JOURNAL OF MATERIALS SCIENCE 12 (1977) 2447–2455

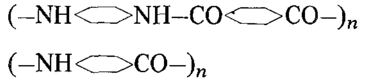
Flexural fatigue and surface abrasion of Kevlar-29 and other high-modulus fibres

J. W. S. HEARLE, B. S. WONG
Department of Textile Technology, University of Manchester Institute of Science and Technology, Manchester, UK

This investigation deals with some flexural fatigue and abrasion studies of Kevlar-29, glass and carbon fibres. The test methods included in the study are fatigue by pure flexing, buckling and rotation over a wire, and abrasion by rubbing against a rotating rod. Kevlar-29 fibres were found to perform well in these tests because they could survive the relatively high bending strains by yielding in axial compression. Carbon and glass fibres, although unable to survive at these high strains, did perform well when very low bending strains and tensions were used. Kevlar-29 fibres were found to be less abrasion-resistant than glass fibres, probably because of their low radial strength. The fracture morphologies of Kevlar-29 fibres in nearly all these tests showed axial splitting, confirming indications of low strength in the fibre perpendicular to its axis.

1. Introduction

This paper describes some fatigue and abrasion studies on Kevlar-29, glass and carbon fibres. Kevlar-29 is a high-modulus organic polymer (aramid) fibre produced by Du Pont. It is intended for use in high strength textiles and is of similar constitution to the higher stiffness version of the material, Kevlar-49, which is being used in reinforced materials. The chemical structure consists of para-oriented benzene rings joined by–CONH–groups:


(–NH⬡NH–CO⬡CO–)$_n$
or
(–NH⬡CO–)$_n$

This molecular structure, along with the fact that the fibres are very highly oriented, results in a fibre of high modulus and tenacity.

It is obviously important to determine the properties of a fibre under conditions similar to those which might be experienced in use. Consequently the present work involved study of various bending fatigue tests and surface abrasion of the Kevlar-29. Bunsell [1] and Hearle and Konopasek [2] have investigated the simple tensile and tensile fatigue behaviour of Kevlar-29 and Kevlar-49 fibres. They reported that extensive splitting along the length of the fibre occurred in the simple tensile situation and that this was even more marked in the tensile fatigue situation, revealing the low radial strength of the fibre.

Carbon and glass fibres have also been studied in the present work, and their performances in the tests compared with those of Kevlar-29. The diameters of the fibres used were 12.4 μm for Kevlar-29, 12.5 μm for glass and 8 μm for carbon. All the experiments were carried out in a controlled atmosphere of 65% r.h. and 20° C.

2. Flex fatigue

Flex fatigue tests were carried out on an apparatus used by Jariwala [3], illustrated in Fig. 1. It consisted of a vibrator to provide an oscillating displacement of the fibre under a tension provided by an elastic string. The life of a fibre was determined

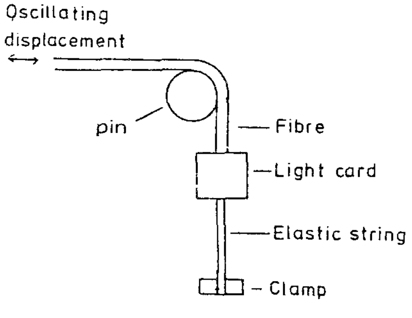


Figure 1 Flex fatigue.

by stopping a clock, through the operation of a photocell which was activated when the fibre broke and the light card dropped. A frequency of 50 Hz and displacement amplitude of 0.6 mm were used in the present tests. An apparent maximum strain, based on the assumption that the neutral plane remained central, was obtained from the formula $[r/(R+r)] \times 100\%$, where r was the radius of the fibre, and R the radius of the wire around which the flex test was performed. The tension was fixed by attaching the necessary weight to the elastic string before clamping, in order to stretch the latter by a certain amount.

The results of the tests on Kevlar-29 are shown in Table I. The median life of a minimum of five tests in each condition is given.

The flex fatigue life of Kevlar-29 fibres can be seen to reduce, as expected, with increasing tension and strain. For comparison, we may note that the breaking load of the Kevlar fibres would be 37 gf and the breaking extension 4%. The flexing conditions are this quite severe.

In a test of this nature there would be some doubt about whether the calculated strain was in fact the actual strain, since the tension used could have been insufficient to make the fibre follow the curvature of the pin. The following formula derived by Schoppee and Skelton [4] was used to check this:

$$F_B = \frac{\pi}{8}\frac{d^4}{D^2}E_T$$

where F_B = axial force on the fibre required to bend it to a certain radius of curvature $D/2$, E_T = elastic modulus, d = diameter of the fibre.

From the load–elongation curve, E_T was found to equal 7.41×10^8 gf cm^{-2}. The fibre diameter was 12.4 μm. The calculated forces required to make the fibre follow the curvature of the wire for apparent strains of 1, 2.64 and 4.65% were 0.044, 0.31 and 0.97 gf respectively. Hence, in all the cases tested, the fibre followed the curvature of the wire.

TABLE I Fatigue lives, in cycles, of the flex tests on Kevlar-29 fibres

Apparent strain (%)	Tension (gf)	
	2.75	6.7
1.0	2.25×10^5	1.02×10^5
2.64	1.075×10^5	9.0×10^3
4.65	4.5×10^4	6.0×10^2

Scanning electron micrographs of two opposite ends of a fibre broken in flexing are shown in Fig. 2a and b. A great deal of long splitting of the fibre along its axis can be observed. Examination of fibres removed from the test before breakage, reveal that considerable abrasion has occurred, as shown in Fig. 2c and d. Kink bands can be seen in Fig. 2d. Fig. 5 shows a fibre which has undergone pure abrasion in a test described later: the similarity of this to Fig. 2d indicates that a similar abrasion process had taken place.

In order to remove the abrasion in the flex tests a new technique was developed as illustrated in Fig. 3. This involved rotating the pin back and forth in unison with the fibre, whilst the test was performed. The pin was held in Teflon bushes and hence extremely fricition free. The former was driven by the test fibre which forms a loop as shown. The fibre was wrapped twice around the pin before forming the loop to ensure that the pin is driven. The system was driven by the vibrator used in the previous apparatus. Tension in the fibre is provided by the freely hanging weight.

Using Kevlar-29 fibres on this apparatus, with an apparent strain of 2.14%, tension 6.5 gf and frequency 25 Hz, a median life of 1.12×10^5 cycles was obtained for 6 tests: this life is similar to that in the flexing test with abrasion at half the strain level. Fig. 4a and b show two opposite ends of a fibre broken using this test technique. Less splitting than in fixed pin tests and some flattening of the fibre can be seen.

The flex fatigue apparatus was also used to test carbon and glass fibres. They were found to break during mounting, due to their brittleness, either at the pin or at the clamps when subjected to the tensions and strains used for Kevlar-29. However, in a test on a carbon fibre using 0.2 gf tension and apparent strain of 1.39% with a stationary pin the fibre lasted for 10^5 cycles at 10 Hz without breaking, but in this case the fibre did not follow the pin curvature. A glass fibre also performed in a similar manner.

3. Abrasion experiments

Abrasion experiments were carried out on an apparatus developed by Calil [5]. The technique involved rubbing a fibre against a rotating rod. In the apparatus, one end of the fibre was held in a jaw and the fibre was then bent around a rod which was at right angles to the axis of the fibre. The other end of the fibre is loaded with a freely

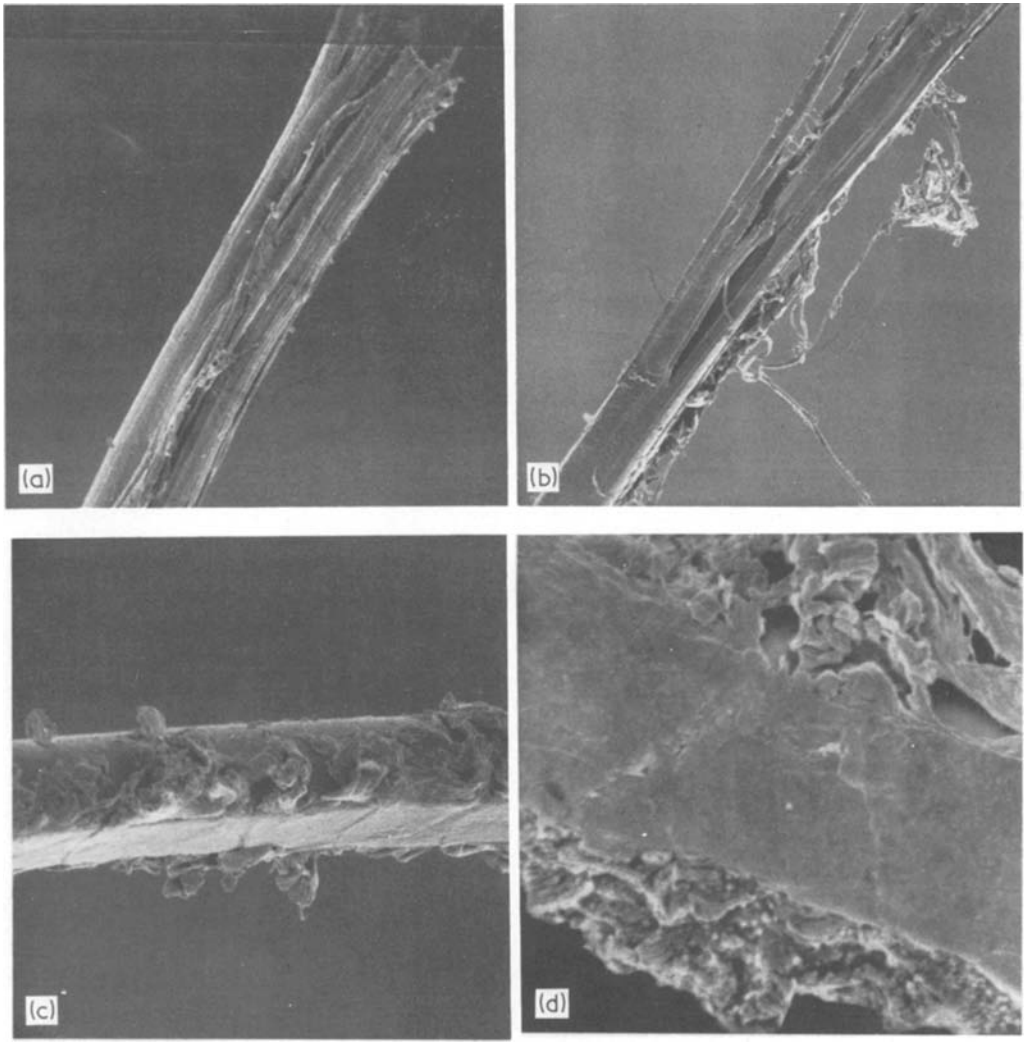


Figure 2 Flex fatigue fracture morphology of Kevlar-29 fibres; (a) and (b) Matching ends of a broken fibre showing splitting of the fibres along their axes; 48 000 cycles, apparent strain 4.65%, tension 2.75 gf (X 1083). (c) Condition of a fibre before failure showing abrasion; 45 000 cycles apparent strain 4.65%, tension 2.75 gf (X 1409). (d) Magnification of (c) indicating presence of kink-bands (X 3094).

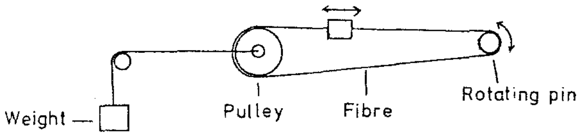


Figure 3 Flex fatigue using a rotating pin to eliminate abrasion during test.

hanging weight, and the rod is rotated so that friction produced a force in the fibre acting in the opposite direction to the weight. The angle of wrap of the fibre around the rod was about 45°. The rod was made of stainless steel, had a smooth surface and a diameter of 7 mm.

The experimental results showed that for a weight of 3.81 g and frequency 25 Hz, a mean life of 3425 cycles was obtained, and for a weight of 1.42 g at the same frequency the mean life was 9458 cycles. (The sample size was 6 in each case). In the tests there was always a ring of fibre residue

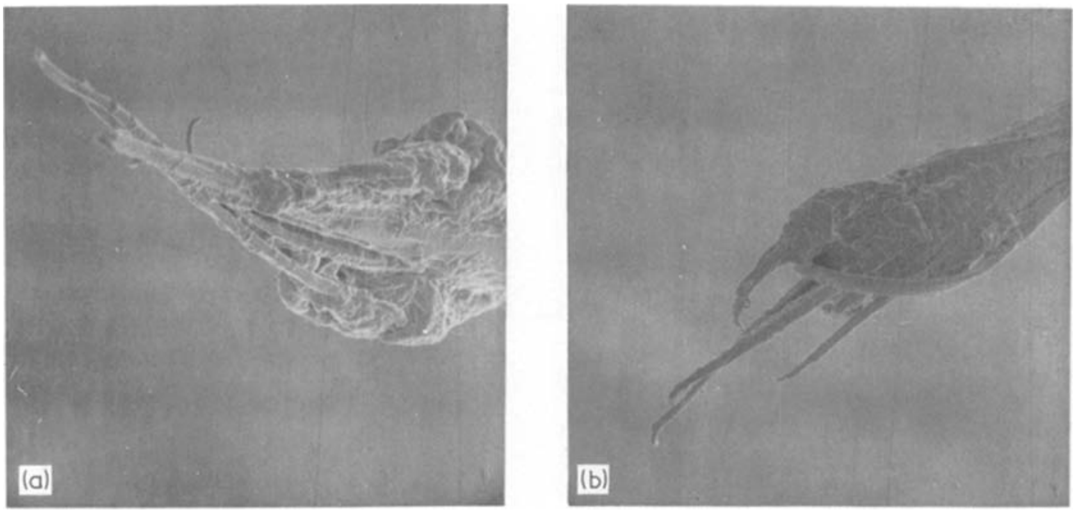


Figure 4 Fracture morphology of Kevlar-29 fibres broken be flex fatigue using a rotating pin. Slight splitting and flattening of the fibres can be observed; 111 600 cycles, apparent strain 2.14%, tension 6.7 gf ((a) × 1176, and (b) × 756).

left on the rotating rod. The fracture morphologies from the two conditions tested are rather different. In the former case (Fig. 5a and b) splitting occurred, probably because a tensile situation was being approached. Figs. 5c shows how the region below that in Fig. 5b has been abraded. Severe abrasion naturally occurs on one side of the fibre. When using the lighter weight (Fig. 6a and b) the fibre was abraded to a relatively smooth point.

Using similarly valued weights it was found impossible to test carbon fibres because they broke due to bending either at the clamps or at the rod

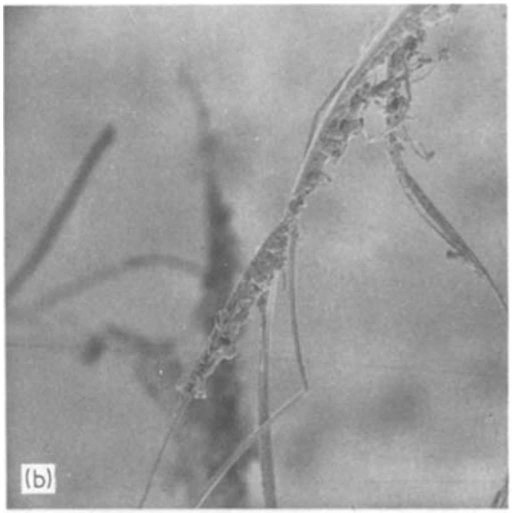
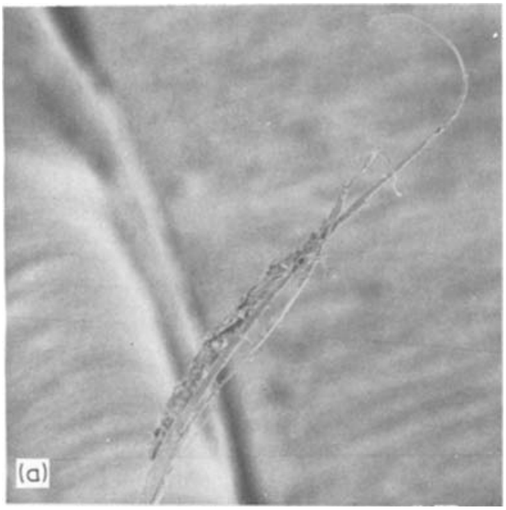
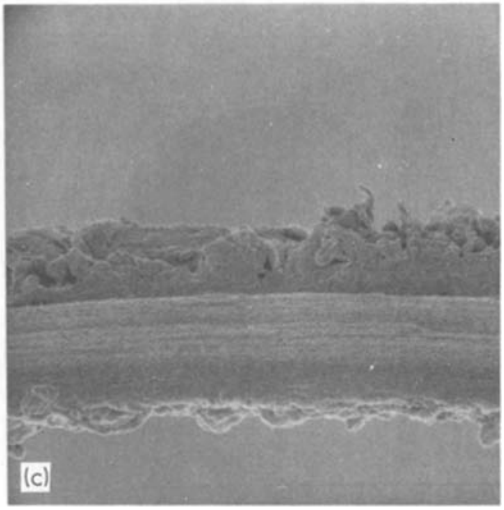


Figure 5 Fracture morphology of Kevlar-29 fibres broken by abrasion with a relatively high tension in the fibre. ((a) and (b) × 344). (c) Region of fibre below that of (b) showing severe abrasion on one side of the fibre (× 1375).





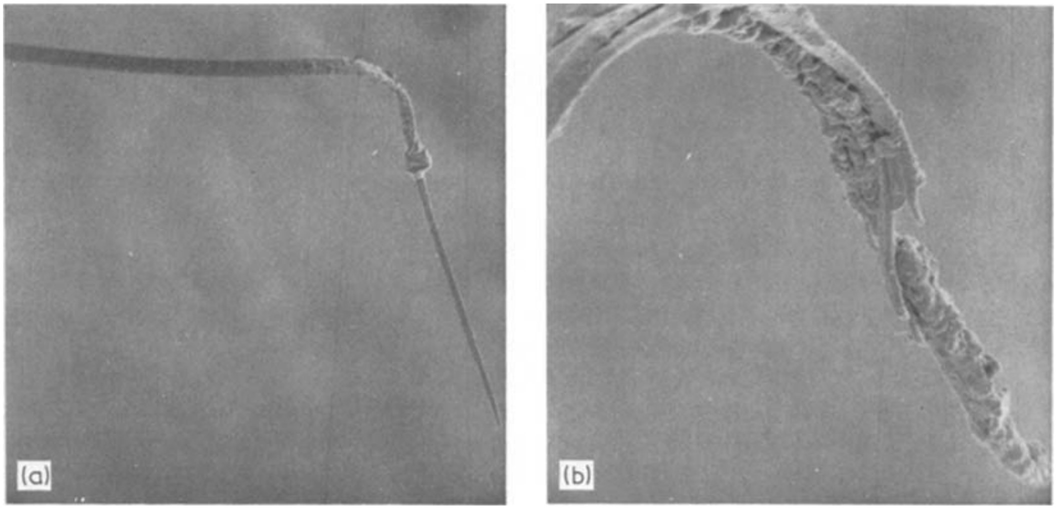


Figure 6 Fracture morphology of Kevlar-29 fibres broken by abrasion with a relatively low tension in the fibres. ((a) × 297, and (b) × 948).

surface. However, with a weight of 0.33 g, carbon fibres did not break after 45 000 cycles. No obvious markings were found on the fibres or the rod due to abrasion.

Glass fibres were tested using weights of 1.42 and 3.81 g. In both cases no breaks were obtained after 45 000 cycles and no abrading of the fibres was observed under the optical microscope indicating, obviously, superior resistance to Kevlar-29.

4. Buckling fatigue

Buckling fatigue experiments were carried out on a simply modified form of the flex fatigue tester. One end of a fibre was gripped in a jaw attached to the vibrator and the other end gripped by a "stationary" jaw with 2.5 mm between the jaws. The "stationary" jaw was then moved towards the "vibrating" jaw until a distance of 1.8 mm existed between them. The buckling test was conducted about this "mean" distance and the amplitude of vibration was chosen as 0.6 mm. The frequency of buckling was 50 Hz. With these parameters Kevlar-29 fibres were usually observed to take up a kinked shape after about 5 or 10 min. After one week's repeated buckling no complete breakage was observed and the condition of the fibre was as shown in Fig. 7a. Occasionally the fibre took up a rounded shape more usual in buckling tests. Probably in these cases the buckling strain on the fibre was reduced by the fact that the grips of the clamps were not holding the fibre tightly. Strength tests using an Instron tensile tester on the buckled fibres revealed that when the fibre was kinked the strength was reduced by about 25%. The matching ends of a kinked fibre broken by a tensile pull are shown in Figs. 7b and c. The fibre can be seen to have split into fibrils in the kinked region.

Carbon and glass fibre broke immediately under similar test conditions because they were unable to take the severe bending involved.

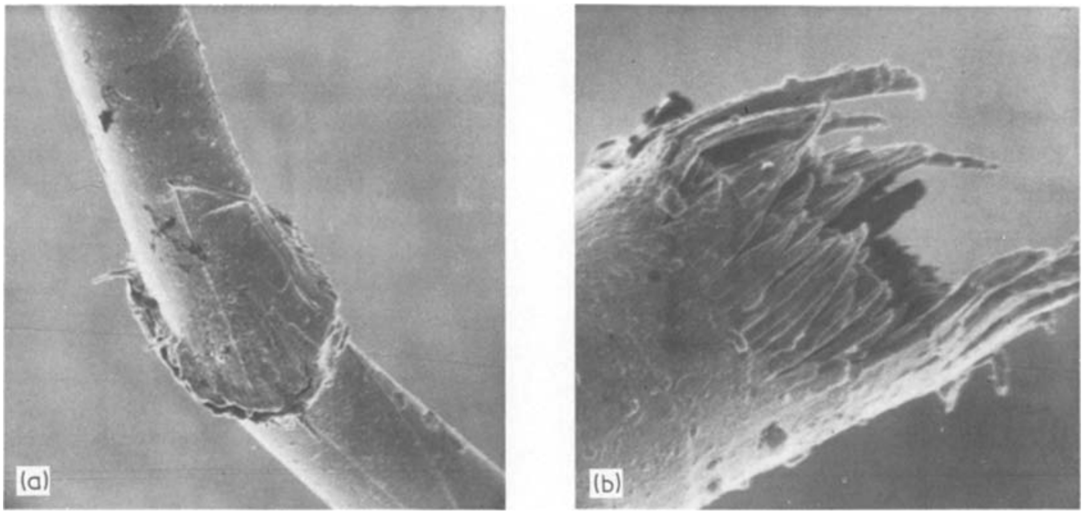
5. Rotation around a wire

Tests using the method of rotation around a wire were carried out on an apparatus developed by the authors [6]. In this method, one end of a fibre was held in a rotatable jaw, and the fibre was then bent around a wire situated at right angles to its aixs. The free end was loaded by a freely hanging weight. If the fixed end of the fibre was now rotated continuously, and the free end followed, a compression–tension action would occur on the fibre at the region bent over the wire.

Table II shows the result of the test on Kevlar-29 fibres. The median life from five failures is given in each case, except for the figures in brackets: the latter indicate the point at which single trial tests at the conditions shown were discontinued without fibre failure.

TABLE II Fatigue lives, in cycles, of the rotation-over-a-wire tests on Kevlar-29 fibres

Apparent strain (%)	Weight (g)			
	0.4	0.54	0.72	1.3
2.64			(>11 000)	3374
4.65			4500	1280
7.76	(>17 025)	3560	2319	603



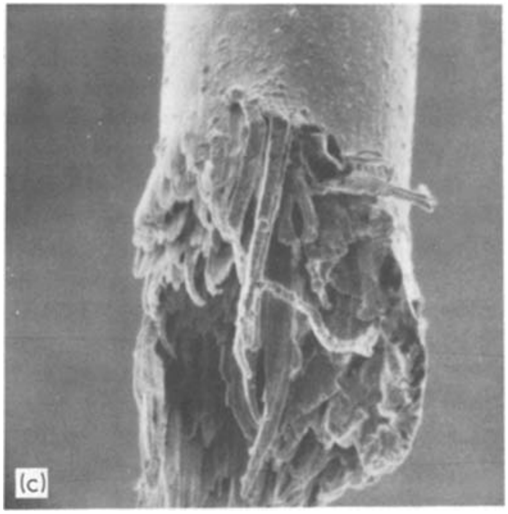


Figure 7 Kevlar-29 fibres in buckling fatigue. (a) Condition of a fibre before failure (X 1409). (b) and (c) Matching ends of a fibre broken in a tensile pull after reaching the condition in Fig. 7a. ((b) X 3506, and (c) X 2750).

Fatigue life as can be seen was very dependent on the strain and weight. A fibre broken in this test is shown in Fig. 8, the great amount of splitting of the fibre into fibrils can be noticed. The formula derived by Schoppee and Skelton [4] would predict that only at the lowest strain (2.64%) would the fibre follow the wire curvature. However, an assessment of the situation is difficult because the ease of compression of Kevlar-29 will shift the neutral plane and allow the fibre to bend more easily. Furthermore, although a fibre may not follow the wire curvature initially, weakening of its structure during testing may cause it to follow the wire during the later stages of its life.

Tests using carbon and glass fibres on this apparatus proved impossible with comparable weights to those used on Kevlar-29 fibres because the fibres broke easily at the clamps or at their point of contact with the wire. However, a test on a carbon fibre with a weight of 0.038 g and apparent strain of 1.73% (the real strain was almost certainly much smaller) did not break after 20 000 cycles, and a test on a glass fibre with a weight of 0.071 g and apparent strain of 2.56% lasted for a similar lifetime. Both fibres were also found to be unmarked by observation under an optical microscope.

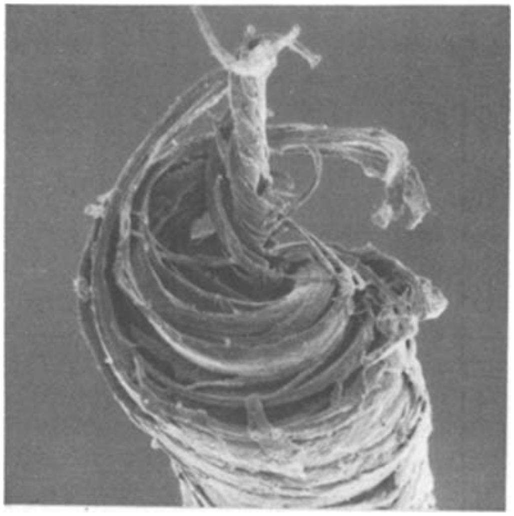


Figure 8 Kevlar-29 fibre broken by the rotation over a wire technique; 10 788 cycles, apparent strain 7.7%, tension 0.48 gf (X 2145).

In order to examine the effect of water, an apparatus developed by Calil [5] was used. The method of fatigue was similar apart from the fact that the weight was driven in this case so that both ends of the fibre were now being driven. The torque on a fibre from a viscous drag on the weight, which can be considerable when using the rotation-over-a-wire method in water (particularly for thin fibres), is thus eliminated. For an apparent strain of 2.6%, tension 4.6 gf and frequnecy of testing of 15 Hz the median life in air for 10 tests was 1092 cycles. This was reduced to 494 cycles when testing was done in water. For the same strain and a tension of 9.6 gf the life was reduced from 585 to 405 cycles.

6. Loop tests

It was thought that it would be valuable to find the strength of the Kevlar-29 fibres in loop tests around wire diameters similar to those used in the previous experiments. Tests were performed on an Instron tensile tester using a transverse rate of 1 cm min^{-1}.

It was found that apparent bending strains of 1 and 4.7% resulted in loop efficiencies of 63 and 47% respectively, but an apparent strain of 50% reduced the loop efficiency to 7%. However the fibre obviously retains a considerable proportion of its tensile strength around the wire diameters which were used in the fatigue experiments. The matching ends of a fibre broken in a loop test were very similar and one is shown in Fig. 9. It is similar to the morphology of a tensile break with deep multiple splitting being evident.

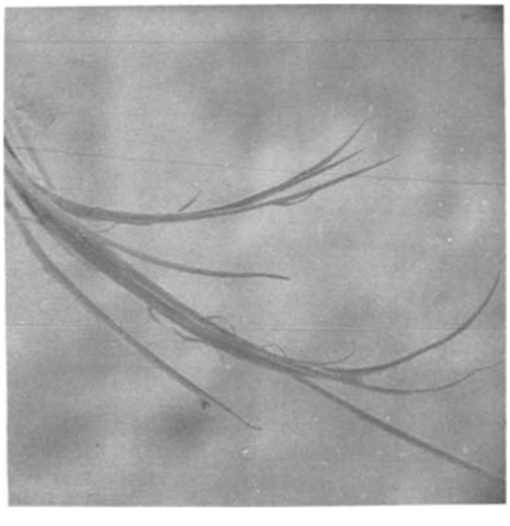


Figure 9 Kevlar-29 fibre broken in a loop tests; apparent strain 4.7% (X 237).

7. Discussion and conclusions

The results in this paper confirm that in addition to their high tensile strength, Kevlar fibres demonstrate a most surprising combination of high stiffness and low-breaking extension with resistance to failure in bending. This has been reported by Schoppee and Skelton [4] for simple bending; they show that a Kevlar fibre can sustain the maximum possible bending deformation, back into contact with itself, with an apparent bending strain of 100%. This behaviour is, of course, due to the ease of yielding in compression and the consequent shift of the neutral plane. While the poor compressive properties may sometimes be a disadvantage, they are also, when appropriately used in the right engineering applications, advantageous in minimizing damage due to bending.

The present paper does show that flexing leads to fatigue failure, (i.e. failure under repetitive stressing at levels which would not cause failure in single loading) though the lifetimes are reasonably long even under severe conditions of flexing. Kevlar thus has flex fatigue properties, which while not as good at a given strain levels as those of more extensible and tough fibres like nylon and polyester, are nevertheless of the same general order of magnitude. With some care to avoid bending strains at as high a level as those adopted for test purposes, very long lives would be obtained.

It is not really possible to make comparative tests on other high modulus fibres such as glass or carbon, since they snap when bent to a degree far smaller than that used in flex fatigue tests on Kevlar. Schoppee and Skelton [4] report that a glass fibre broke at 7.3% apparent strain and graphite fibres at 1.4% and 2.8%. Thus flex fatigue tests on these fibres must be made under conditions which are very much less severe; the few tests made under these conditions suggest that fatigue effects, as such, were not having any appreciable effect.

In contrast to studies of nylon and polyester fibres (but similar to wool and hair), Kevlar showed marked surface abrasion. When this was avoided, the flex fatigue tests showed longer lives; and conversely abrasion without repeated flexing (though on a bent fibre) led to breakage. In the engineering use of Kevlar, care should therefore be taken to minimize rubbing of Kevlar fibre surfaces or to protect them from abrasion. Glass and carbon fibres showed good resistance to surface abrasion.

Another remarkable feature of Kevlar fibres, shown by the buckling studies, is the extent to which they can suffer "damage", in the sense of kinking and splitting into fibrils, with only a comparatively small loss of tensile strength.

All the tests used in these studies, including the "pure" abrasion tests, involved fibre bending. the first type of inelastic deformation, leading in the direction of failure, would be the development of kink-bands on the compression side. Shear stresses will then lead to pronounced axial splitting. The shear stresses may arise (a) directly from frictional effects, (b) indirectly as a consequence of rotation effects [5], or (c) indirectly, as in tensile tests, from discontinuities [2]. Both kink-band formation and splitting under shear stresses are commonly found to develop under repeated stressing (fatigue) conditions, and the presence of the kink bands will both weaken the structure and give additional shear stresses due to discontinuities and points of stress concentration. The more severe combined stress situation of biaxial rotation leads to earlier failure than uniaxial flexing. Where there is surface rubbing the kinked and split material gets torn away and leads to the flattened surface, with loose material at the edge. The progressive removal of material continues until failure occurs. However in the absence of surface rubbing, it is necessary for

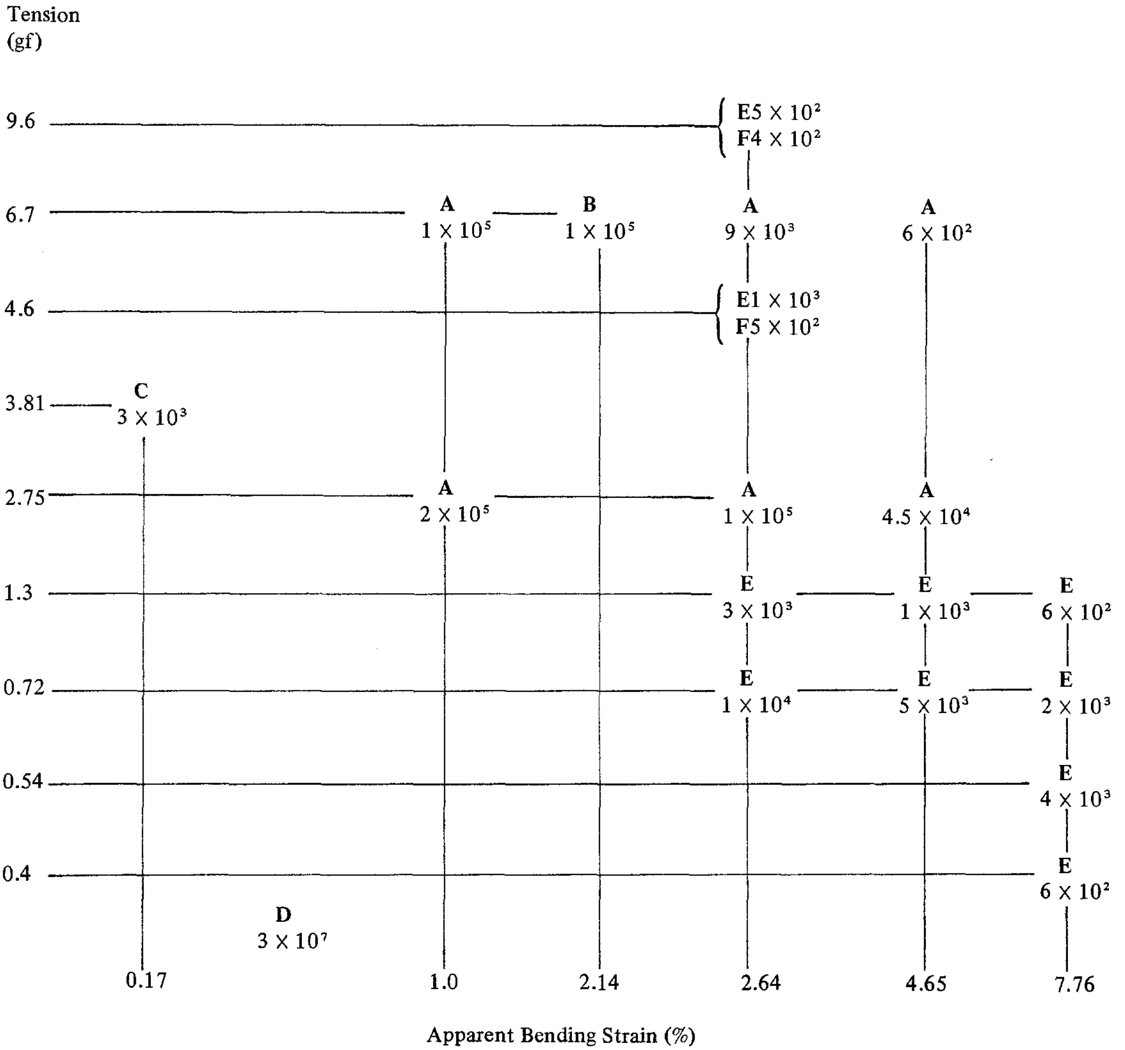


Figure 10 Approximate comparison of fatigue lives in various tests and conditions: uniaxial flex, with surface abrasion **A**; uniaxial flex, without surface abrasion **B**; surface abrasion, without flexing **C**; free buckling **D**; biaxial rotation, with surface abrasion, in air **E**; biaxial rotation, with surface abrasion, in water **F**.

the multiple splits to extend for much greater lengths and join up with one another, before separation of the ends can occur. Thus in the absence of abrasion, the fatigue lives are longer.

There was a reduction in the fatigue life of Kevlar in the presence of water.

The intention of the work described in this paper was to illustrate general effects and mechanisms, and not to make a thorough comparative study of fatigue lives under different conditions. However the summary of the results, given in Fig. 10 may help to indicate the comparative levels.

References

1. A. R. BUNSELL, *J. Mater. Sci.* **10** (1975) 1300.
2. J. W. S. HEARLE and L. KONOPASEK, to be published.
3. B. C. JARIWALA, Ph.D. Thesis, University of Manchester, 1974.
4. M. M. SCHOPPEE and J. SKELTON, *Textile Res. J.* **44** (1974) 968.
5. S. F. CALIL, Ph.D. Thesis, University of Manchester, 1977.
6. J. W. S. HEARLE and B. S. WONG, *J. Phys. E.* to be published.

Received 21 February and accepted 11 March 1977.