42
compression	2.0	175	34

Here, Eqn (1) instead of Eqn (2) is used to calculate the interfacial shear strength for the fiber under compression. The interfacial shear strength calculated with Eqn (2) is 0.4 MPa, and is too small. By comparison, τ_c is about 19% lower than τ_t. One possible reason for this difference may be the inversion of Poisson's ratio effect. It is known that when tensile stress is applied to the fiber/ matrix specimen, a compressive radial stress is created perpendicular to the interface due to the contraction of the matrix. On the contrary, under a compressive nominal stress, a tensile radial stress will be caused across the interface. It is clear that the latter situation is favorable for the interfacial debonding. Therefore the inverse Poisson's ratio effect can affect the stress transfer across the interface, which further influences fiber fragmentation, i.e. fragment length.

In Fig. 4, two pictures of the fiber fragmentation are shown. It can be seen that the birefringent patterns have clearer outline for the fiber under tension than that under compression. Besides, at the fiber breakage ends, a weak birefringent patterns can still be observed for the fiber broken under compression, and there exists no such evidence for the fiber broken under tension. These phenomena come from the different mechanisms of stress transfer at the fiber breakage points and at the interface.



(a) fiber broken by tension (b) fiber broken by compression

Fig. 4: Different birefringent patterns for the fiber fragmentation (50×)

CONCLUSIONS

The twin-fiber composite four-point bending beams were used to study the fiber fragmentation phenomena by tension and compression. The experimental results showed the different mechanisms of fiber fragmentation by tension compared with that under compression. It was found that under a given bending stress, the fiber fragment under compression is shorter than that under tension. This phenomenon was considered to be related to lower compressive than tensile strength of the carbon fibers. The interfacial shear strength calculated with Kelly-Tyson's model for the fiber under compression was smaller than that under tension. The inversion of Poisson's ration effect was the main reason for the difference. The different birefringent patterns proved the different stress transfer process.

REFERENCES

1. van den Heuvel, P.W.J., van der Bruggen, Y.J.W. and Peiji, T., "The Influence of Carbon Fiber Surface Treatment on Fiber-Fiber Interaction in Multi-Fiber Microcomposites", *Advanced Composites Letters*, Vol. 3, No.6, 1994, pp 197-201.
2. Li, Z.F., Grubb, D.T. and Phoenix, S.L., "Fiber Interaction in the Multi-Fiber Composite Fragmentation Test", *Composite Science and Technology*, Vol. 54, 1995, pp 251-266.
3. Grubb, D.T., Li, Z.F. and Phoenix, S.L., "Experimental Studies of Fiber Interactions with Multi-Fiber Model Composites", *Proc. 8th Tech. Conf. of American Society for Composites*, Lancaster, PA. 1993.
4. Wagner, H.D., Migliaresi, C., Gilbert, A.H. and Marom, G., "Transverse Loading of Monofilament Reinforced Microcomposites: A Novel Fragmentation Technique for Measuring the Fiber Compressive Strength", *J. Material Science*, Vol. 27, 1992, pp 4175-4180.
5. Wood, J.R., Wagner, H.D. and Marom, G., "The compressive fragmentation phenomenon: using microcomposite to evaluate thermal stresses, single fiber compressive strength, Weibull parameters and interfacial shear strength", *Proc. R. Soc. A*, London , 452, 1996, pp 235-252.