JOURNAL OF MATERIALS SCIENCE 22 (1987) 853–859

Tensile recoil measurement of compressive strength for polymeric high performance fibres

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Recoil forces acting on the broken ends of a fibre after tensile failure are known to cause substantial damage to polymeric high performance fibres. This damage is the result of compressive stresses developed during snap-back, or recoil, whose magnitude exceeds the compressive strength of the fibre. An analysis describing the axial stress history experienced by a fibre following a tensile failure has been performed and the results have led to the development of a simple, single filament, recoil technique for measuring fibre compressive strength. A number of polymeric high performance fibres were examined using the technique and compressive strengths measured are in excellent agreement with values obtained from composite tests.

1. Introduction

A current limitation to the broader usage of composites of highly oriented, polymeric high performance fibres is associated with their inherently low compressive strengths relative to other engineering materials [1]. As a result, a considerable amount of research effort is being expended to understand the factors limiting compressive strength in these high performance fibres as well as in attempting to improve their compressive properties. An often overlooked problem in this field is that of measuring compressive strengths of polymeric high performance materials, many of which are available only as fibres. Presently, bending techniques are employed to estimate fibre compressive strengths and for fibre compressive strength comparisons [2–6]. While such techniques do provide comparisons, fibre compressive strengths obtained are generally much higher (two to three times) than those observed in composites. Single filament composite techniques [7–9] appear to provide better agreement but often require tedious procedures. One is thus left obtaining meaningful compressive strength data from composite tests. This is unfortunate as far as research fibres are concerned where insufficient sample generally prohibits composite fabrication. Obviously, other techniques are desired for obtaining meaningful compressive strengths from single filaments.

Researchers who have been involved with the tensile testing of polymeric high performance fibres have long appreciated that, after tensile failure, the recoil forces acting upon the broken fibre ends cause significant damage to the fibre [4, 10, 11]. Typical tensile recoil damage observed in Kevlar 49 filaments (Du Pont Registered tradename, Delaware) is shown in Fig. 1. This damage is apparently the result of compressive stresses developed during snap-back, or recoil, whose magnitude exceeds the compressive strength of the fibre. The observation of such massive kinking or compressive damage resulting from tensile failure suggests an examination of the stresses in the fibre following tensile failure is warranted.

This work reports on the development of a simple, single filament, recoil technique for measuring fibre compressive strengths. The technique has been used to measure the compressive strengths of a number of polymeric high performance fibres and the results are in excellent agreement with compressive strengths measured in fibre composite tests. Tensile properties of the high modulus, high strength fibres examined are given in Table I. The fibres include: aramids – Kevlar 49, Kevlar 29, Asahi-A5; rigid-rod aromatic heterocyclic polymers – poly-(p-phenylene benzobisthiazole) [12, 13] (PBT), poly-(p-phenylene benzobisoxazole) [14] (PBO); anisotropic melt polyesters – AMP1 and AMP2 based on chloro- and phenylhydroquinones; cellulose triacetate processed from anisotropic solutions [15]; a gel-spun polyethylene sample; and two carbon fibres, "Magnamite" AS4, "Thornel" P-55.

2. Experimental basis

A simplified analysis of the axial stress history experienced by a fibre following tensile failure was carried out to gain insight into the recoil compressive damage observed in polymeric high performance fibres. The equation of motion was solved for the axial stresses in the fibre following a tensile failure. In the analysis it is assumed that the fibre (1) obeys Hooke's law for a linear elastic material, (2) is rigidly clamped at each end of the gauge length, (3) has a zero initial velocity and (4) has an initial uniform tensile stress σ_0 along its length at failure except that the stress is zero at the break location, L. The details of the analysis are given in the appendix. The fibre axial stress history, $\sigma(x, t)$, following tensile failure can be described by the

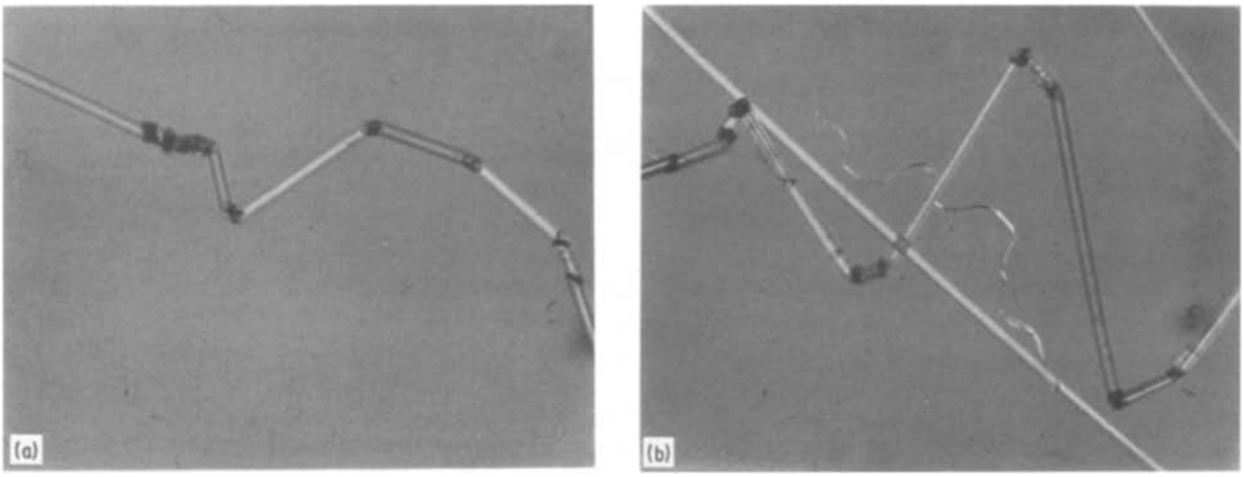

Figure 1 Typical tensile recoil damage observed in Kevlar 49 fibres (fibre diameter 12 μm).

fourier series solution,

$$\frac{\sigma(x, t)}{\sigma_0} = \sum_{m=0}^{\infty} \frac{4}{(2m + 1)\pi} \sin \frac{(2m + 1)\pi}{2} \times \cos \frac{(2m + 1)\pi x}{2L} \cos \frac{(2m + 1)\pi(E/\varrho)^{1/2} t}{2L}$$

where x is the axial fibre coordinate measured from a clamped end; L, the length of the broken fibre end; E, Young's modulus; ϱ, density; t, time and m is an integer number ranging from zero to infinity. Normalized values of the stress, σ/σ_0, were evaluated as a function of axial position and time by simple numerical summation of this expression.

Fig. 2 presents this solution for various times after failure. A zero stress front is found to move from the fractured end toward the clamped end as the initial tensile strain energy is converted to kinetic energy (Figs 2a to c). At a characteristic time after failure (Fig. 2d) the strain energy is completely transformed into kinetic energy and the fibre is effectively being driven at high speed into the clamp. Because the clamp forms a rigid boundary the fibre kinetic energy is transformed back into strain energy (Figs 2e and f) and a compressive stress begins to propagate back down the length of the fibre. If no dampening or damage occurs, this wave continues and with time the axial stress oscillates between a tension and a compression.

TABLE I Typical tensile properties of some high modulus/high strength fibres

Fibre	Modulus (GPa)	Strength (GPa)
Kevlar 49	130	3.4
Kevlar 29	80	3.4
Asahi A5	40	3.4
PBT	275	3.6
PBO	200	3.2
AMP1	75	2.3
AMP2	80	2.6
Cellulose triacetate	25	1.5
Polyethylene	140	2.7
"Magnamite" AS4	235	3.6
"Thornel" P-55	380	2.1

Neglecting dissipation effects, this solution shows that the magnitude of the compressive stress wave generated during recoil is equal in magnitude to (but of opposite sign to) the tensile stress at failure. This being the case, one would expect to observe manifestations of compressive failure in a tensile tested fibre whose compressive strength is lower in magnitude than its tensile strength. This is exactly the observation which motivated this analysis of recoil (recall Fig. 1). Unfortunately, nothing can be said about the number of kinks formed or their spacing as a result of tensile recoil without knowledge of the energy dissipated during compressive failure. The observation of compressive damage occurring as a result of tensile failure does, however, indicate that the fibre compressive strength is lower in magnitude than its tensile strength.

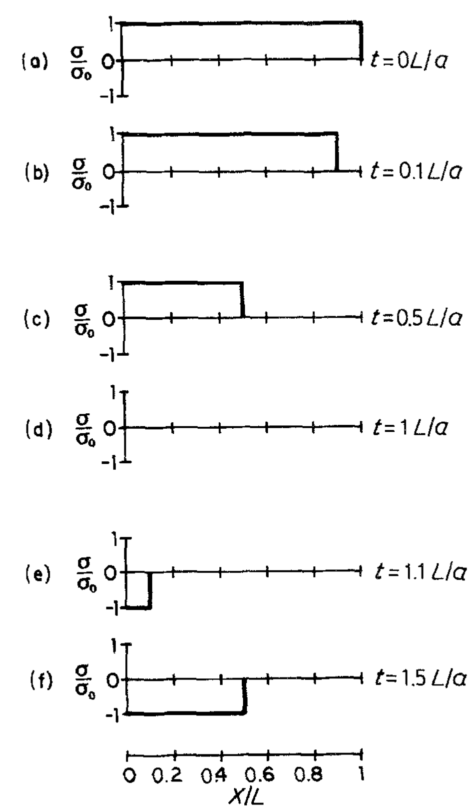

Figure 2 Fibre axial stress history following tensile failure.

3. Technique development

The solution presented above provides a means of obtaining quantitative information regarding the compressive strength of fibres. The magnitude of the compressive stress generated during snap-back or recoil is directly related to the magnitude of the tensile stress at failure. If the tensile failure stress could be selectively reduced below its normal value (i.e., tensile strength), then one could locate a threshold stress value leading to the first observation of recoil compressive damage. If the magnitude of the tensile failure stress were to be reduced below the magnitude of the fibre compressive strength, then no recoil compressive damage should be observed, whereas tensile failure stresses of greater magnitude than the compressive strength would result in the observation of some recoil compressive damage. Wilfong and Zimmerman [10] have previously alluded to this fact now made clearer by the present analysis. By selectively controlling the tensile failure stress, a threshold stress for observation of recoil compressive damage could be determined and hence a measure of fibre compressive strength obtained.

The analysis also indicates that the recoil compressive damage is expected to occur near the clamp in the region of the fibre that first experiences the compressive stress. As compressive damage develops in the fibre the intensity of the compressive stress wave will be diminished and away from the damaged region the stress will not be sufficient to cause further damage. This is consistent with the observations generally made on tensile failed samples that the intensity of kinking (compressive damage) decreases in going from the clamp location to the break location (Fig. 1). Thus in defining a threshold recoil stress sufficient to induce compressive failure in the fibre a small region near the clamp is to be observed for the first evidences of compressive failure.

Kevlar 49 filaments were selected as a model fibre to determine the feasibility of measuring fibre compressive strengths from tensile recoil observations. The compressive strength of this fibre has been widely reported from both composite and filament measurements and its kinking in compression typifies the behaviour of polymeric high performance fibres. In order to reduce the fibre tensile strength below its normal value attempts were made at inducing localized mechanical damage to the centre of the gauge length. Spot etching using sulphuric acid was also tried but both techniques suffered from poor reproducibility owing to difficulties encountered in precisely controlling the reduction in tensile strength.

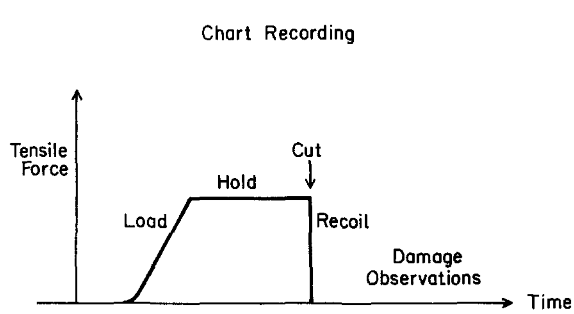

Figure 3 Procedure for tensile recoil testing.

TABLE II Ranked recoil test results (Kevlar 49 filaments, 5.08 cm gauge length)

Stress (MPa)	Observations*
300	N,N
310	N,N
310	N,N
325	N,N
325	N,N
330	N,N
330	K,N
340	N,N
350	N,N
350	N,N
360	N,N
360	N,N
360	N,K
365	K,K
365	N,K
375	N,N
375	K,K
375	K,K
385	K,K
390	K,K
410	K,K
410	K,K

*N designates no compressive damage observed; K designates a kink band was observed.

It was found that stressing the fibre in an Instron to a desired tensile stress and then cutting the centre of the gauge length with very sharp surgical scissors provided better control of failure stress and generated reproducible results. Fig. 3 illustrates the testing procedure. Extreme care is exercised in cutting the filament symmetrically (a scissors mount was constructed to aid in stabilizing the scissors and aligning the cut). Poor cutting practice results in spikes in the force against time recording and such samples were discarded. After the filament is cut, both halves recoil naturally and are then carefully removed from the clamps and a determination is made whether or not compressive damage occurred by examining the filaments near where they were clamped. An observation is made for each half of the cut filament providing two observations per test sample.

Figs 4 to 6 illustrate the appearance of the Kevlar 49 fibres after tensile recoil from various initial tensile loadings. In practice the determination of whether or not compressive damage occurred could be made without the aid of a microscope. For low initial tensile stresses, no recoil damage was observed (Fig. 4). At higher initial stress, compressive damage at the clamped ends could be easily identified (Figs 5, 6 and 1). After performing a number of tensile recoil tests the threshold stress value just sufficient to produce recoil compressive damage was identified from a ranking of the observations as done in Table II. Each table entry is one test sample from which two observations are obtained. The recoil compressive strength is taken as the stress above which compressive damage is observed.

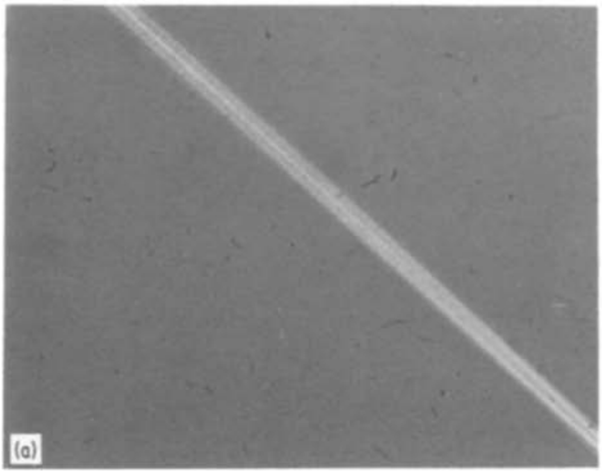
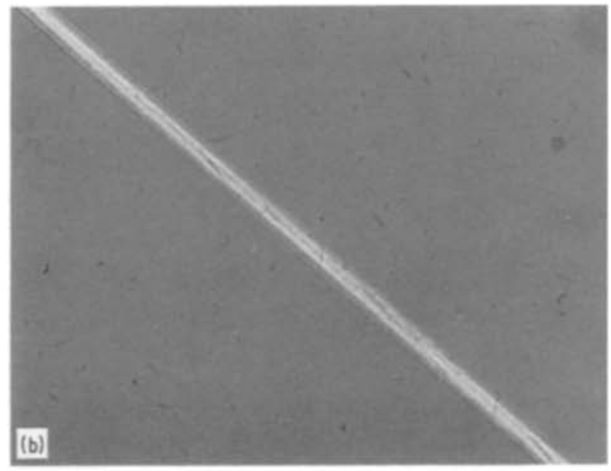

Figure 4 Kevlar 49 fibre appearance near clamp after recoil. Initial tensile stress 350 MPa.

4. Results and discussion

The ranking of the recoil test data in Table II yields a compressive strength of roughly 365 MPa for the Kevlar 49 fibres tested. Compressive strengths measured in elastic loop tests [3, 6, 16] provide values of 740 to 790 MPa. Single filament composite bending tests [8, 9] report values of 620 to 700 MPa for Kevlar 49. Unidirectional composite tests [17, 18] give compressive strengths of 240 to 270 MPa for 60 vol % fibre loading. This translates to a fibre compressive strength of 400 to 450 MPa. The results from tensile recoil measurements are in better agreement with composite data than are the other single filament test methods.

The present interpretation of the recoil test results has assumed that material damping can be neglected. Possible complications due to damping of the stress wave intensity during recoil were addressed by analysis and experiment. An analysis similar to the one presented was performed for a Maxwell solid and the major difference in the resulting solution is the incorporation of an exponential decay term. Other constitutive equations allowing damping are expected to yield comparable decay effects. Dissipation would then be expected to depend on the travel time of the wave, or equivalently on the fibre test length. Assessment of dissipation effects was carried out by performing recoil tests at gauge lengths of 2.54, 5.08 and 7.62 cm. Identical results were found for each test length indicating that damping was not a factor for the Kevlar 49 fibres. In practice, a gauge length of 5.08 cm was found to be most convenient for initial work on new fibre samples.

Material dissipation effects on the stress wave intensity were observed for other fibres tested. In these cases higher recoil compressive strength values were obtained the longer the test length. The compressive strength in these cases was obtained by extrapolation of the data to zero test length as illustrated in Fig. 7 for the Asahi-A5 fibre.

Table III summarizes compressive strengths for various fibres obtained from single filament recoil tests. It should be noted that in the case of the carbon fibre recoil tests the compressive failure criterion was not the observation of kink band formation but rather of a brittle failure. At loadings just greater than the critical recoil compressive strength two half-gauge length pieces of fibre could be observed floating away from the clamps. A minor limitation to general applicability of the technique is that the fibre of interest should fail brittlely or by a kinking or microbuckling mechanism to permit easy identification of compressive failure. For example, nylon fibres tested

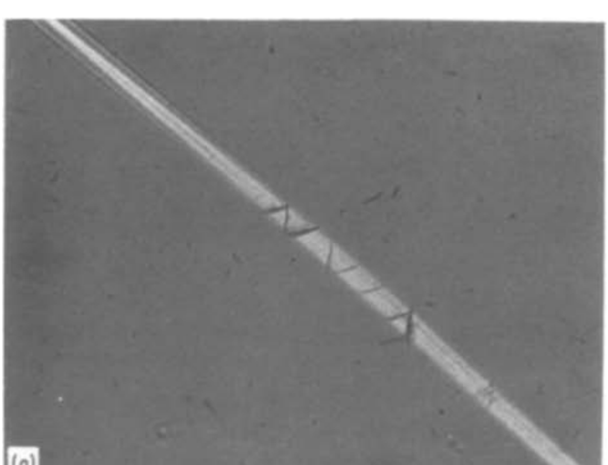
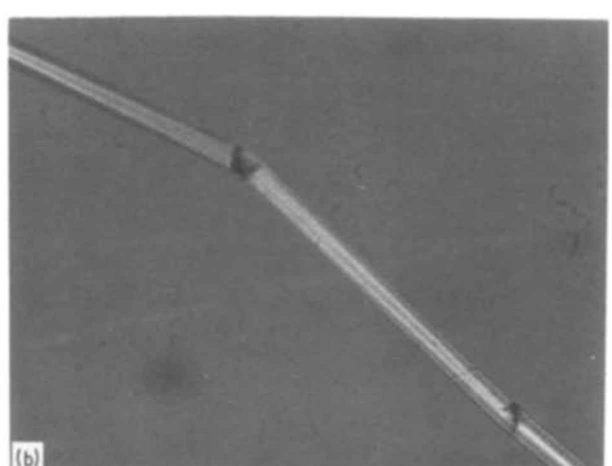

Figure 5 As Fig. 4, initial tensile stress 400 MPa.

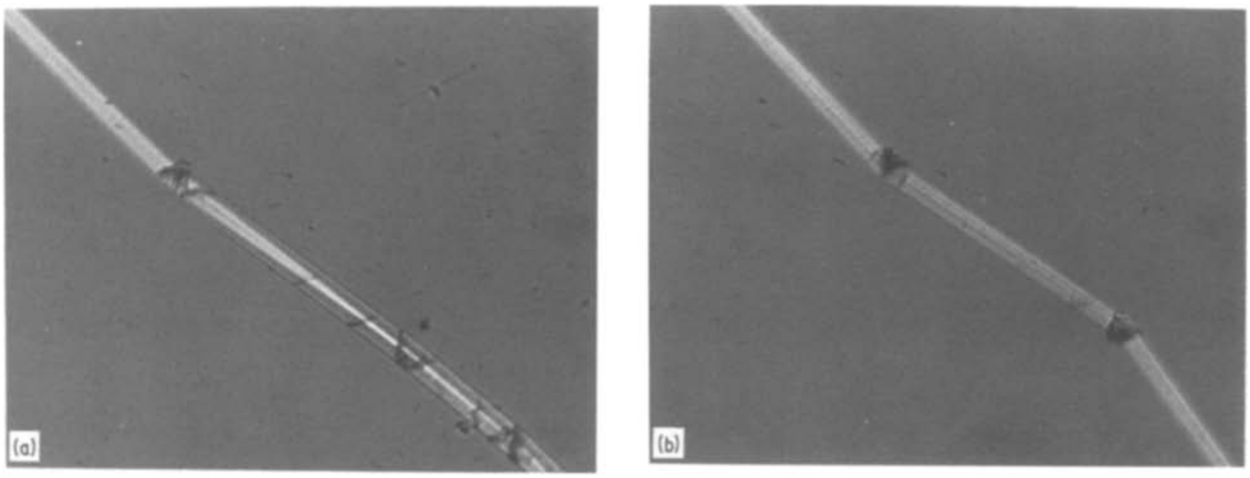

Figure 6 As Fig. 4, initial tensile stress 450 MPa.

showed evidence of plastic deformation (waves instead of kinks) in compression and a compressive strength could not be easily identified. If a suitable method of detection of plastic deformation (change in birefringence, for example) were employed, then these recoil tests could also provide a measure of compressive strength for materials which do not kink. In general, however, polymeric high performance fibres whose compressive strength would be of interest for composite applications do exhibit kinking as a result of compressive failure and hence their compressive strengths may be easily obtained in recoil tests.

Table IV compares recoil test results with available composite and elastic loop data. While elastic loop tests generally provide reliable comparisons between fibres, compressive strengths calculated from loop data are as much as 3 times higher than fibre composite compressive strengths. Compressive strengths of the polymeric high performance fibres obtained from recoil tests are, however, in quite good agreement with the composite data as shown in Table IV.

The recoil compressive strengths measured for the carbon fibres agree reasonably well with lower reported values from composite tests. However, fibre strength values of up to twice the recoil values have been obtained (Table IV) from composite tests. This may indicate an influence of the matrix resulting from a greater refinement of composite fabrication requirements for carbon fibres than for the polymeric fibres. Further refinement of the recoil technique and interpretation of its results should aid in evaluating this possibility.

TABLE III Recoil compressive strengths (RCS)

Fibre	RCS ($g\,denier^{-1}$)	Density ($g\,cm^{-3}$)	RCS (MPa)
Kevlar 49	2.9	1.44	365
Kevlar 29	2.9	1.44	365
Asahi-A5	2.8	1.44	350
AMP1	1.7	1.48	220
AMP2	1.5	1.38	180
PBT	2.0	1.57	275
PBO	1.5	1.56	200
Cellulose triacetate	1.5	1.30	170
Polyethylene	0.85	0.985	70
"Magnamite" AS4	9.1	1.80	1440
"Thornel" P-55	2.6	2.00	400

TABLE IV Comparison of recoil, composite and loop data

	Fibre compressive strength (MPa)		
Fibre	Recoil	Composite*	Loop
Kevlar 49	365	400–450 [17, 18]	740–790 [3, 6, 16]
Kevlar 29	350	400	
PBT	270	340 [19]	680 [16]
PBO	200	200	680
AMP2	180	230	
Cellulose triacetate	170	170	
PE	70	40–50†	

*Composite strength/fibre volume fraction.
†From direct axial compression of oriented PE [20, 21].

Acknowledgment
The author wishes to acknowledge many fruitful discussions with Professor Richard J. Farris which led to this work.

Appendix
Recoil analysis
Combining the equation of motion with Hooke's law for a consideration of axial fibre stresses yields the standard wave equation,

$$\frac{\partial^2 u}{\partial t^2} = a^2 \frac{\partial^2 u}{\partial x^2} \quad \text{(A1)}$$

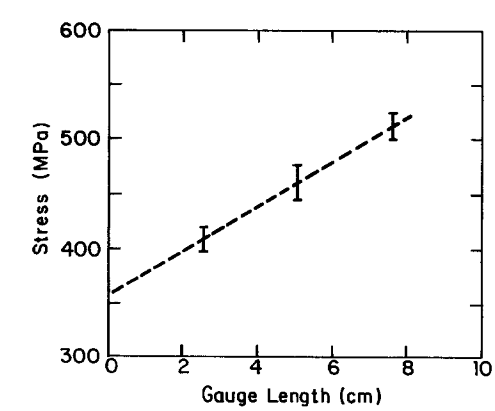

Figure 7 Observed recoil compressive strength against gauge length for Asahi-A5 fibre.

where u describes the axial displacements, t time, x the fibre direction with $x = 0$ taken at a rigidly clamped end, and $a^2 = E/\varrho$ where E is Young's modulus and, ϱ density. Using a separation of variables approach, a solution is given by

$$u(x, t) = (A1 \sin \lambda at + B1 \cos \lambda at) \times (A2 \sin \lambda x + B2 \cos \lambda x) \quad \text{(A2)}$$

where λ is the separation constant and $A1$, $A2$, $B1$ and $B2$ are constants to be evaluated from initial and boundary conditions (BC).

Boundary condition 1: Fixed end

At $x = 0$ we maintain that $u(0, t) = 0$, from which $B2 = 0$.

Boundary condition 2: Zero initial velocity

We take the initial velocity of the fibre as being equal to zero, i.e.,

$$\frac{\partial u(x, 0)}{\partial t} = 0. \quad \text{(A3)}$$

This is satisfied by having $A1 = 0$, and the governing equation reduces to

$$u(x, t) = B \sin \lambda x \cos \lambda at \quad \text{(A4)}$$

Boundary condition 3: Zero stress at fracture location

We take $\sigma(L, t) = 0$ where L is the axial location of fracture. Equivalently, from Hooke's law we take

$$\frac{\partial u(L, t)}{\partial x} = 0 \quad \text{(A5)}$$

which gives

$$B\lambda \cos \lambda L = 0.$$

Trivial solutions are obtained for either $B = 0$ or $\lambda = 0$. Solutions are also given by

$$\lambda = \frac{(2m + 1)\pi}{2L}, \qquad m = 0, 1, 2, 3, \ldots \quad \text{(A6)}$$

The governing equation becomes

$$u(x, t) = B \sin \frac{(2m + 1)\pi x}{2L} \cos \frac{(2m + 1)\pi at}{2L} \quad \text{(A7)}$$

again for $m = 0, 1, 2, 3, \ldots$

Boundary condition 4: Initial displacement

The initial displacements for a tensile elongation are given by

$$u(x, 0) = \varepsilon_0 x \quad \text{(A8)}$$

where ε_0 is the initial tensile strain. In order to solve for the remaining constant B, we must superpose the solutions for all values of m, i.e.,

$$u(x, t) = \sum_{m=0}^{\infty} B_m \sin \frac{(2m + 1)\pi x}{2L} \cos \frac{(2m + 1)\pi at}{2L} \quad \text{(A9)}$$

The initial displacements are then given by

$$u(x, 0) = \varepsilon_0 x = \sum_{m=0}^{\infty} B_m \sin \frac{(2m + 1)\pi x}{2L} \quad \text{(A10)}$$

From fourier series theory B_m values are obtained from

$$B_m = \frac{2}{L} \int_0^L \varepsilon_0 x \sin \frac{(2m + 1)\pi x}{2L} \, dx, \quad \text{(A11)}$$

which yields

$$B_m = \frac{8\varepsilon_0 L}{(2m + 1)^2 \pi^2} \sin \frac{(2m + 1)\pi}{2}, \quad \text{(A12)}$$

$$m = 0, 1, 2, 3, \ldots$$

The governing equation for displacements is thus given in final form as

$$u(x, t) = \sum_{m=0}^{\infty} \frac{8\varepsilon_0 L}{(2m + 1)^2 \pi^2} \sin \frac{(2m + 1)\pi}{2} \times \sin \frac{(2m + 1)\pi x}{2L} \cos \frac{(2m + 1)\pi at}{2L} \quad \text{(A13)}$$

The axial stress is then obtained from Hooke's law

$$\sigma(x, t) = E \frac{\partial u(x, t)}{\partial x} \quad \text{(A14)}$$

which gives

$$\frac{\sigma(x, t)}{\sigma_0} = \sum_{m=0}^{\infty} \frac{4}{(2m + 1)\pi} \sin \frac{(2m + 1)\pi}{2} \times \cos \frac{(2m + 1)\pi x}{2L} \cos \frac{(2m + 1)\pi at}{2L} \quad \text{(A15)}$$

where $\sigma_0 = E\varepsilon_0$ is the initial or failure stress.

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Received 4 April
and accepted 30 June 1986