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The tensile and fatigue behaviour of Kevlar-49 (PRD-49) fibre

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The tensile, creep and tension-tension fatigue properties of Kevlar-49 fibre (formerly known as PRD-49) have been determined. The fracture morphology of the fibre has been examined and is shown to be complex due to considerable splitting. The fibre quickly stabilizes under a steady load but failure due to creep can occur when it is loaded very near to its simple tensile breaking load. Kevlar-49 has been found to fail by fatigue, and its fatigue lifetime is dependent on the amplitude of the applied oscillatory load as well as the maximum load to which the fibre is cycled.

1. Introduction

The recent development of wholly aromatic polyamide fibres offers the possibility of a new range of filaments with exceptional properties. These fibres have been developed independently by the Monsanto-Chemstrand companies [1] and Du Pont de Nemours [2], and this latter organization is planning the full scale production of a range of these fibres under the general name of Kevlar fibres. The molecular structure of this type of fibre is such as to result in a high modulus, high strength, small breaking strain and low density. There appears to be a wide range of possible applications for this type of fibre in industrial cables, tyres and in forming a new type of fibre-reinforced composite material [3, 4].

The Kevlar series of fibres consists of filaments drawn by different amounts to produce fibres with a variety of moduli and breaking strains. In this study the fibre type tested was Kevlar-49, originally known as PRD-49 type III. This fibre has the highest modulus and least breaking extension of the series and is intended for use in light-weight very strong cables and also in fibre-reinforced composite material.

It is clearly important to determine the properties of this type of fibre under conditions similar to those which might be experienced in use. For this reason, in addition to the simple monotonic tensile loading properties, the fatigue and creep behaviour has been studied.

It has been shown for nylon 66 [5] and other polymeric fibres [6, 7] that tension-tension load cycling of fibres can result in their fatigue failure when taken to more than about 60% of their nominal tensile strength. Two types of fatigue behaviour have been distinguished. Nylon and polyester fibres subjected to zero-tension cycling to a suitably high percentage of their simple tensile breaking load fail after distinctive fatigue fracture development. The fracture initiates at the fibre surface and develops radially into the fibre for a short distance when it is then sharply deflected along a direction at some small angle to the fibre axis. The fracture develops along the length of the fibre and at the same time gradually reduces the load-bearing cross-section of the fibre. Eventually the remaining intact region of fibre cannot support the maximum applied load experienced during cycling, and fails in tension. It has been found that for fatigue failure of nylon fibres to occur they must be cycled from zero load. Increasing the minimum load above zero load, even if the same oscillatory load is applied so that the maximum load is also increased, safeguards the fibre from fatigue failure.

Polyacrylonitrile fibres have been found to fail during cycling after splitting of the structure. These splits do not appear necessarily to originate at the fibre surface and there is often more than one split in the same region so giving rise to fairly complex fracture morphologies.

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Even a small oscillatory load superimposed on a high steady load will result in splitting which leads to failure so that a zero minimum load is clearly not a criterion for fatigue failure of polyacrylonitrile fibres. The splitting is probably associated with the weak radial strength of the acrylic fibre and it is found that very highly drawn fibres of this type, for example those used as precursors in the manufacture of carbon fibres, split on failure even in simple monotonic tensile loading. The probable low radial strength of any highly drawn fibre, such as Kevlar-49, may therefore be expected to be a major source of weakness under cyclic loading conditions.

2. Experimental procedure

All of the tests have been conducted at room temperature (20°C) and an Instron tensile testing machine has been used for the monotonic tensile tests and some cyclic tests. A strain rate of 10% min^{-1} was used in the Instron and a specimen gauge length of 50 mm was used throughout all tests. The diameters of the fibres were measured optically using a Watson image-shearing eyepiece.

The fatigue apparatus used was a version of the fibre fatigue apparatus described in detail elsewhere [8]. The fibre is gripped between two jaws, the lower one being attached to a vibrator and the upper being connected directly to a piezoelectric PZT-5 ceramic transducer which in turn is attached to the end of a cantilevered beryllium-copper beam. The oscillatory load on the fibre is monitored by the transducer while the steady load is measured by a strain-gauge bridge bonded to the beam. In this way electrical signals proportional to the mean load, oscillatory load amplitude and maximum load each cycle, can be obtained. In testing extensible inelastic fibres such as nylon it is necessary to incorporate these signals into a servo system by which means a motor moves the grips apart whenever creep of the fibre results in a significant load drop and so brings the load back to the desired level. Kevlar-49 was found to be essentially elastic after the first loading cycle and creep was found not to be a major problem so the servo system was dispensed with and extension was made manually. The oscillatory loading signal on the fibre was displayed on an oscilloscope and in this way some indication of hysteresis losses obtained. When the fibre broke an automatic switch stopped a counter and so recorded the lifetime to failure. A loading frequency of 50 Hz was used throughout this study.

The creep behaviour of Kevlar-49 was also obtained with the fibre fatigue apparatus. The vibrator was not used and the fibre merely loaded monotonically by moving the grips apart. The increase in extension necessary to maintain the steady load on the fibre as creep occurred was measured by a vernier scale and the deflection of the cantilevered beam measured by a travelling microscope.

3. Tensile and creep behaviour

The stress-strain curve of Kevlar-49 is shown in Fig. 1 compared to three of the major reinforcing fibres used in composites, glass and carbon fibres types I and II. The initial region of the stress–strain curve of high tenacity polyester fibre as used in tyre cords and which has a breaking extension of around 20% illustrates the high modulus of Kevlar-49 compared to other synthetic polymeric fibres. The stress–strain curve of Kevlar-49 is not quite linear and an increase in its gradient occurs during extension. Table I compares the modulus of Kevlar-49 with the moduli of some other fibres. The properties of the monofilament as found from these studies are shown in Table II together with its density which is taken from the work of Chiao and Moore [3]. As the standard deviation of the tensile strengths, shown in brackets, indicates there is considerable variability in the strengths of these fibres. The calculated percentage variation was 17%. The mean breaking load of the Kevlar-49 fibres tested in this study was 35 g but, as Fig. 2 shows, a plot of probability of failure against load indicates that fracture was likely over a wide loading range.

The appearance of the Kevlar-49 fibre in the scanning electron microscope is of an essentially smooth cylinder although examples of surface roughness in the form of surface striations have been observed. There is usually a great deal of swarf associated with the fibre, as shown in Fig. 3, and this appears to have become detached from the surface of the fibre during manufacture. The fracture morphology of Kevlar-49 is complex and, as can be seen from Fig. 4, shows evidence of severe splitting.

An indication of the percentage of strain energy liberated on fibre failure and absorbed by the process of creating the large fracture surfaces involved in splitting has been obtained by Fuwa [9]. Separate bundles of ten or so Kevlar-49, glass and carbon fibres types I and II have been monotonically loaded to failure and the amount of energy converted to acoustic emissions, that is, stress wave vibrations travelling through the silicone grease coupling agent, has been monitored by a suitable piezoelectric transducer. It can be shown [10] that the initial signal voltage generated at the transducer (v) is proportional to the square root of the energy (E) released by an acoustic emission generating mechanism. If the constant of proportionality is α, we can write

$$\alpha E = v^2 .$$

The fracture of the carbon and glass fibres are similar [11] in that they behave as brittle materials and their failure results in a minimum

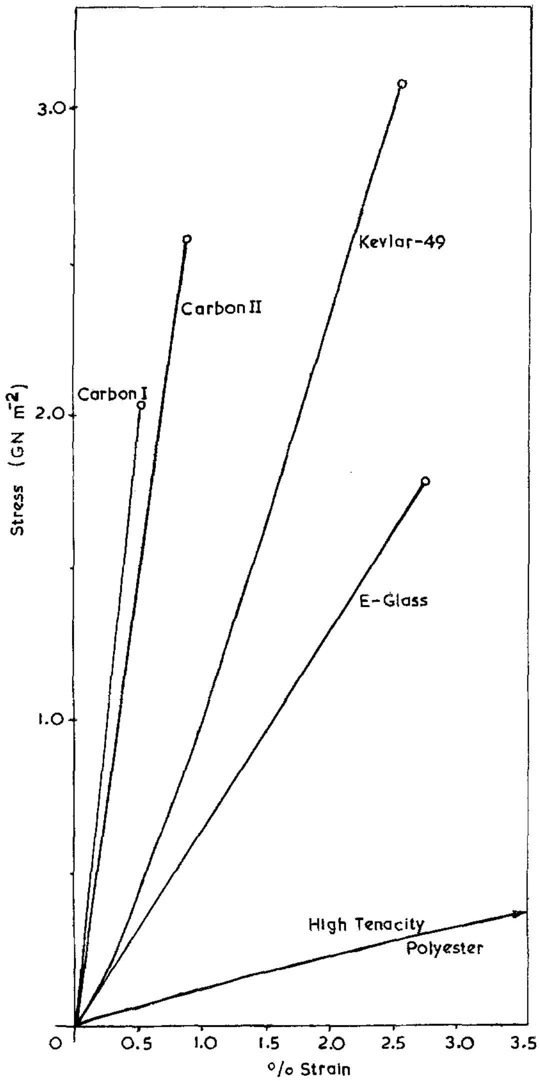

Figure 1 The stress–strain curves of Kevlar-49 and other higher modulus fibres.

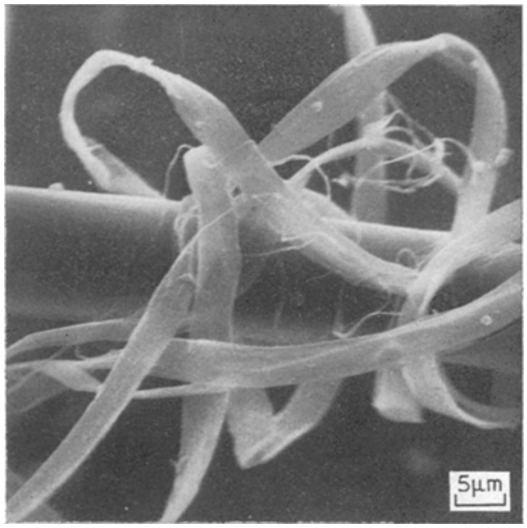

Figure 3 Swarf which is commonly found on the surface of untested Kevlar-49 fibres.

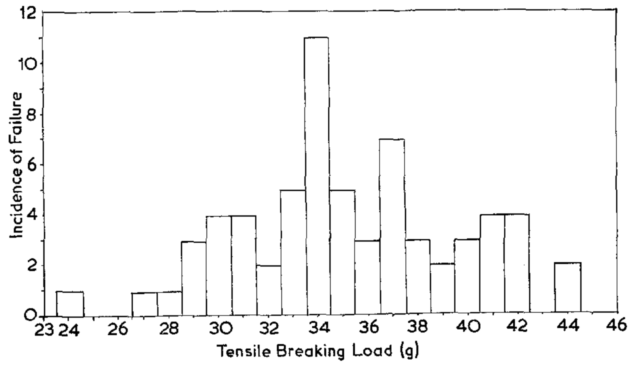

Figure 2 A histogram showing the distribution of strengths of all the Kevlar-49 fibres, broken by monotonic tensile loading in this study.

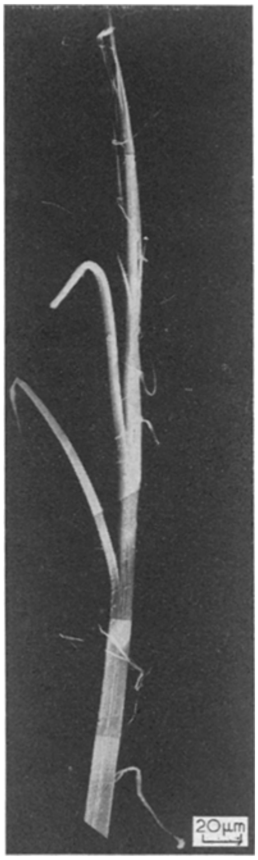

Figure 4 Tensile fracture morphology of Kevlar-49 showing severe splitting.

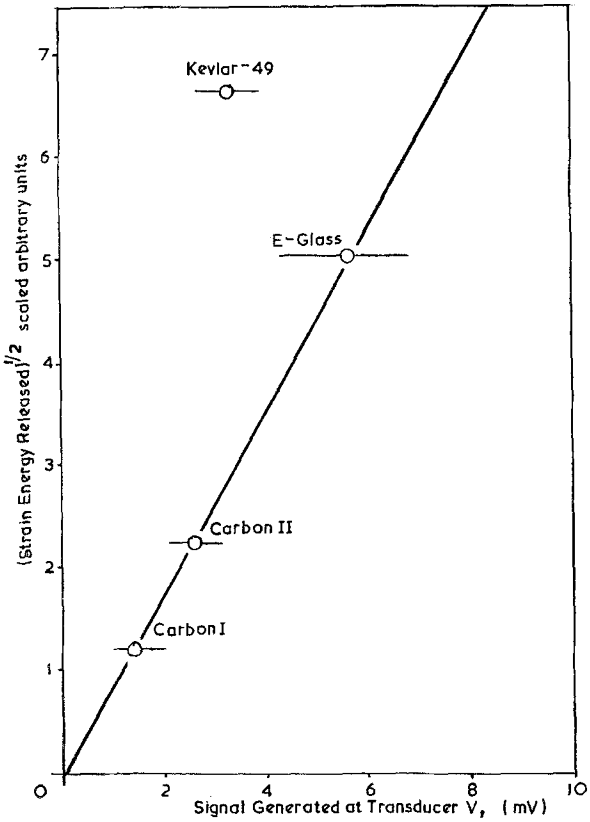

Figure 5 Acoustic emissions generated by the fracture of single fibres, of the different types used for reinforcing materials, showing that less strain energy is freed with Kevlar-49 to create vibrations than with other brittle fibres. This is presumably because the fracture of Kevlar-49 involves the development of much greater fracture surface areas due to splitting than is the case with the other fibres [9].

of fracture surface area. A more complex fracture such as that of Kevlar-49 would be expected to generate less acoustic emission as more of the strain energy is used in creating the much larger fracture surface. Strain energy will also be lost in plastic deformation both before and after fracture. The acoustic emission signal corresponding to the failure of these fibres was obtained by noting the signal which was associated with a sudden load drop equivalent to the failure of one fibre in the bundle. The four types of fibre were of differing diameters and there is no attempt at normalization in Fig. 5 which shows that the acoustic emission signal received from the Kevlar-49 was only half of that which would be expected if it broke in a brittle manner. This indicates that only a quarter of the strain energy was available to generate acoustic emissions and that probably this means that three-quarters of the strain energy went to creating fracture surfaces and non-recoverable plastic deformation.

In determining the creep behaviour of Kevlar-49 fibre the fibre was loaded up to 85% (30 g) of its expected breaking load and the extension due to creep noted. As Fig. 6 shows, little creep occurred and after 5 min of loading the fibre appears to have stabilized. At higher loads the fibre usually failed after several hours of loading even though no further measurable extension was observed after the first few minutes. The exact time to failure varied widely and this may reflect the scatter of strengths found with these fibres.

4. Fatigue behaviour

The effect of repeatedly cyclically loading

TABLE I Comparison of properties for various fibre types

Fibre type	Young's modulus ($GN\ m^{-2}$)	U.T.S. ($GN\ m^{-2}$)	Breaking strain (%)	Specific gravity
Kevlar-49	144	3.06	2.3	1.45
Polyester (high tenacity)	18.5	1.4	20	1.2
Nylon 66 (high tenacity)	12.5	1.0	17	1.2
E-glass	70	1.8	3	2.5
Carbon type I	400	1.9	0.5	2.0
Carbon type II	200	2.6	1.0	1.7

TABLE II Basic fibre properties measured at 20°C. The standard deviation for each value is shown in brackets

Tensile strength	3.06 $GN\ m^{-2}$ (0.5)
Breaking strain	2.34% (0.18)
Young's modulus	144 GN (16)
Diameter	12.56 μm (0.88)
Specific gravity	1.45

Kevlar-49 up to various maximum loads has been examined using an Instron and the fibre fatigue apparatus. Fig. 7 shows that stabilization of the fibre structure occurs after the first few cycles during which about 0.2% plastic strain deformation occurs. There was no measurable difference between the Young's modulus of the fibre after ten cycles and after 10^6 cycles. After the initial cycle the fibre behaves essentially elastically and Fig. 8 shows the narrow hysteresis curve obtained when cycling at 50 Hz. The hysteresis curve for Kevlar-49 is considerably narrower than the similar curve for nylon 66 shown in [6] and which was used to calculate the rise in temperature for nylon 66 fibre under cyclic loading. The non-recoverable energy absorbed by the nylon fibre during cycling was balanced with that estimated to be lost by radiation. This calculation indicated a temperature rise of the order of 6°C for a nylon 66 fibre cycled at 50 Hz to about 80% of its expected ultimate tensile strength. This being so the narrower hysteresis curve found with Kevlar-49 indicating that a lower percentage of irrecoverable work was being done than was the case with the nylon 66 fibre, means that the Kevlar-49 fibre was not heating up significantly during the fatigue tests.

Cycling the fibre to more than 85% of the fibre's nominal tensile strength at 50 Hz normally leads to failure and two examples were found, after the exact stresses involved were calculated, to have failed after they had been cycled to only 70% of their nominal strength. The number of cycles to failure under any particular loading condition varied over a considerable range, as can be seen from the survival diagram in Fig. 9. There was, however, a definite trend for the fibre to survive longer when the minimum load was raised but the maximum load held constant.

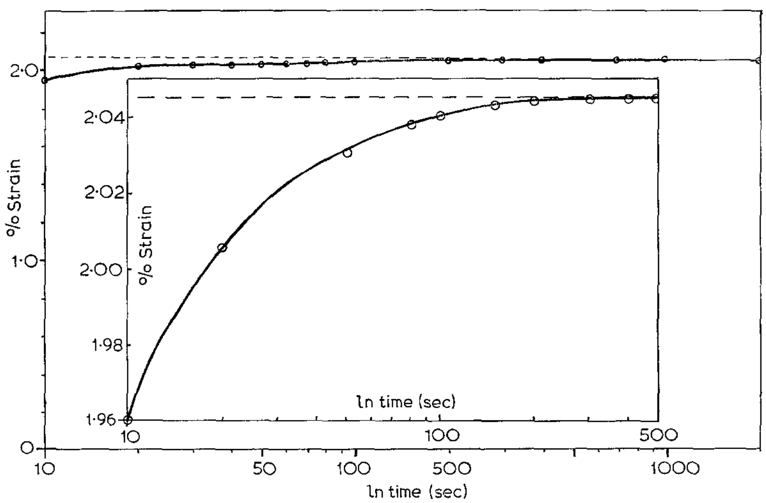

Figure 6 Creep deformation at a steady load of 30 g equivalent to 85% of nominal tensile strength. The inset graph is an enlarged view of the strain deformation over the first 500 sec of loading.

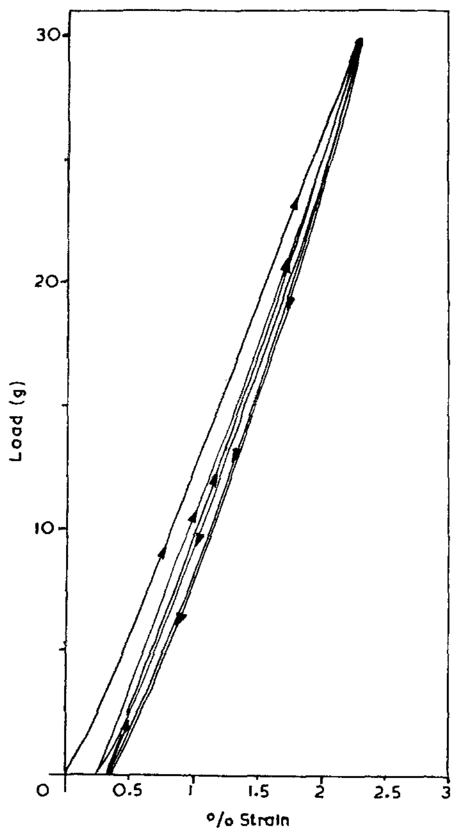

Figure 7 Load-elongation curves for the first three cycles of a constant-maximum load fatigue test of Kevlar-49.

Fig. 10 shows the median survival lifetimes of fibres under the various constant maximum loading conditions plotted against the *minimum load* experienced in cycling. Lifetimes of the order of 10^5 cycles were not unusual with high oscillatory loads and can be compared to similar fatigue lifetimes for nylon and polyester fibres [6], however, reducing the oscillatory load but keeping the maximum load constant results in fatigue lifetimes of more than 10^6 cycles. Figs. 9 and 10 show that below a certain oscillatory load amplitude the damaging effect of the oscillatory load is superseded by failure due to creep.

The failure morphology of fatigued Kevlar-49 fibre appears to be very similar to that found after simple monotonic tensile failure and also involves extensive splitting. Fig. 11 shows a highly magnified view of the end of a split in the fibre after failure by fatigue. The striations are parallel to the fibre axis but there are also unexpected markings at right angles which may be inbuilt into the structure at the time of manufacture or more likely produced by compression due to snap back at failure.

5. Discussion

The highly drawn aromatic molecular structure of the Kevlar-49 fibre clearly results in it having exceptionally high strength and modulus for a polymeric fibre. The gradual increase in stress–strain slope especially prominent at low strains suggests that some of the strain can be accommodated by internal relative movement of the molecular structure but that this is limited. The high draw ratio employed in the manufacture of these fibres probably results in a low radial strength. This weak radial bonding may account for some of the surface layers becoming detached and resulting in the large amount of surface swarf which can be seen on the untested fibre. Tensile failure of the fibre results in a complex fracture morphology and the elastically stored

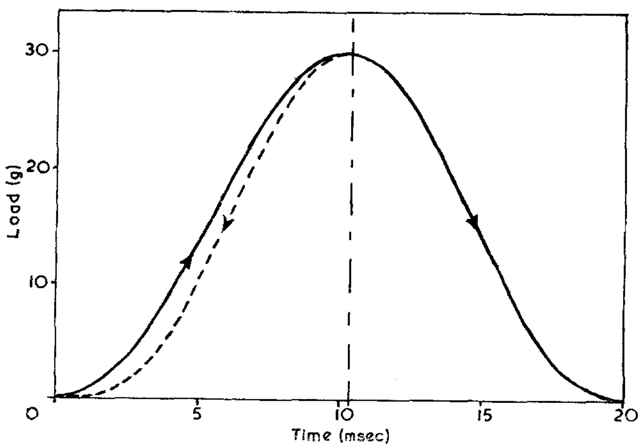

Figure 8 Hysteresis loop of a Kevlar-49 fibre undergoing load cycling at 50 Hz. The dotted line is the mirror image of the recovery section and shows the hysteresis.

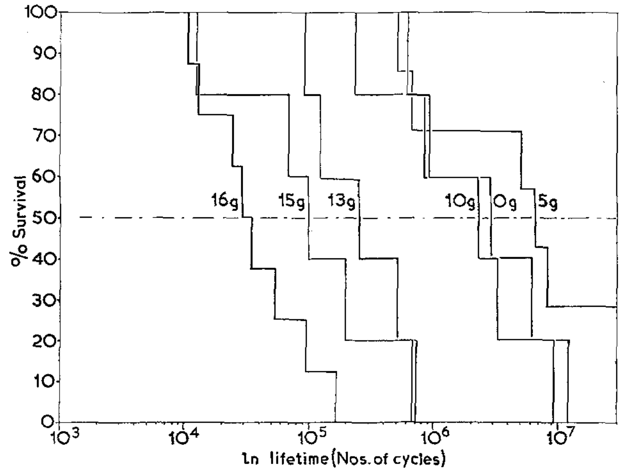

Figure 9 Survival graphs of Kevlar-49 fibres all cycled to 32 g maximum load at 50 Hz but with various oscillatory loads. The loads next to each graph indicate the oscillatory load amplitude applied, so 15 g is next to the survival graph for fibres cycled from a minimum load of 2 g up to a maximum load of 32 g.

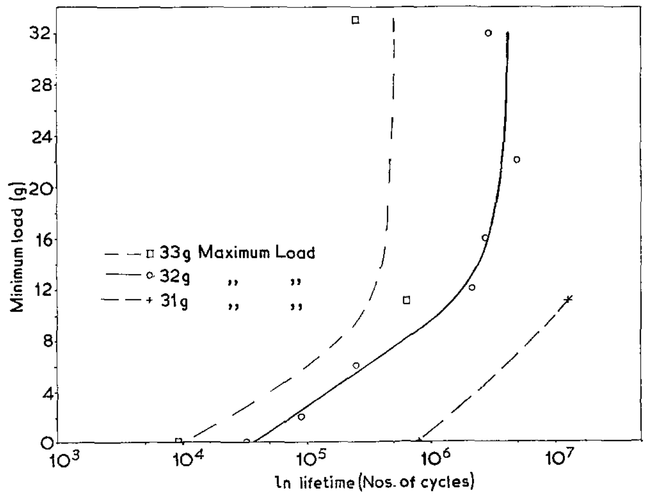

Figure 10 Median survival lifetimes for Kevlar-49 fibres cycled at 50 Hz to different maximum loads showing the influence of the minimum load experienced throughout the cycling.

strain energy dissipated in the splitting of the fibre results in a large total fracture surface area.

The creep behaviour of Kevlar-49 has been shown to be very similar to that of Kevlar-29 [12]. Both fibres show little tendency to extend under a steady load and after a few minutes appear to be fully stabilized. This supports the view that after some readjustment the molecular structure becomes locked and further movement under a constant applied load is inhibited.

The reduction in lifetime with increasing oscillatory load but with the maximum load held constant, for example from 2.5×10^6 cycles to 3.5×10^4 cycles with a constant maximum load of 32 g, is evidence of the existence of a fatigue mechanism. The complex splitting in fatigue failure does not suggest a mechanism of ordered crack growth as is found in nylon fibre and it more closely resembles the fatigue failure of acrylic fibres. A zero minimum load is clearly not necessary for the fatigue failure of the Kevlar-49 fibre and this is again similar to the acrylic fibres. The existence of swarf on even the untested fibre has made clear evidence of early fatigue damage difficult to obtain but failure most probably occurs after splitting of the fibre which originates at some surface or possibly internal flaw. After initiation a split would easily develop in a longitudinal direction because of the low radial strength and failure would occur when the load bearing cross-sectional area was sufficiently reduced so as to cause failure under the maximum applied load. The initiation of the split may be as a result of stress concentrations at flaws in the fibre or be due to fretting of parts of the fibre separated from the time of manufacture.

TABLE III Summary of the fatigue properties to be expected with a number of polymeric fibres

Fibre type	Usual range of fatigue lifetimes when cycled from 0–80% UTS (cycles × 10^5)	Minimum load to cause fatigue failure (% UTS)	Comments
Kevlar-49	0.5–25	80	Lifetime varies greatly with magnitude of oscillatory load
Nylon 66	0.5–1.25	60	Zero minimum load criterion for fatigue failure
Nomex	0.1–0.6	60	
Polyester	0.9–5	70	
Courtelle (PAN)	0.1–2.5	65	Small oscillatory load superimposed on high steady load will cause fatigue failure

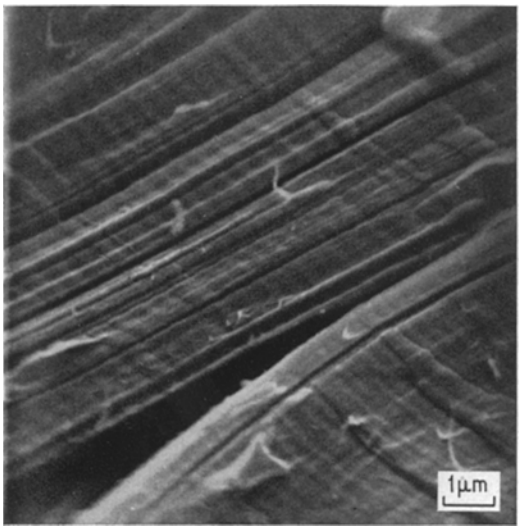

Figure 11 End region of a split in one end of a fractured Kevlar-49 fibre showing markings at right angles as well as parallel to the axial direction.

This latter process would be exacerbated with larger oscillatory loads and could lead to the observed fatigue behaviour.

The high loads and large numbers of cycles to which the Kevlar-49 fibre has to be cycled for fatigue failure to occur means that fatigue of the individual fibres in a cable or composite should not be a serious hazard. The possibility of fatigue should not be completely ignored, however, as in any fibre structure under load there exists a distribution of loads to the individual fibres, some of which may be carrying considerably higher loads than that nominally applied. In addition this study has not investigated other effects such as wear and abrasion between fibres which could cause the failure of Kevlar-49 fibres when used collectively under cyclic loading conditions.

6. Conclusion

Within the confines of this study of the monotonic tensile and tensile fatigue properties of Kevlar-49, the fibre has been found to have high strength, modulus and resistance to fatigue damage when compared to other polymeric fibres tested under similar conditions. The fatigue properties of several types of fibre are summarized in Table III. The fracture morphology of the fibre indicates a low radial strength and a failure mode similar to that of highly drawn polyacrylonitrile fibres. Kevlar-29 was found to suffer little from the effect of creep when subjected to a constant applied load.

Based on these findings, Kevlar-49 should have a useful role to play in tensile load bearing structures whether they are cables or composite materials.

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