Compressive response of Kevlar–epoxy composites: experimental verification

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The initial misalignment of Kevlar fibres in Kevlar–epoxy composites is quantitatively investigated. This misalignment has been found to be one of the most important factors for determining the compressive response of these composites. A theoretical model, which considers initial fibre misalignment and assumes that the compressive response of Kevlar–epoxy composites is dominated by kink band failure, is in good agreement with experimental results. In addition, photomicrographs of the failure surfaces suggest that kink band formation is the predominant failure mode in this composite system.

1. Introduction

Advanced composite materials offer significant potential for significant improvement in the performance of materials; the characterization of their behaviour in compression is crucial. Kevlar 49 composites are considerably weaker in compression than other composites with high-strength, high-modulus fibres. Much effort has been expended on understanding failure mechanisms and predicting the compressive strength of fibrous composites. Fibre microbuckling and fibre kinking are the two compressive failure modes that are most frequently reported in the scientific literature. Based on fibre microbuckling, the analytical prediction of compressive strength was first proposed by Rosen [1]. Although Lager and June [2] showed that Rosen's model can be used to predict the compressive strength of boron–epoxy composites, the model fails to apply to Kevlar–epoxy composites. This suggests that fibre microbuckling may not be the failure mode for Kevlar–epoxy composites. Since then, Greenwood and Rose [3], Hahn *et al.* [4] and Hull [5] have reported that fibre kinking is the predominant failure mechanism in Kevlar–epoxy composites.

As a consequence of significant differences between the mechanical properties of the components, fibrous polymeric composites are extremely sensitive to fibre misalignment and waviness. Misalignment means deviation of the fibre direction in the laminae from the planned direction. Such deviations are due to imperfections in the technology, and they can be one of the causes of the large scatter of the test results, especially for unidirectional materials reinforced with high-modulus fibres. The longitudinal compressive strength of unidirectional composites depends not only on the mechanical properties of the matrix and fibre, but also on initial fibre misalignment. The existence of initial fibre misalignment and its effect on composite compressive strength has been investigated by Lanir and Fung [6], Hanasaki and Hasegawa [7] and Davis [8]. It was found that initial fibre misalignment can considerably reduce the predicted compressive strength.

The scope of this paper focuses on the experimental verification of a previous mathematical model [9] to show the effect of the initial fibre misalignment on the compressive response in Kevlar–epoxy composites. First, the longitudinal compressive response and the failure mechanism of Kevlar–epoxy composites are initially determined from experiments. Then, the influences of initial fibre misalignment and non-linear shear deformation of the matrix are considered, and the experimental results and theoretical predictions are compared.

2. Experimental procedure

The unidirectional Kevlar–epoxy composites, supplied by 3M, have 16-ply laminae. Each lamina has a thickness of 0.0085 in. (0.216 mm) and consists of du Pont Kevlar 49 fibres and 3M AF-163-2U epoxy adhesive. Seven replicas were cut from the original Kevlar–epoxy panel by using a diamond cutting wheel. The specimens were 2.65 in. (67.31 mm) long by 0.75 in. (19.05 mm) wide. It is assumed that all fibres in a rectangular specimen were parallel to the specimen edges. The compression axis was parallel to the specimen longitudinal edge. Specimen layout is shown in Fig. 1. Four plate specimens (L1 to L4) were prepared

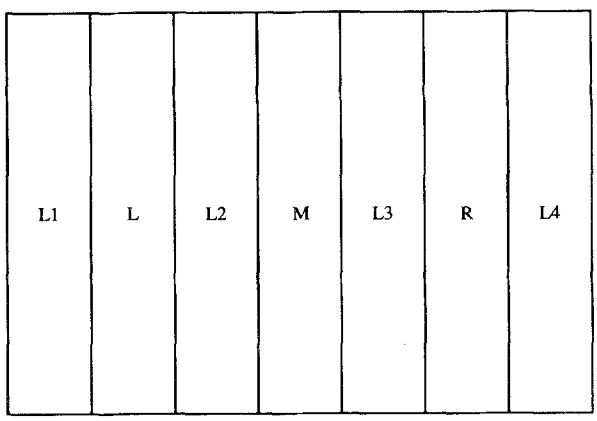

Figure 1 Specimen layout.

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for the compression tests, and specimens R, M and L were prepared for initial fibre misalignment measurements.

The standard face-sheet type compression fixture [10] was used in the experiment. This direct end-loading method uses specimens having relatively long gauge sections that are fully supported along the face of the specimen. A crosshead speed of 0.05 in. min^{-1} (1.27 mm min^{-1}) was used to test the plate specimens. The tested specimens were then submitted for failure mode observation using an optical metallographic procedure.

In addition, three untested plate specimens were submitted for optical metallographic observation for the evaluation of initial fibre misalignment. The specimens were polished and inspected under a high-magnification microscope. Seven different locations of each plate specimen were selected for photomicrographs as illustrated in Fig. 2. Twenty one photomicrographs in total were taken for the initial fibre misalignment measurement. Typical photomicrographs of these fibre arrangements in Kevlar–epoxy composites are shown in Fig. 3.

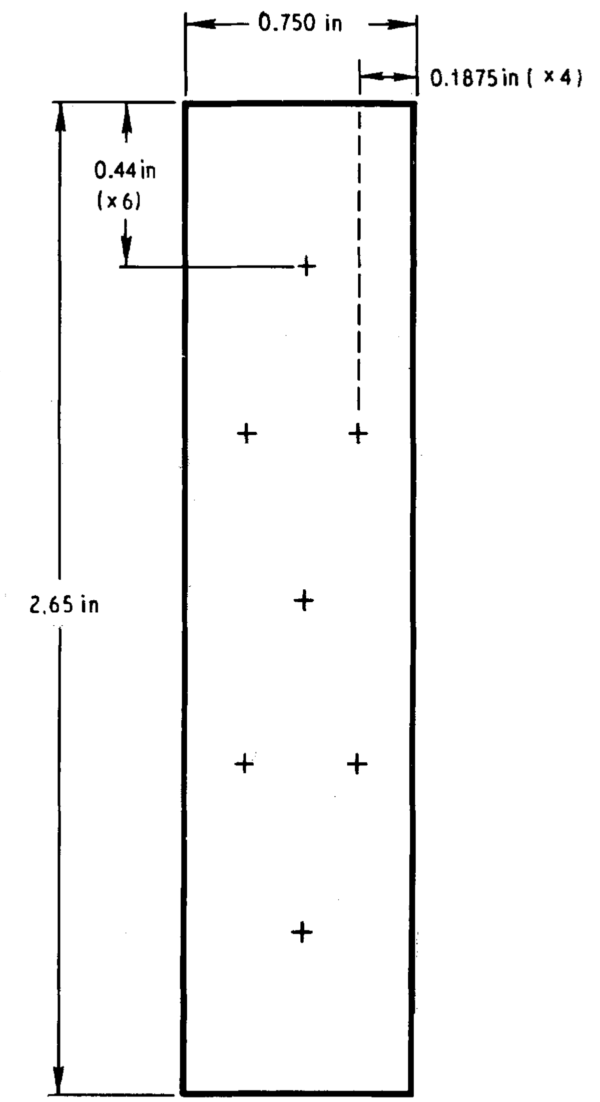


Figure 2 Selected locations in photomicrographs for initial fibre misalignment measurement (1″ = 25.4 mm).

TABLE I Mechanical properties of 16-ply unidirectional Kevlar–epoxy composites

Specimen No.	Ultimate stress (MPa)	Elastic modulus (GPa)	Ultimate strain (%)
L1	188.0	53.0	0.53
L2	192.0	53.4	0.53
L3	191.2	51.7	0.50
L4	192.1	53.4	0.50
Average	190.8	52.9	0.52

3. Experimental results

3.1. Mechanical properties

A total of four 0° specimens were tested. Average values of the initial elastic moduli, ultimate stresses, and strains of these tests are summarized in Table I. The compressive stress–strain curves of four longitudinal specimens are plotted in Fig. 4. It indicates that the test results are fairly reproducible.

3.2. Failure modes

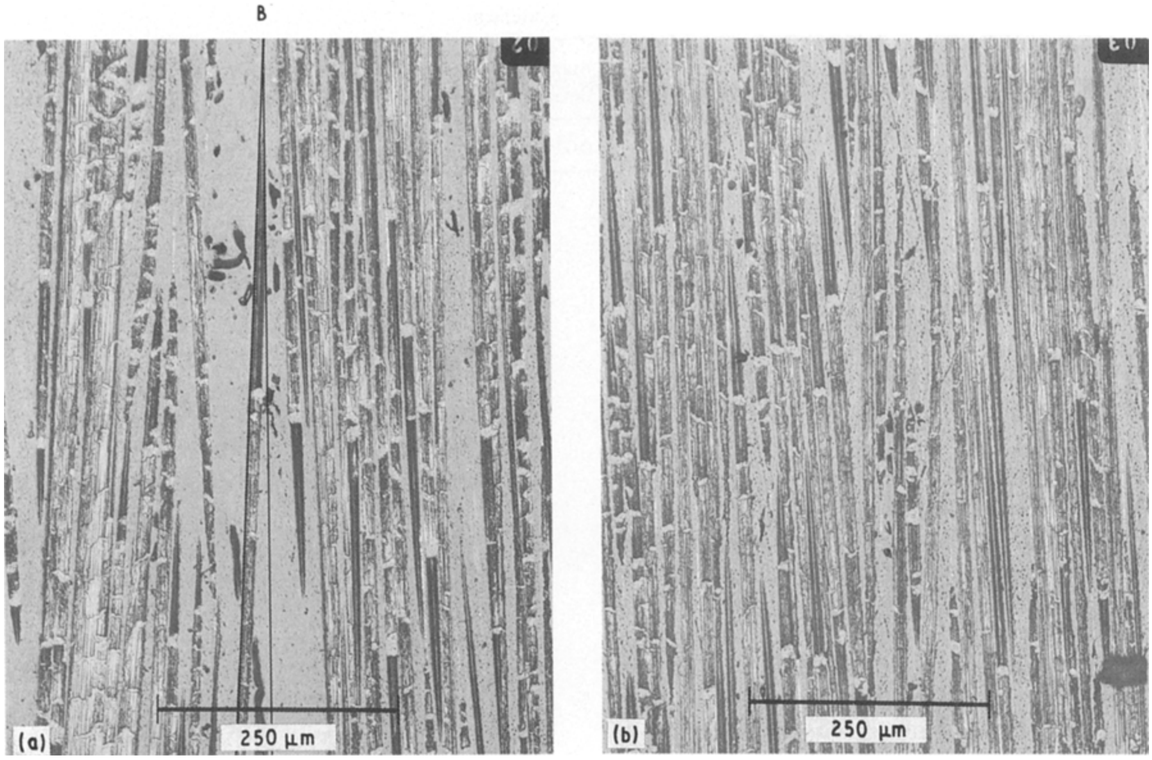
The two compressive failure modes most frequently encountered in the literature are fibre microbuckling and fibre kinking. In the microbuckling mode of failure the fibres usually fracture at several points and there is no relative displacement of the fibres across the failure zone. In kinking, the fibres initially fracture at two points and there is relative displacement of the fibres across the failure zone.

Photomicrographs of the fracture surfaces of a Kevlar–epoxy composite system under compression are shown in Fig. 5. It shows the overall failure characteristics of the tested specimens. The results support the conclusion that this composite system failed by fibre kinking through the specimen thickness. In the photomicrograph, no fibre fracture was found at the boundary, although the fibres are sharply bent. Instead, fibres are kinked at the boundary, and the specimens as a whole are still intact after failure.

3.3. Initial fibre misalignment measurements

The idealized initial fibre misalignment is illustrated in Fig. 6. In the figure, f_0 is the amplitude and l the length of the region of kink band failure. The dimensionless parameter e is defined as the ratio of f_0 to l.

Twenty one photomicrographs from the three global locations were taken for the measurements of initial fibre misalignment. The locations of the initial fibre misalignment were randomly selected. In Fig. 3, one may select any misaligned fibres to be measured. By drawing a straight line, AB, along that misaligned fibre, the line intercepts the two edges of the photomicrograph. A vertical line, BC, is then generated from point B down to the bottom edge of the photomicrograph. e can be calculated as AC divided by two times BC (see Fig. 6). The measurements of initial misalignment of 642 fibres were recorded and analysed statistically. The basic statistics are summarized in Table II. It shows that the average value of e is about 0.029.



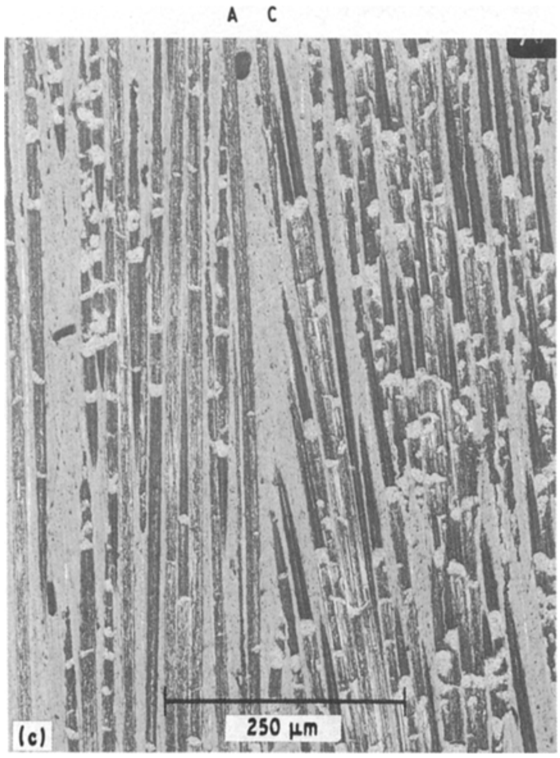


Figure 3 Typical photomicrographs of fibre arrangements in Kevlar–epoxy composites: (a) R, (b) M, (c) L.

4. Discussion

A theoretical study of the compressive response of Kevlar–epoxy composite systems has been conducted using a mathematical model [9]. In the model, the influence of initial fibre misalignment and non-linear shear deformation of the matrix were considered. Based on the model, the compressive stress–strain

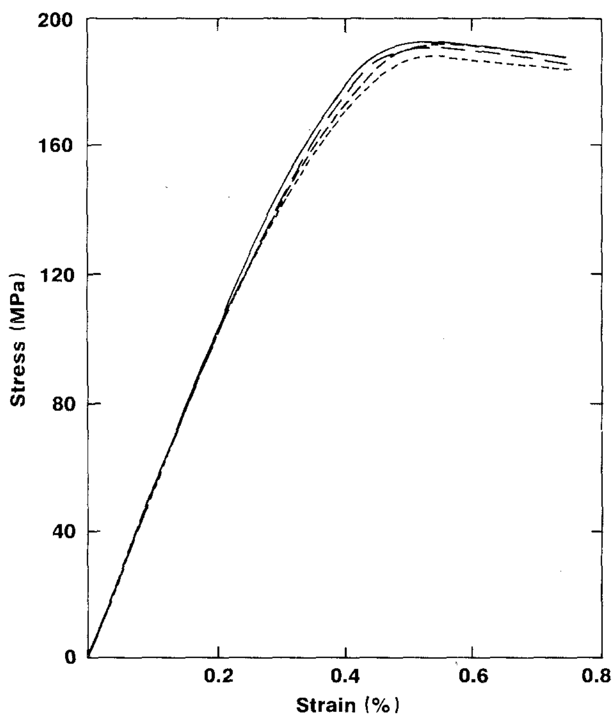


Figure 4 Experimental stress–strain curves of compressive response of Kevlar–epoxy composites: (– – – –) L1, (— – —) L2, (— —) L3, (——) L4.

In order to determine the distribution for *e*, several distribution fitting functions were selected. Based on the Kolmogorov–Smirnov goodness-of-fit test, the data best fit a two-parameter Weibull distribution. The Weibull shape parameter, 1.197, and scale parameter, 0.031, were determined using the method of maximum likelihood (MLE) [11]. Using Weibull coordinates, the data were plotted in Fig 7. The low Weibull shape parameter shows that the measurements of the initial fibre misalignment have a large scatter.

TABLE II Summary statistics for the initial fibre misalignment measurements

Sample size	Average	Median	Mode	Geometric mean	Standard deviation	Skewness	Standard skewness	Kurtosis	Standard kurtosis
642	0.029	0.022	0.022	0.019	0.025	1.79	18.49	4.11	21.26

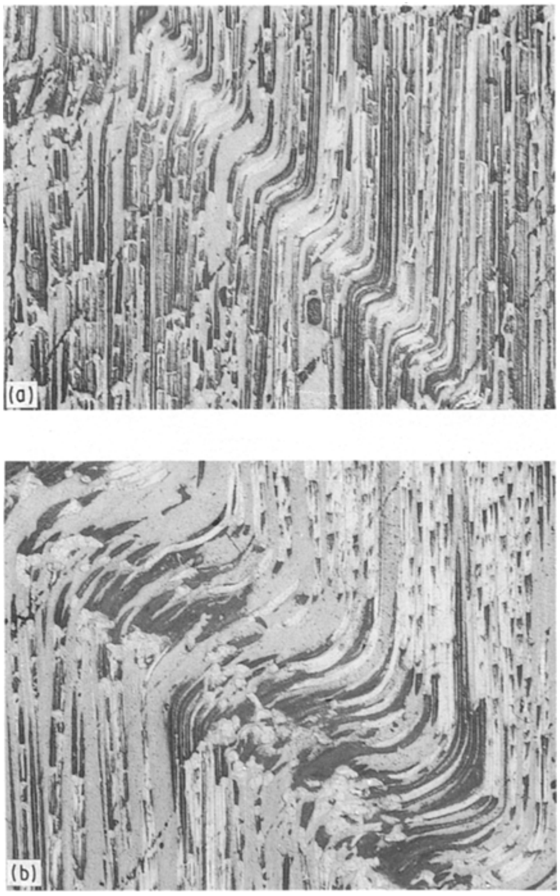


Figure 5 (a, b) Photomicrographs of typical kinking failure in Kevlar–epoxy composites (100 ×).

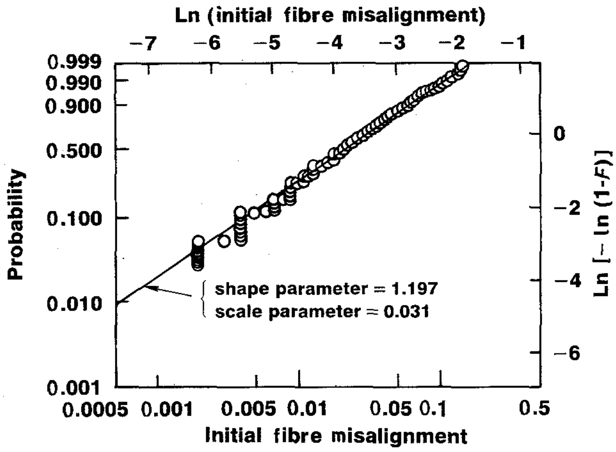


Figure 7 Weibull probability plot for initial fibre misalignment of Kevlar–epoxy composites.

relationship of a composite is given in the Appendix. In order to determine the compressive strength of Kevlar–epoxy composites, a failure criterion is needed.

In general, the experimental results verify that the compressive failure of a Kevlar–epoxy composite is caused by a kink band failure. This work well supports the previous published work [3–5]. The failure criterion used in this model is as follows. Let S be the shear strength measured from experiments. Assume that failure occurs when the maximum shear stress on a plane normal to the fibre direction at any point along the kink band exceeds S (see Fig. 8).

A numerical study was conducted to determine the compressive response of the Kevlar–epoxy composites used in the experiments. Material properties

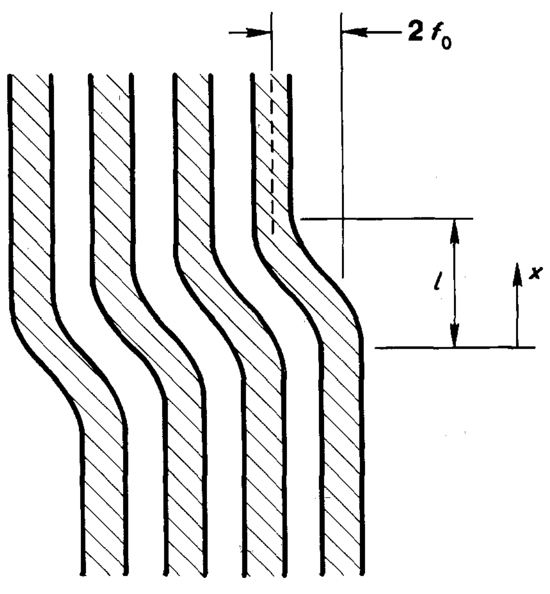


Figure 6 Idealized initial fibre misalignment in Kevlar–epoxy composites under longitudinal compressive stress.

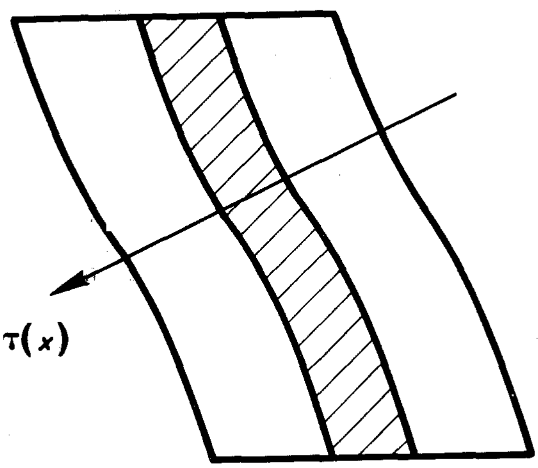


Figure 8 Shear stress in kink band failure. Failure occurs when $\tau(x)_{max} = S$.

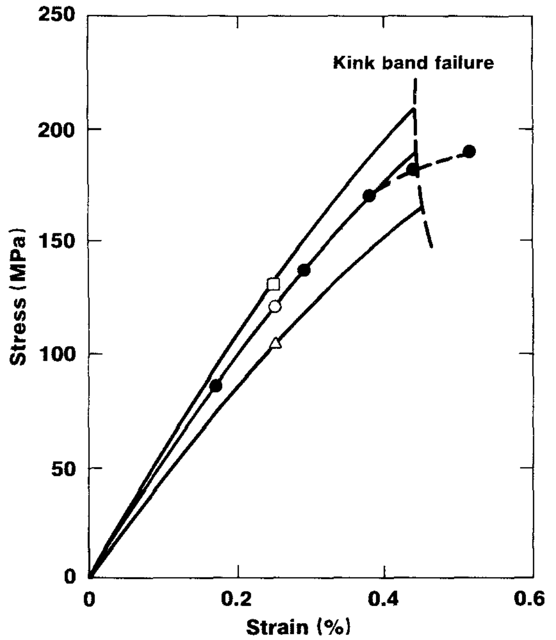


Figure 9 Longitudinal compressive stress versus strain for Kevlar–epoxy composites: (□) $e = 0.025$, (○) $e = 0.0287$, (△) $e = 0.035$, (●) experimental data.

used in this calculation were obtained from 3M [12], VPI [13] and du Pont [14]. The fibre volume fraction of Kevlar–epoxy composites is 0.5 [12] and the shear strength, S, is found to be equal to 46.6 MPa [13]. The axial tensile and shear moduli of Kevlar 49 fibre are 124 and 2.76 GPa [14], respectively.

The non-linear shear stress–strain curve of the epoxy resin [13] can be represented by the followng equation:

$$\tau_m \text{ (MPa)} = 413.8\gamma_m - 3740\gamma_m^{2.62} \quad (1)$$

For numerical calculation, the value of e is chosen in the range 0.025–0.035. The predicted compressive responses of the Kevlar–epoxy composite system up to kink band failure are compared with experimental results in Fig. 9. It appears that the compressive response predicted by the present study coincides well with the experimental results when e equals 0.0287, which is the average value of e obtained from the experiments

5. Conclusions

1. An analytical model that considers initial misalignment in the fibres gives a good prediction of the longitudinal compressive response of Kevlar–epoxy composites.

2. The observed failure mode suggests that kink band formation is the pronounced fracture for the compressive strength of Kevlar–epoxy composites.

3. The distribution of initial fibre misalignments follows a two-parameter Weibull distribution with a large variability.

Appendix

The fibres may have initial misalignment with the initial deflection of fibres described by

$$V_0 = f_0 \cos\frac{\pi x}{l} \quad (A1)$$

where f_0 is the amplitude of the initial fibre misalignment and l is the length of the region of kink band failure as shown in Fig. 6. When a compressive stress σ is applied, the final deflection of fibres becomes

$$V = f\cos\frac{\pi x}{l} \quad (A2)$$

Then V minus V_0 is equal to the displacement, v, of the fibres in the y direction. The associated displacement, u, of the fibres in the x direction can be described by

$$u = A\cos\frac{\pi x}{l} \quad (A3)$$

where A is the amplitude of displacement which depends on the applied compressive stress. From the requirements of shear stress continuity and strain compatibility at the fibre–matrix interface, the shear strain in the fibre and matrix can be determined. Then the potential energy, Π_p, of the system can be obtained by the strain energies of the fibre, U_f, and the matrix, U_m, plus the potential of the applied force, W; i.e.

$$\Pi_p = U_f + U_m + W \quad (A4)$$

Note that for a given compressive stress, σ, potential energy is a function of two unknowns, f and A. These two unknowns can be determined using the principle of minimum potential energy. It can be shown that an approximate solution may be obtained as follows [9]

$$f = \frac{f_0}{1 - (\sigma/B)} \quad (A5)$$

and

$$A = \frac{4l\sigma}{\pi^2 E_f v_f} \quad (A6)$$

in which

$$B = \frac{G'_m}{1 - v_f + (v_f G'_m/G_f)} \quad (A7)$$

where E_f and G_f are the Young's and shear moduli of the fibre, respectively; G'_m is the secant shear modulus of the matrix and v_f is the fibre volume fraction.

The compressive strain, ε, is defined by

$$\varepsilon = \left\{\frac{1}{2}\int_0^l\left[\left(\frac{dV}{dx}\right)^2 - \left(\frac{dV_0}{dx}\right)^2\right]dx + 2A\right\}l^{-1} \quad (A8)$$

Substitution of Equations A1, A2 and A6 into Equation A8 gives

$$\varepsilon = \frac{\pi^2 e^2}{4}\left(\frac{1}{[1 - (\sigma/B)]^2} - 1\right) + \frac{8\sigma}{\pi^2 E_f v_f} \quad (A9)$$

The above equation describes the stress–strain relationship of a composite under compression.

References

1. B. W. ROSEN, in "Fiber Composite Materials" (American Society for Metals, Metal Park, Ohio, 1965) p. 37.

2. J. R. LAGER and R. R. JUNE, *J. Compos. Mater.* **3** (1969) 48.
3. J. H. GREENWOOD and P. G. ROSE, *J. Mater. Sci.* **9** (1974) 1809.
4. H. T. HAHN, M. SOHI and S. MOON, NASA Contractor Report 3988 (US Department of Commerce, Springfield, Virginia, 1986).
5. D. HULL, "An Introduction to Composite Materials", Cambridge Solid State Science Series (Cambridge University Press, Cambridge, UK, 1981) p. 157.
6. J. LANIR and Y. C. B. FUNG, *J. Compos. Mater.* **6** (1972) 387.
7. S. HANASAKI and Y. HASEGAWA, *ibid.* **8** (1974) 306.
8. J. G. DAVIS, "Composite Reliability" ASTM STP 580 (American Society for Testing and Materials, Philadelphia, 1975) p. 364.
9. J. R. YEH and J. L. TEPLY, *J. Compos. Mater.* **22** (1988) 245.
10. ASTM E9, "Standard Methods of Compression Testing of Metallic Materials at Room Temperature" (American Society for Testing and Materials, Philadelphia, 1989).
11. A. C. COHEN, *Technometrics* **7** (1965) 579.
12. Product Data Street, Structural Adhesive Film AF-163-2 (3M Co., St. Paul, Minnesota, 1986).
13. M.-J. PINDERA, Z. GURDAL, J. S. HIDDE and C. T. HERAKOVICH, "Thermal Characterization of Unidirectional Aramid/Epoxy", CCMS-86-08, VPI-86-29 (Virginia Polytechnic Institute and State University, Blacksburg, Virginia, 1987).
14. Data Manual for Kevlar 49 Aramid (du Pont Company, Wilmington, Delaware, 1986).

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