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Compressive and torsional behaviour of Kevlar 49 fibre

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The mechanical anisotropy of an aromatic polyamide fibre, Kevlar 49, was studied in tension, compression and torsion. A new technique involved applying small and defined compressive strains to filaments by bonding them to one side of a beam which is subsequently bent to compress the fibres. Using scanning electron and optical microscopy, fibres were shown to form regularly-spaced helical kink bands at 50 to 60° to the fibre axis after the application of small axial compressive strains. Tensile tests of previously-compressed fibres revealed only a 10% loss in tensile strength, after application of as much as 3% compressive strain. A torsion pendulum apparatus was used to measure the shear modulus and an apparent shear strength of fibres. A loss of tensile strength after the application of large (> 10%) torsional shear strains coincided with a loss in recoverable shear strain due to longitudinal fibre splitting. Ratios of tensile-to-compressive strength, tensile-to-shear strength and tensile-to-shear moduli of 5:1, 17:1, and 70:1, respectively, were measured for Kevlar 49.

1. Introduction

Reinforcing fibres based on aromatic polyamides (aramids) consist of highly oriented and therefore highly anisotropic structures. Consequently such fibres are expected to exhibit anisotropy in their mechanical behaviour. To predict the performance of composites reinforced with anisotropic filaments it is necessary to consider the fibre elastic constants and strengths along all three material axes. In this study the results of an investigation of the behaviour of an aramid fibre under axial compression and torsion are presented.

The high modulus aramid fibres manufactured by E. I. DuPont de Nemours and Co. under the name Kevlar have been used widely in composites and as cables and fabrics for aerospace, industrial and consumer applications. Kevlar fibres are based on highly oriented rigid chains of poly(*p*-phenylene terephthalamide) (PPTA) and exhibit tensile moduli and strengths comparable to high performance metal, glass and carbon fibres. Although the substantial tensile properties along the fibre axis have been well characterized, relatively little information concerning the response of these aramid fibres to other states of stress or strain is available.

We have restricted our attention in this work to Kevlar 49 fibres because they exhibit the highest orientation and tensile modulus, and therefore presumably the largest degree of anisotropy among the Kevlar family of commercial fibres.

In this study we seek to contribute further to understanding the compressive behaviour of Kevlar by studying the fibre under "uniform" axial compression. Uniform compression of fine filaments is achieved with techniques that involve compression or shrinkage of a matrix containing the aligned fibres. We also introduce a new method which allows the application of small and known compressive strains to fibres by bonding them to the compression side of an elastic beam.

In preliminary publications [1, 2] we reported on the formation of kinks in Kevlar 49 fibres subjected to uniform compression due to matrix shrinkage. The results included information on the tensile properties of compressed Kevlar fibres. With this paper we present a more detailed study of the kink phenomenon with emphasis on the

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consequent effect on the tensile behaviour of uniformly compressed Kevlar 49 fibres.

Due to the minute lateral dimensions of high modulus fibres (diameter ~ 10 μm), determination of the elastic constants and material strengths is difficult in directions other than along the fibre axis. However a shear modulus and an apparent shear strength can be obtained from simple torsion tests. Although the shear strains in a fibre under torsion are radially distributed from a maximum at the surface to zero at the core, the test provides a reasonable measure of some of the shear properties of fibrous materials [3]. Indeed torsional rigidities of textile fibres are frequently measured and and as a result a number of torsion test methods have been developed (see, for instance, [3, 4]). We have constructed a simple torsion pendulum apparatus to characterize Kevlar 49. As in our compression studies, we complete this work by examining the effect of torsion on the tensile properties of the Kevlar fibre. To our knowledge, this is the first time any information on the torsional properties of Kevlar 49 has been reported.

2. Background

Previous studies of the compressive behaviour of Kevlar fibres had been undertaken to explain the limited axial compressive strength of Kevlar-reinforced composites [5, 6]. Although the tensile properties of unidirectional aramid composites compare favourably with carbon and glass fibre-reinforced materials, the axial compressive strength of Kevlar composites is known to be significantly less than the compressive strengths of glass and carbon composites [7–9]. Typical fibre composite properties are listed in Table I. The compressive stress–strain curve for unidirectional Kevlar–epoxy composites has been shown to exhibit elastic–plastic behaviour with yield at approximately 0.3% compressive strain [9, 10].

The first attempt to characterize the compressive properties of Kevlar fibres themselves was reported by Greenwood and Rose [5]. By measuring the geometry of the elastica they were able to determine that the fibres apparently yielded at bending strains of about 0.7%. The apparent plasticity corresponded to the formation of kink bands at oblique angles to the fibre axis on the compressive side of the bent fibre. Because most polymer matrices have elastic limits in compression greater than 0.7%, it was concluded that the low compressive strength of Kevlar composites can be attributed to the poor compressive strength of the fibres and not to either the matrix or the fibre–matrix interface.

TABLE I Unidirectional composite lamina properties of fibre-reinforced epoxy [7]

Axial property	Reinforcement		
	Kevlar 49	E-Glass	Graphite
Tensile strength (GPa)	1.38	1.10	1.24
Compressive strength (MPa)	276	586	1100
Tensile and compressive moduli (GPa)	75.8	39.3	131
Tensile to compressive strength ratio	5	1.9	1.1
In-plane shear modulus (GPa)	2.07	3.45	4.83
In-plane shear strength (MPa)	44.1	62.0	62.0
Interlaminar shear strength (MPa)	48–69	83	97

The formation of the kink bands in Kevlar fibres subjected to compressive strains in bending has been well documented [6, 8, 11, 12]. Similar band formation has also been seen in fibres extracted from axially compressed unidirectional composites [6, 8].

The morphology of compressive kink bands in Kevlar fibres has been investigated using scanning and transmission electron microscopy by Dobb and co-workers [6]. Fibres were compressed by bending techniques and by the compression of a Kevlar composite. Some of their results and conclusions that are pertinent to this study are:

1. Deviation from elastic behaviour with accompanying kink band formation occurred at ~ 0.5% bending strain in the elastica test.

2. Kinks were observed to unfold under tension indicating that the kink boundary acts somewhat like a hinge.

3. Flexural fatiguing at an apparent bending strain of 2% resulted in a loss in tensile strength of $\leqslant$20%.

4. The tensile fracture morphology of previously compressed fibres was a surface plane oriented at 45° to the fibre axis.

In this study, every technique for applying a uniform compressive strain to fibres has in common a surrounding matrix that supports the fibre against Euler buckling instabilities and at the same

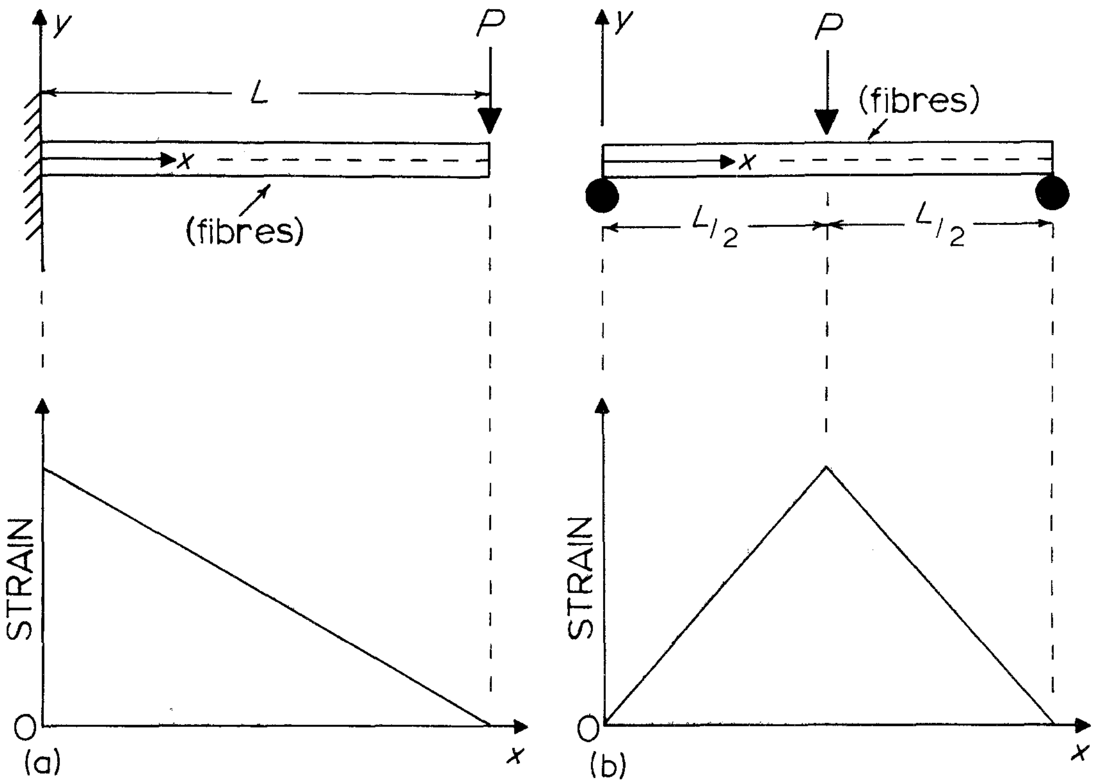


Figure 1 Longitudinally distributed axial strains of elastic beams loaded in (a) cantilever and (b) three-point bending.

time transmits the compressive loads to the fibre. Compression of the fibres embedded in a matrix has previously been used to study the axial compression fracture of carbon fibres [13], the buckling modes of synthetic fibres [14, 15] and the buckling of model systems for collagen fibres [15]. In these prior studies fibre compression was achieved by the mechanical compression of the matrix parallel to the fibre axis [13], by differential thermal shrinkage [14, 15], by matrix contraction during solvent casting [2, 16] or by shrinkage of a matrix polymerized around the fibres [16].

3. Experimental details

3.1. Compression

In this work we introduce a new method for applying known and uniform compressive strains to fine filaments. The technique involves bonding fibres to the compressive side of an elastic rectangular beam and orienting them parallel to the beam length. On subjecting the beam with bonded fibres to either three-point or cantilever bending, tensile and compressive strain distributions are set up which vary linearly along the length of the beam as shown in Fig. 1. In this manner the compressive strain to kink formation can be determined from the equations of elastic beam theory.

Filaments of Kevlar 49 (diameter = 12.2 μm) were separated from a 380 denier yarn. The fibres had no sizing or finish and were used in all tests without any special pretreatment.

To prepare test specimens, single Kevlar fibres were first aligned with ends taped to one side of a clear polycarbonate tensile bar which had been milled down to a uniform cross-section of 1/8" x 1/2". By hanging a 0.5 g weight from one end of the fibre it could be affixed to the bar under a calculated tensile pre-strain of 0.03%. The fibres were then bonded to the polycarbonate by applying several layers of a clear acrylic spary (Krylon® Acrylic Spray Coating, Borden, Inc.) until well coated. After allowing 24 h for the film to dry, the bars with bonded fibres were loaded in three-point bending in an Instron to a maximum strain on the beam surface of 1.0% at the load point. To minimize stress relaxation of both the polycarbonate bar and acrylic film, the specimens were unloaded immediately after reaching the maximum deflection. After a single loading the bars were removed from the Instron and the fibres examined for kink formation. The advantage of bonding fibres to a

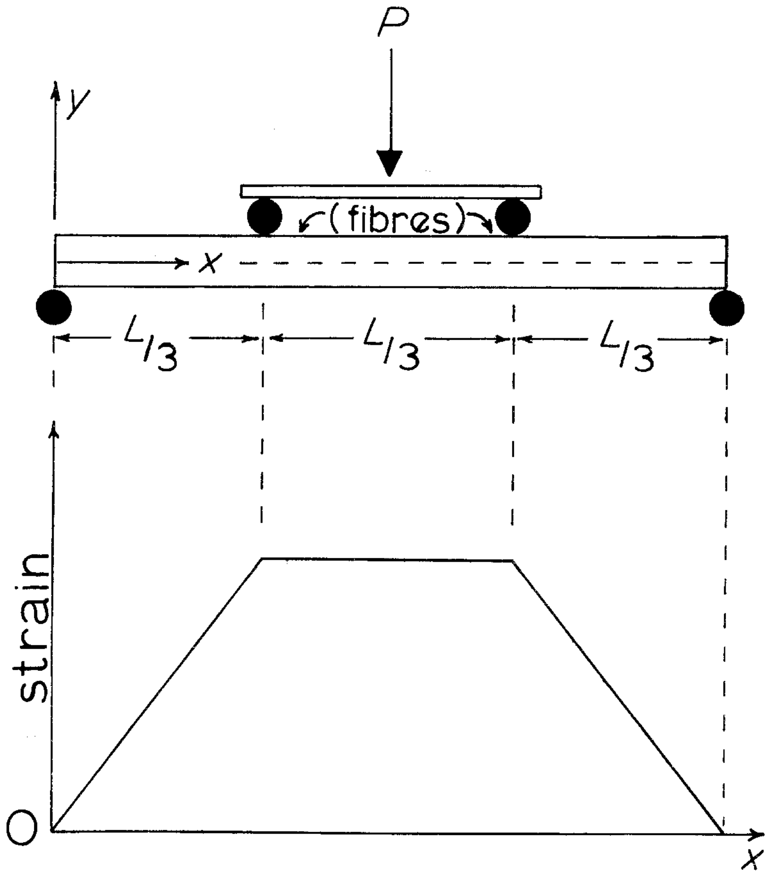


Figure 2 Longitudinally distributed axial strains of elastic beam loaded in four-point bending.

transparent polycarbonate bar with a clear acrylic spray is that they can be observed directly after loading under an optical microscope.

It is recognized that the strain in the bent beam also varies through the beam thickness from zero at the neutral axis to a maximum on the outer surfaces. However, the relative thickness of beam to fibre is so large (250:1) that the variation in strain across the fibre diameter can be neglected.

A matrix shirinkage technique was used to obtain fibres in a compressed state for scanning electron microscopy (SEM) studies and tensile tests. The details of this method have been reported [1, 2]. With this method the fibres are compressed by solvent casting a nylon-6 film about single Kevlar 49 filaments which are held aligned under a known tensile strain (0.03%) on a glass plate. Using a 10 wt % solution of nylon-6 in formic acid, a film shrinkage along the fibre axis of 2 to 3% was measured. Because the nylon film is easily dissolved with formic acid, fibres in the compressed state could be recovered over a filter.

Compressed fibres were carefully mounted onto cardboard tabs with epoxy and tensile tested at an initial gauge length of 50 mm and a crosshead rate of 0.1 cm min^{-1}. Each fibre sample was loaded twice. Fibres were first loaded to ~75% of the anticipated breaking strength and after immediate unloading, were reloaded to fracture. Samples of compressed fibres before and after tensile testing were examined in the scanning electron microscope.

The effect of axial compressive fatigue on the tensile strength of Kevlar fibres was investigated using a variation of the elastic beam compression technique. By bonding fibres to the compressive side of a beam which is then loaded in four-point bending, the length of fibre between the two loading points is subjected to a constant compressive strain. This constant strain region is shown schematically in Fig. 2.

Single filaments of Kevlar 49 were bonded under a known tensile pre-strain to milled tensile bars as already outlined. However for these tests glass-filled polyphenylene oxide/polystyrene blend tensile bars were used in place of polycarbonate bars in the attempt to minimize stress-relaxation and stress cracking of the bar during fatigue bend-

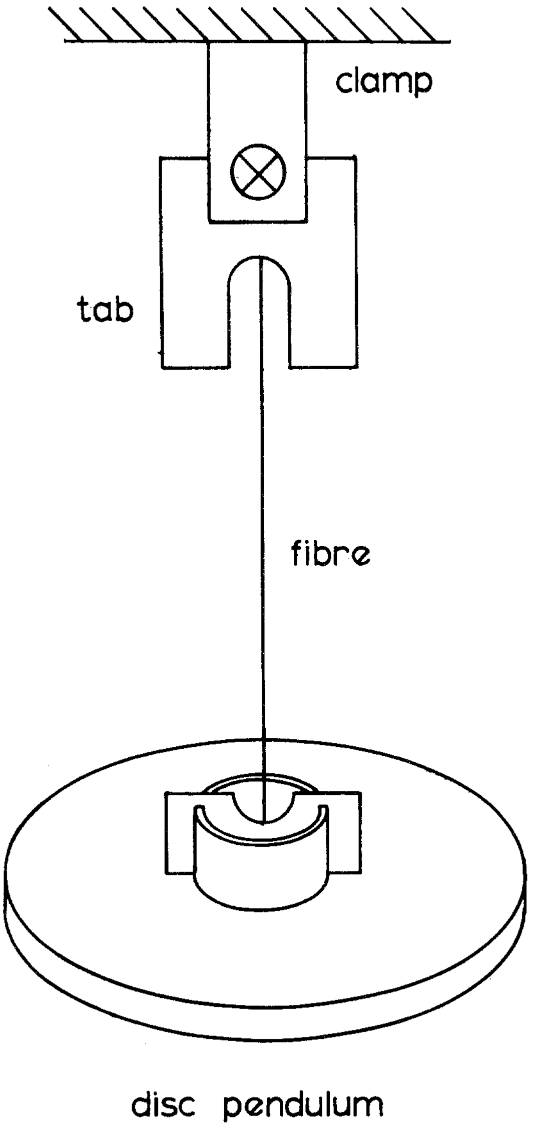


Figure 3 Schematic diagram of torsional pendulum apparatus.

ing. Fibres were loaded in compression between a minimum strain of 0.1% and maximum strain of 0.4, 0.8 or 1.2% for 1, 10, and 100 cycles. After loading, the fibres were recovered for SEM observations and tensile testing by soaking the bars in acetone to dissolve the acrylic film.

3.2 Torsion

The torsion pendulum apparatus used in these studies is similar to the one used by Gloor [17] and is schematically illustrated in Fig. 3. Fibre samples for these tests were prepared in the same manner as for the tensile tests by bonding single filaments to cardboard tabs at a gauge length of 20 mm. One end of the fibre was then clamped in a fixed grip and the other carefully centred in a slotted disc pendulum as shown in the figure. The sides of the cardboard tab were then cut away to free the fibre and disc. Two different pendulum discs were employed having moments of intertia (including the minor contribution from the cardboard tab) of 115 and 56 g mm^2. The entire apparatus was then covered with a bell jar to eliminate air currents.

The experiment consisted of imposing a 180 degree twist (maximum shear strain = 0.1%) to the free fibre end and then allowing the fibre/disc system to rotate freely. The period of oscillation of the resulting motion was then measured with a stopwatch by following the motion of a reference mark on the disc relative to a similar mark on a stationary platform mounted below the disc.

The behaviour of Kevlar 49 under large torsional shear strains was investigated using an apparatus similar to the one used for torsional moduli measurements. In these experiments large strains were imposed on the fibre sample by twisting the pendulum. The elastic component of this applied shear strain was then determined from the amount of unwinding or recoverable strain.

The effect of pre-twisting on the subsequent tensile strength of Kevlar 49 fibres was investigated. To perform these experiments, mounted fibres were twisted as just described and while maintaining the twist, were placed in an Instron for tensile testing. All samples were loaded to failure.

3.3. Instrumentation

Fibre samples were examined in an ETEC Autoscan Scanning Electron Microscope (SEM) after coating with ~20.0 nm thick layer of gold in a Polaron E5100 SEM sputtering unit. For tensile tests, all fibres were mounted on cardboard tabs with epoxy and tested in an Instron Universal Testing Machine. A small Zeiss optical microscope with polarizers was used to observe fibres embedded in matrices.

4. Results

4.1. Compression

A schematic diagram of a compressed Kevlar fibre bonded to a polycarbonate bar which had been previously loaded in three-point bending is shown in Fig. 4. Because maximum compressive strains occur at the bar midpoint (i.e. the point of load application), it is the length of the fibre in this

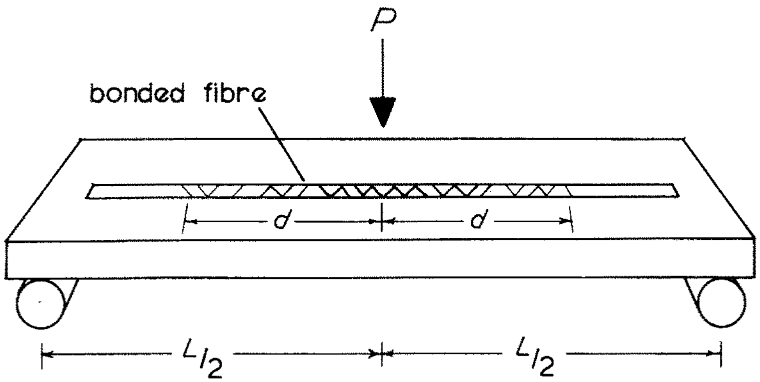


Figure 4 Schematic diagram of compressed Kevlar 49 fibre bonded to beam which had previously been loaded in three-point bending.

section of the bar which exhibits kink banding. The bands appear fainter and less frequently at distances along the fibre away from the load point. At some point along the fibre length no kinks are observed. The distance, d, along the fibre from load point to this region where the fibre appears free from kinks was recorded. By assuming good bonding of the acrylic film to the polycarbonate bar, the strain in the fibre should be equal to the surface strain of the bar at the same point. Therefore the strain in the fibre at a distance d from the load point can be readily calculated using elastic beam theory. This calculated strain to visible kink formation is defined as the critical compressive strain.

To determine the critical compressive strain for kink formation, ϵ_c, in Kevlar 49, it was then assumed that the polycarbonate bar and acrylic film behave elastically at least up to a maximum bending strain of 1%. Then the strain on the surface of the beam in three-point bending varies linearly from a maximum at the load point to zero at each of the supports (see Fig. 1). Therefore, between the load point and each of the supports, the beam strain is directly proportional to the distance away from the supports. Critical fibre compressive strains could then be calculated using Equation 1.

$$\epsilon_c = \left(1 - \frac{d}{L/2}\right) \epsilon_m \tag{1}$$

where ϵ_m is the maximum beam strain at load point, L is the beam length between supports, and d is the distance from the beam centre to where the last fibre kink band was observed.

After subtracting the fibre tensile pre-strain, a critical compressive strain of 0.53% (±0.02%) was calculated for ten fibre samples. The compressive fibre kink bands appear as black, V-shaped bands when viewed under an optical microscope. An optical micrograph which shows these kink bands for a compressed Kevlar fibre embedded in a matrix is shown in Fig. 5. It should be emphasized that the bonded fibres were examined after compression in the unloaded state. The kink bands were seen in the fibre after unloading the bar indicating that either slip occurred at the fibre–matrix interface and/or that permanent deformation occurs in the fibre at the kink boundary.

Some of the bars were loaded more than once to the 1% maximum strain. After repeated loadings no change was observed in d and therefore ϵ_c. However, in the length of fibre which was subjected to compressive strains greater than ϵ_c, the kink bands appeared to increase in both number and severity with repeated loadings.

An axial compressive strength for Kevlar 49 of ~0.7 GPa is calculated from the product of ϵ_c and the axial compressive modulus. For this calculation it is assumed that the fibre is linear elastic to ϵ_c and that the axial tensile and compressive moduli are identical and equal to 130 GPa. That the moduli are equivalent is demonstrated indirectly by the measured equivalent tensile and compressive moduli of Kevlar composites [7] and by the elastica test in which Kevlar fibre conforms to the loop geometry predicted for linearly elastic materials [5].

The surface morphology of as-received fibres and fibres that were compressed during solvent casting of a surrounding nylon matrix is illustrated in Fig. 6. After a ~3% compressive strain the fibres have apparently yielded with the formation of helical kink bands having a pitch angle of 50 to 60° (Fig. 6b). Both left- and right-handed helices are observed which propagate for various distances along the fibre axis. These helical bands correspond to the V-shaped bands observed for a com-

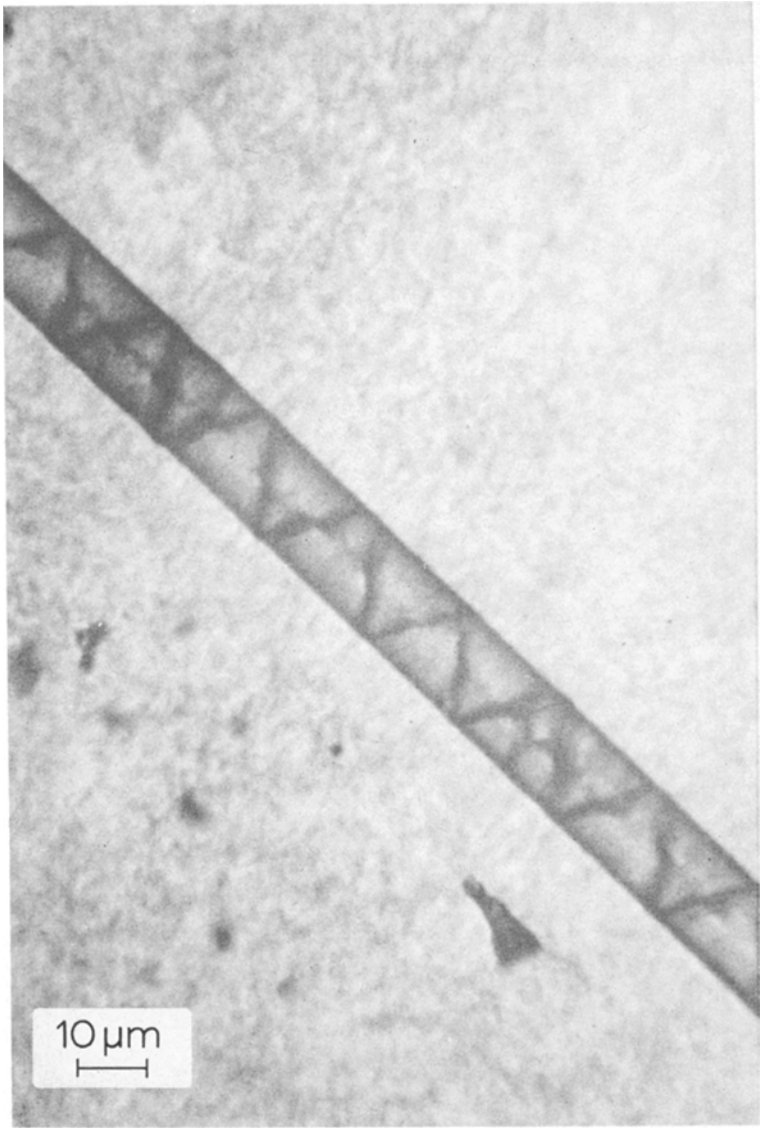
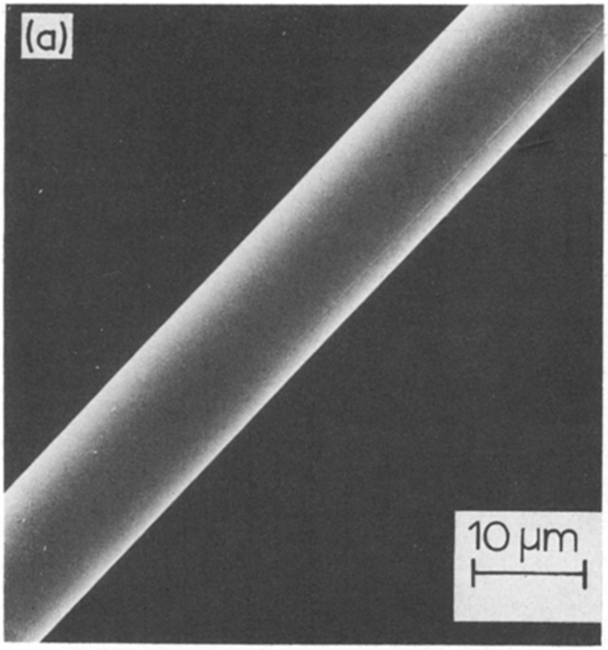


Figure 5 Optical micrograph of compressed Kevlar 49 fibre embedded in matrix.

pressed fibre using light microscopy. At slightly higher compressive strains the bands become sharper and more numerous as shown in Fig. 6c. At this level of compression there are lateral shifts of fibre segments, similar to slip bands observed in metals. It also appears that fibre material piles up at the kink boundaries with no evident change in the surface texture between the bands. None of the compressed fibres gave any indication of surface cracking or splitting within the limits of SEM resolution. Interestingly, the single Kevlar fibres could sustain compressive strains of up to 3% without exhibiting the sinusoidal microbuckling instabilities normally associated with fibre-reinforced composite compressive failure [8].

Fibres recovered from the solvent cast matrix are in a permanently compressed state in the sense that the kink bands remain after removal of the matrix-induced compression load. The tensile behaviour of such compressed fibres is illustrated in Fig. 7. The dramatic change in the shape of the stress–strain curve from that of the as-received Kevlar 49 fibre is seen with initial tensile loading. The fibre extends at a near constant and low stress to approximately 2% elongation. With further extension there is a large upturn in the curve as the apparent fibre modulus increases. After removing the tensile load, the fibres had attained a new unloaded gauge length which was 2.0 ± 0.5% greater than the initial 50 mm gauge length. SEM micro-



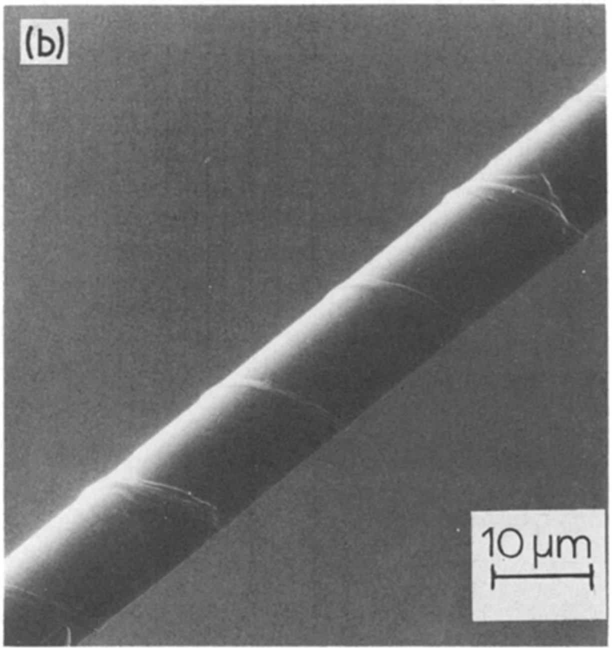


Figure 6 SEM micrographs of Kevlar 49 fibre; (a) as-received; (b) after ~ 2% compression and (c) after > 3% compression due to nylon matrix shrinkage.

graphs of previously kinked fibres after the first tensile loading are shown in Fig. 8. These pictures reveal that the kinks have unfolded, appearing only as stretch marks or depressions on the fibre surface.

Upon reloading the fibres to break, the measured tensile stress–strain curve is almost indistinguishable from the curve of the as-received fibre as shown in Fig. 7. The tensile properties of compressed and as-received Kevlar fibres are summarized in Table II. Surprisingly, the only effect of prior compressive kinking is a small loss in tensile strength.

The tensile fracture surface of a previously compressed fibre loaded in tension to failure is given in Fig. 9. The topology is identical to the longitudinal splitting observed for the as-received fibres also fractured in tension [18]. Examination

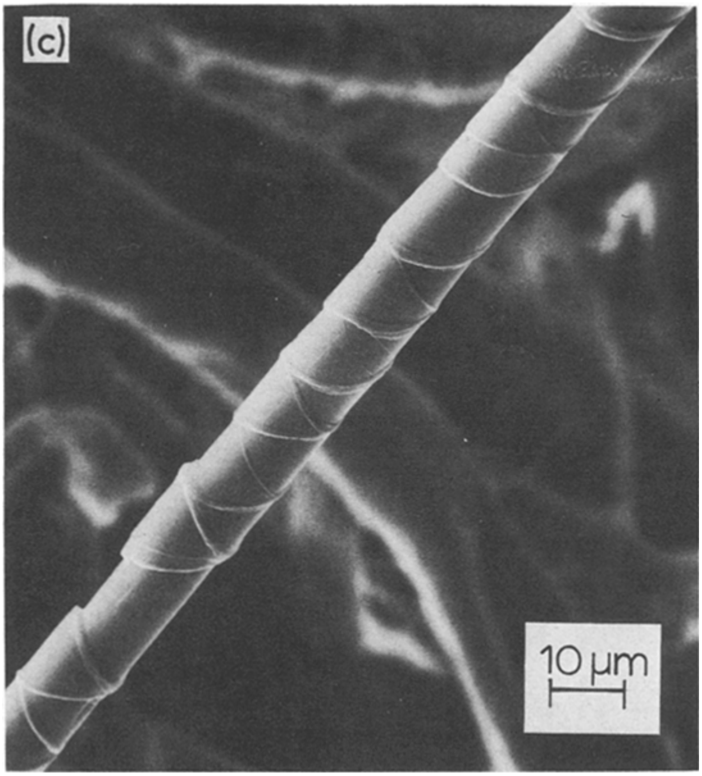


Figure 6 Continued.

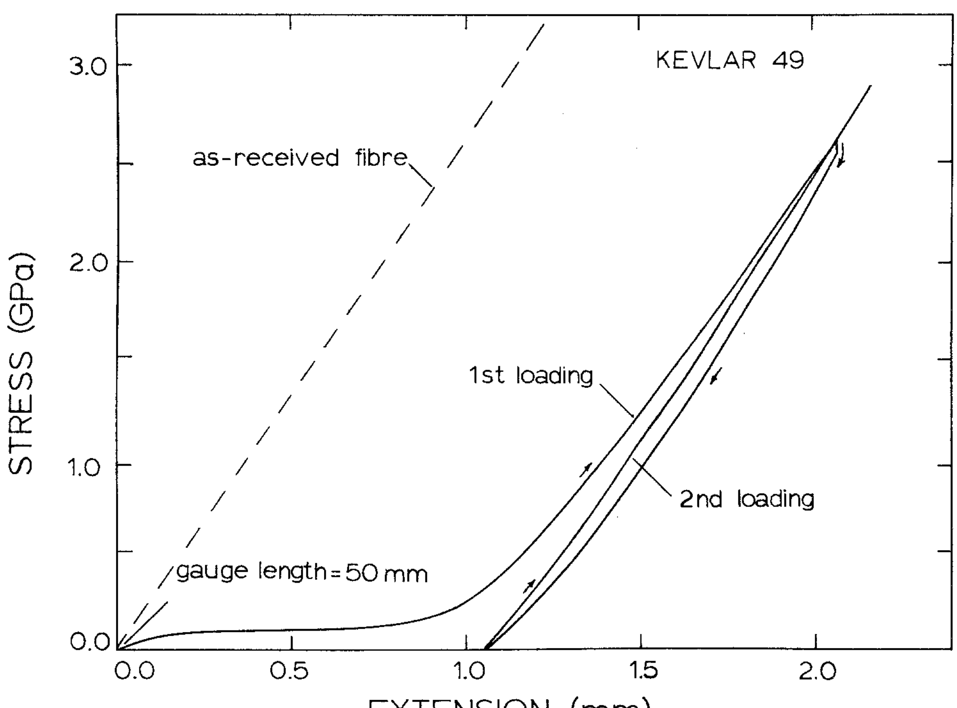


Figure 7 Tensile stress–elongation curve of Kevlar 49 fibre previously compressed ~ 3% due to matrix shrinkage.

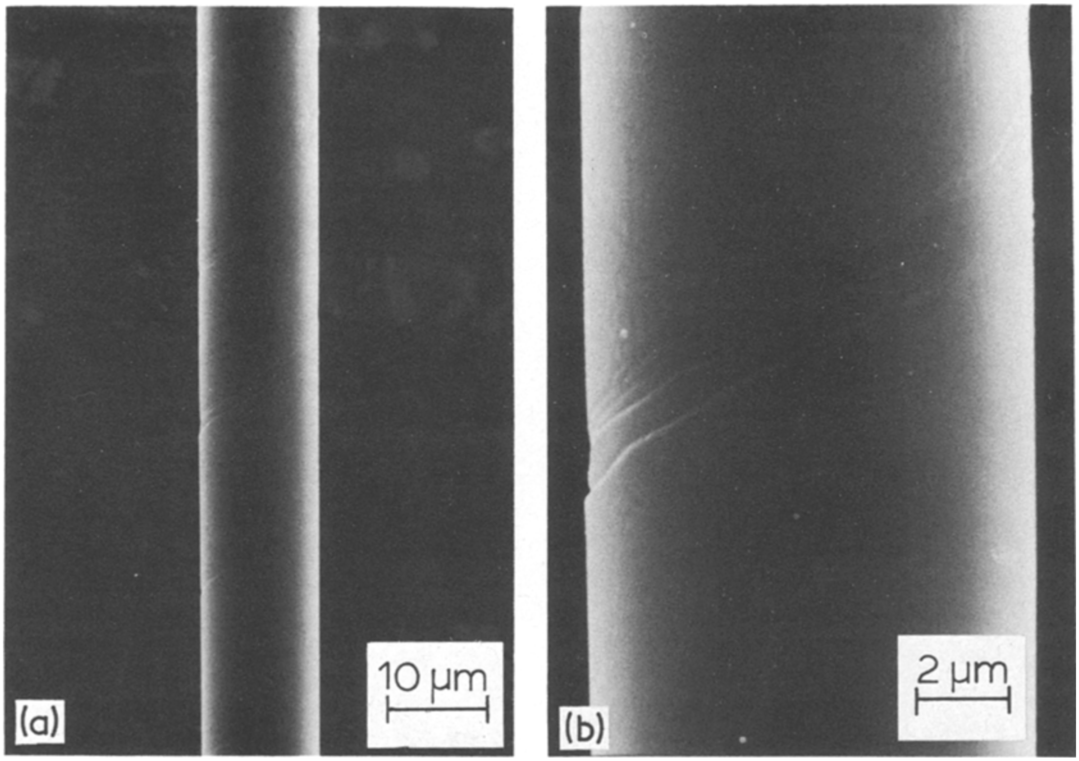


Figure 8 SEM micrographs of previously kinked Kevlar 49 fibres after loading in tension to ~ 75% of break strength: (a) mag 1000X; (b) same region at 5000X mag.

of the fibres at high magnifications gave no indication that failure initiated from a kinked region.

Further proof that the recoverable tensile properties of Kevlar fibres are relatively insensitive to axial compression is the small measured loss in tensile strengths of fibres subjected to compressive fatigue using the four-point beam bending technique. The tensile strengths of these fibres are listed in Table III showing that even after 100 cycles to 1.2% compressive strain there is only a 10% loss in strength. Faint helical kink bands were observed only on isolated fibres which had been compressed to maximum strains of 0.8% and 1.2%.

TABLE II Effect of 2 to 3% axial compressive strain on tensile properties of Kevlar 49

Fibre history	Tensile modulus (GPa)	Elongation at break (%)	Tensile strength (GPa)
As-received	130	2.5	3.4
Compressed* 2–3%	130	2.5	3.1

*Taken from 2nd loading curve. Values represent average of 8 samples tested.

4.2. Torsion

The torsional shear modulus, G, is determined from the dynamic oscillation of a torsional pendulum using Equation 2

$$G = \frac{8\pi LI}{r^4\tau^2} \qquad (2)$$

where L is the fibre gauge length, r is the fibre radius, I is the moment of inertia of disc, and τ is the period of oscillation.

Because G depends on the fourth power of the fibre radius, the diameter of each sample was measured at several locations along the gauge length using a laser diffraction technique [19]. A

TABLE III Effect of axial compressive fatigue on tensile strength of Kevlar 49

Maximum compressive strain (%)	Tensile strength (GPa)		
	Number of compressive cycles		
	1	10	100
0.4	3.4	3.2	3.3
0.8	3.1	3.2	3.1
1.2	3.4	3.4	3.0

(As-received Kevlar 49: 3.4 GPa).

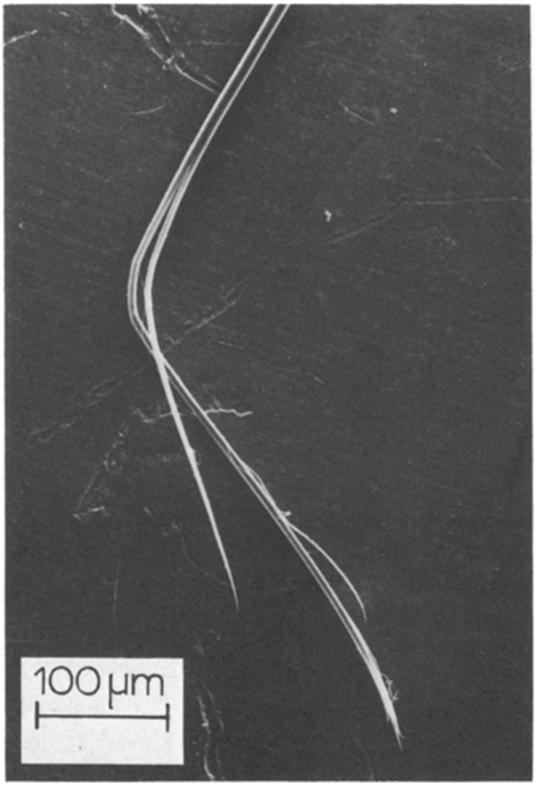


Figure 9 SEM micrograph of tensile fracture surface of Kevlar 49 fibre previously compressed ~ 3%.

summary of all the torsional properties and the axial tensile properties of Kevlar 49 is given in Table IV. The torsional shear modulus was calculated to be 1.8 GPa, nearly two orders of magnitude less than the tensile modulus.

The measurements of large torsional strain recovery are plotted in Fig. 10. Up to torsional strains of ~10% Kevlar 49 behaves elastically. Above 10%, the percentage of recoverable strain falls off almost linearly with an applied strain of up to 40%. To better understand this loss of recoverable strain, Kevlar fibres were held fixed at several torsional strains and examined in the SEM. Photomicrographs of representative samples are presented in Fig. 11. At > 10% torsional strain the fibres split longitudinally. These splits run parallel to the chain axis which presumably follows a helix due to the imposed shear strain. Because splitting coincides with the onset of permanent torsional deformation, these splits most likely represent shear slippage between longitudinal fibre segments. The strain at which irrecoverable torsional deformation and presumably longitudinal splitting initiates is defined as the critical torsional strain. An apparent shear strength in torsion of 180 MPa has been calculated from the product of critical torsional strain and torsional shear modulus.

The effect of torsion on the tensile strength of Kevlar 49 is illustrated in Fig. 12. The shape of this curve is very similar to the plot of recoverable against applied torsional strain (Fig. 10). Tensile strength begins to drop off at about 10% applied torsional strain and continues to fall off nearly linearly with applied strains up to 35%. It is possible that there is a correlation between longitudinal splitting and tensile strength reduction above 10% torsional strain.

The fracture surface of a tensile tested fibre which was tested after applying a large torsional strain is given in Fig. 13. This picture shows that the shear deformation due to torsional splitting is permanent and probably contributes to the formation of fracture planes under tension.

5. Discussion

The measured compressive and torsional properties of Kevlar 49 fibre are compared to the fibre tensile properties in Table IV. Also, to emphasize the large differences in mechanical properties of Kevlar 49 under different stress states, fibre compressive and torsional properties have been normalized to corresponding tensile properties and are listed in the last two columns of Table IV.

A critical axial compressive strain (ϵ_c) of 0.5% measured for Kevlar 49 using the beam bending technique is comparable to strain values calculated at the apparent yield point in the elastica tests of Kevlar. However this value for ϵ_c was determined in the beam bending tests from the appearance of permanent and therefore visible kink bands in unloaded fibres. Therefore the value of ϵ_c reported

TABLE IV Summary of mechanical properties of Kevlar 49 fibre

Property	Tensile	Compressive	Torsion	Tensile / Compressive	Tensile / Shear
Modulus (GPa)	130	130	1.8	1	70
Strain to break or yield (%)	2.5	0.5	10	5	0.25
Strength (GPa)	3.4	0.7	0.18	5	17

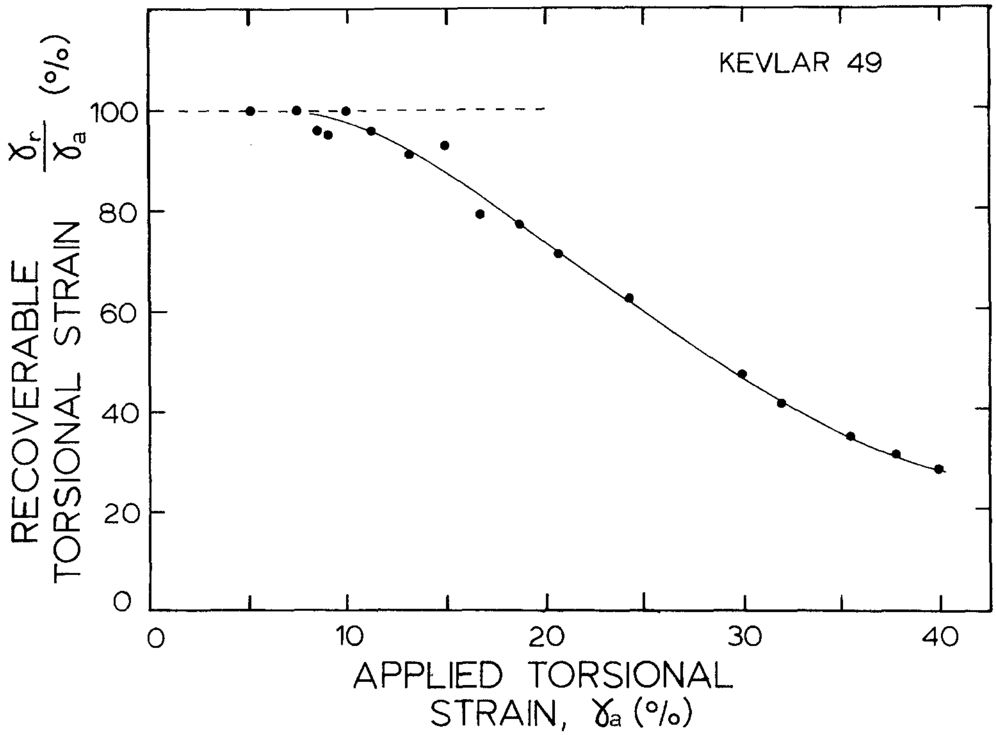


Figure 10 Loss of recoverable torsional strain with applied torsional strain.

here represents an upper limit for the strain to kink formation. This could account for the slight discrepancy between ϵ_c and the reported 0.3% compressive yield point for unidirectional Kevlar 49 composites.

No sinusoidal microbuckling instabilities were observed for the nylon matrix-compressed single Kevlar filaments with up to 3% axial strain. This observation implies that the microbuckling theories of unidirectional composites which can satisfactorily predict the compressive strengths of composites based on (isotropic) glass fibres may have no bearing on the compressive strength of Kevlar composites. This would explain the differences found by Rosen and co-workers [8] between measured Kevlar composite compressive strengths and the predicted strengths calculated using a fibre microbuckling theory which was modified to account for fibres having a low shear modulus.

Kevlar 49 composites exhibit deviations from elastic behaviour in both compression and flexure at strains similar to ϵ_c [7, 9, 10]. In addition, the 5:1 ratio of fibre tensile to compressive strength (see Table IV) is identical to same strength ratio for the unidirectional Kevlar composites (see Table I). Therefore, it can be concluded that in reasonably stiff matrices such as epoxies, the low strength of aramid composites is limited by an apparent fibre compressive yield strength. Although the compressive strength of Kevlar 49 appears poor in comparison with the strengths of glass and carbon fibres, it is significantly better than the compressive yield strengths of most polymers. For instance, commercial nylons exhibit yield strengths in compression of ~0.1 GPa compared to ~0.7 GPa calculated here for Kevlar 49.

A small and nearly constant tensile load is required to unfold the kink bands of compressed Kevlar 49 fibres. The draw region at this load persists until the point of extension where all the compression set is eliminated, i.e. until the kinks unfold completely. Once the kinks are unfolded and the fibre segments are realigned, the initial as-received fibre modulus can be regained. The large difference in stiffness between kinked and straightened fibres indicates that the compressive buckling and kinking occurs throughout the fibre cross-section rather than on the fibre surface alone. Since there is little evidence of fibre splitting and loss of tensile properties after the application of as much as 3% compressive strain and after compressive fatiguing, it seems unlikely that much chain scission occurs. The Kevlar fibres appear to be able to accommodate axial compres-

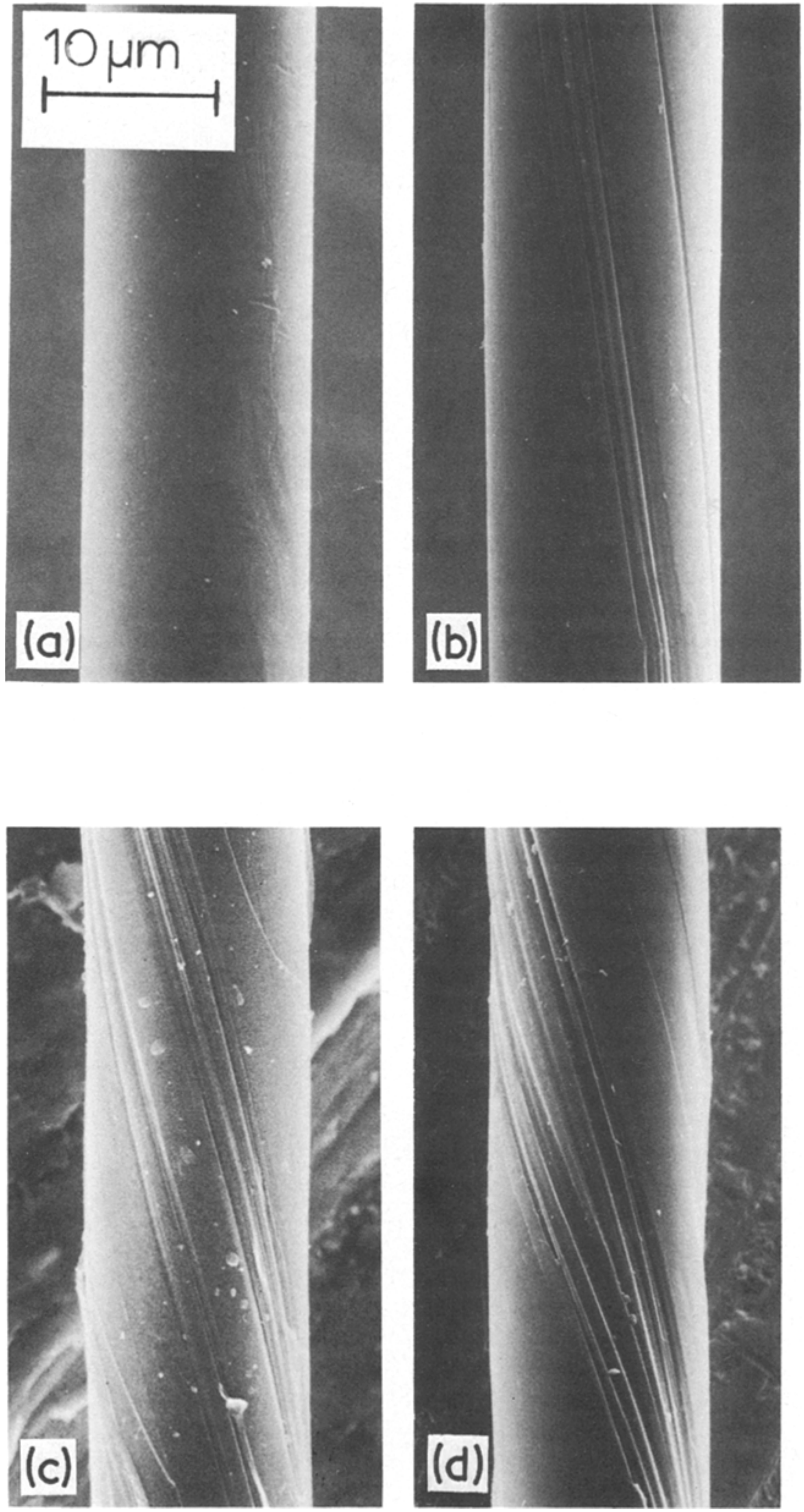


Figure 11 SEM micrographs of Kevlar 49 held at several torsional strains. (a) $\gamma = 8\%$. (b) $\gamma = 15\%$. (c) $\gamma = 25\%$. (d) $\gamma = 35\%$.

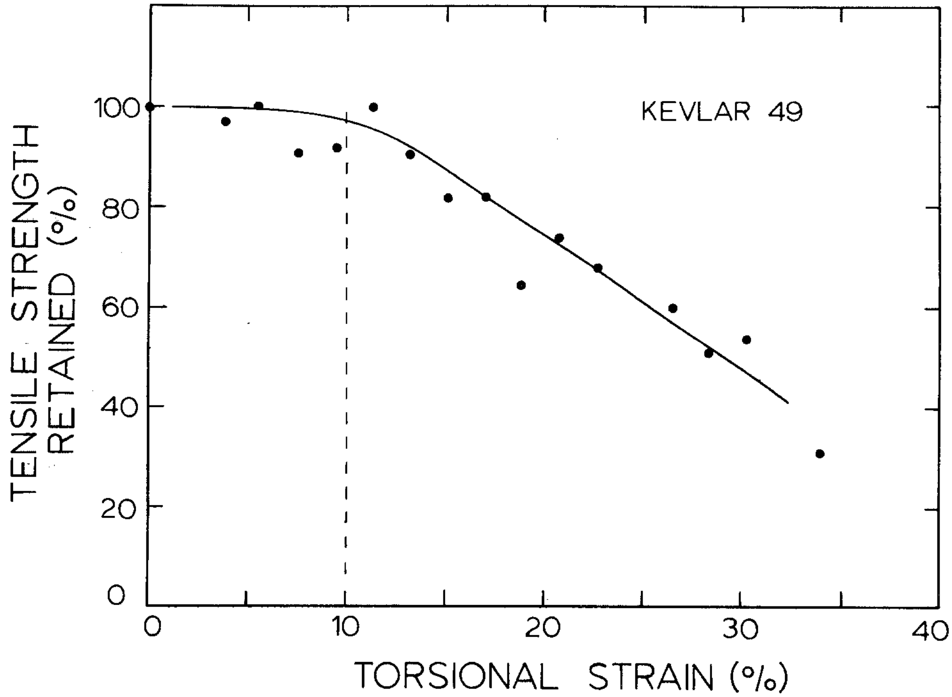


Figure 12 Loss in tensile strength of Kevlar 49 with torsional strain.

sion without significant permanent structural damage. It is conceivable that the formation of kinks occurs by bond bending and rotation, and by chain slippage. Such kink formation may be viewed as the buckling of microfibrils or of the PPTA chains themselves. Also, because the kink bands tend to take on a helical shape at the fibre surface, there may be a propagation of the band from some nucleation or defect point.

Although the kinks seem to form almost reversibly, SEM observations show that there is always some permanent surface structural change which remains after unfolding. These residual bands probably form defect regions which reduce the fibre compressive strength and possibly the compressive modulus in subsequent loadings.

The high anisotropy of mechanical behaviour for Kevlar 49 is illustrated by the measured 70:1 ratio of tensile to shear moduli. Comparison of a similar ratio for other fibres is given in Table V. The values clearly show that Kevlar 49 is an extreme among anisotropic fibres.

The relatively low values of shear strength and modulus measured for Kevlar 49 may account for

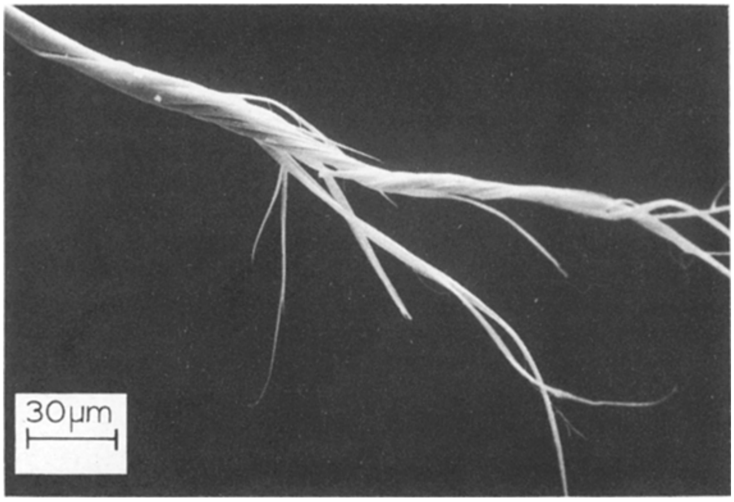


Figure 13 Tensile fracture surface of Kevlar 49 held twisted at a large torsional strain during tensile testing.

TABLE V Ratios of tensile to shear moduli for fibres [3]

Fibre	Tensile Modulus / Shear Modulus
Glass	2.0
Steel	2.8
Wool	3.2
Cotton	3.7
Silk	3.9
Nylon	5.8
Viscose rayon	8.2
Flax	19.0
Tenasco (rayon)	28.0
Kevlar 49	70.0

the relatively low in-plane shear modulus and strength and interlaminar shear strength of Kevlar composites (see Table I). For composites having a strong fibre–matrix interfacial bond, failure may occur within the Kevlar fibre rather than in the matrix or at the interface. Therefore any analysis of mechanical performance for Kevlar composites should consider that the fibre shear modulus and strength are in the range of matrix shear properties. We wish to point out that although the measured shear properties of Kevlar 49 seem poor in relation to those of glass and carbon fibres, the Kevlar shear values are greater than the values measured for most polymeric and natural fibres. Values of shear moduli for several polymeric fibres including the value measured in this study are listed in Table VI.

The longitudinal fibre splitting observed for Kevlar 49 at large torsional strains probably initiates at the fibre surface where the shear strain is a maximum. Concomitant with splitting, irrecoverable torsional strains are measured. Twisting to larger torsional strains causes further splitting which probably propagates toward the fibre centre as the inner regions of the fibre reach critical shear strain values. As a result of further splitting, larger irrecoverable strains are measured. Splitting under torsion is most likely a result of permanent slippage between radial planes of H-bonded PPTA chains [20] or microfibrils which should be weakly bonded by only van der Waals forces.

TABLE VI Torsional shear moduli of fibres [3]

Fibre	Shear modulus (GPa)
Nylon	0.33–0.48
Polypropylene	0.75
Polyester fibre (Terylene)	0.85
Viscose rayon	0.84–1.2
Wool	1.3
Acrylic fibre	1.0–1.6
Kevlar 49	1.8

The decrease in tensile strength after application of large torsional strain appears to be related to the amount of irrecoverable shear strain and accompanying fibre splitting. However, the recoverable and nonrecoverable components of the torsional strain must be separated before drawing any conclusions on the mechanisms of tension–torsion failure. Suffice it to say that longitudinal splitting can provide defect planes for premature tensile fracture.

6. Conclusions

An apparent yielding of Kevlar 49 fibres with the formation of helical kink bands has been shown to occur at small axial compression strains. The critical fibre compressive strain and corresponding calculated compressive strength correlate well with the behaviour of Kevlar reinforced composites in compression and flexure. This sensitivity of Kevlar 49 fibres to compressive strains could possibly be exploited for strain measurements by bonding fibres to materials which subsequently undergo compression or shrinkage. The effect of axial compression on the recoverable tensile properties of Kevlar 49 fibre was surprisingly small.

The highly anisotropic nature of Kevlar 49 was demonstrated by the measurement of an extremely large ratio of tensile to shear modulus. Therefore, analysis of Kevlar 49 composites must consider the significant anisotropy in mechanical properties of the Kevlar fibres themselves. The Kevlar 49 fibres were shown to be durable in the sense that they can sustain large compressive and torsional strains without catastrophic failure. Comparison of the compressive and torsional properties with the excellent tensile properties of Kevlar 49 reveals a dual nature for the mechanical properties of this fibre. On one hand, Kevlar 49 exhibits tensile properties that include high modulus and strength, and low elongation to brittle failure (typical of inorganic reinforcing fibres) which result from a structure of extended and well-oriented rigid chains. However the compressive and torsional behaviour reveal the anisotropic nature of a material that is laterally bonded by only weak secondary forces.

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