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The fatigue behaviour of Kevlar-29 fibres

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Single Kevlar-29 fibres have been subjected to a variety of tensile cyclic and steady loading conditions. The dispersion of tensile strengths of the samples tested was found to be inherent to the fibre due to the distribution of defects in it and not due to variations of diameter between samples. Cyclic loading was found to produce both longer and shorter lifetimes than those recorded under steady loads equal to the maximum cyclic load. Longer lifetimes indicated failure due to creep mechanisms whereas shorter lifetimes, seen with greater load amplitudes, suggest a fatigue mechanism. No difference was seen in the fracture morphologies of Kevlar-29 fibres broken under simple tensile, fatigue and creep conditions because of the complex splitting which occurs in all cases.

1. Introduction

Aramid fibres, produced under the commercial name of Kevlar by Dupont de Nemours, are finding increasing applications where their high tensile strength, Young's modulus and structural stability may be exploited. Table I shows some physical properties of Kevlar fibres compared to those of other fibres. It will be seen that these aramid fibres fit into the class of reinforcing fibres such as are used for composite materials and they possess properties which are very different from those of traditional textile fibres. The remarkable properties of these fibres are due to their molecular structure which consists of rigid chains aligned parallel to the fibre axis and which is highly ordered leading to a high degree of crystallinity. The chemical structure of Kevlar fibres, as given by the manufacturers, is shown in Fig. 1. The molecular structure of the fibres has been extensively studied and described by Dobb *et al.* [1] who have shown that superimposed on the axial alignment there is a radial arrangement of pleated sheets.

Although the fibres are strong and rigid in tension it has been known for some time that they are weak in axial compression [2] which has been shown to be associated with the development of slip bands [3]. A recent study by Lafitte and Bunsell has also shown that the fibre is weak radially [4]. This weakness in directions other

TABLE I Comparison of the properties of a number of different filaments

Sample	Strength ($GN\ m^{-2}$)	Modulus ($GN\ m^{-2}$)	Breaking strain (%)	Density ($g\ cm^{-3}$)	Specific strength (km)	Specific modulus (km)
Kevlar 29	2.60	62.0	4.2	1.44	190	4 300
Kevlar 49	2.70	130.0	2.0	1.45	190	9 000
Nylon T 728	1.00	5.6	18.5	1.14	88	500
Nomex	0.65	20.0	23.0	1.38	47	1 450
Steel	2.80	200.0	2.0	7.83	36	2 550
Boron	3.00	370.0	1.0	2.70	110	14 000
Glass	3.50	70.0	4.8	2.54	137	2 750
Carbon HS	2.70	270.0	0.8	1.80	150	15 000
Carbon HM	2.00	400.0	0.5	1.95	108	20 000

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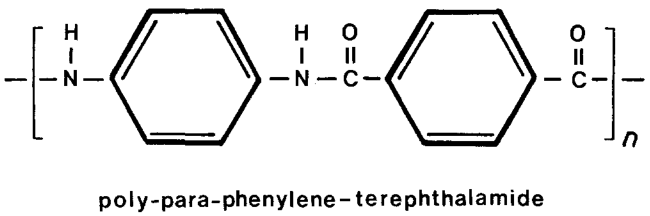

Figure 1 Chemical structure of Kevlar-29 fibres (after Du Pont de Nemours).

than the axial and in tension is apparent in the fracture morphology of the fibres which fibrillate greatly on failure, see Fig. 2.

As the Kevlar fibres are very different from other fibres and it is proposed to use them to replace more conventional materials such as steel wire in structures such as cables and tyres it was considered important to study their behaviour under cyclic conditions.

The difficulties of conducting fatigue tests on fibres have been expounded by Hearle [5] who showed that the best way of doing so was by load cycling in which the maximum load on the fibres was kept constant. Other types of test such as accumulative extension cycling have been shown to lead to ambiguous results whereby failure after cycling can be caused by the tensile breaking strain being reached and not because of any specific fatigue mechanism [6]. In order to conduct load cycle tests it is necessary to compensate for the accumulated plastic strain which develops due to the plastic and viscoelastic behaviour of the fibres. A fibre fatigue tester was developed by Bunsell *et al.* [7] which was capable of conducting cyclic load tests on very fine fibres. The fineness of fibres, Kevlar has a diameter of 13 μm, means that only tension–tension cyclic tests may normally be envisaged without introducing the possibility of wear by passing the fibre over a pulley.

Load cycling has revealed distinctive fatigue mechanisms in a number of fibres. Bunsell and Hearle [8] showed that nylon 66 fibres can fail by a fatigue mechanism which leads to a characteristic fracture morphology which is clearly different from that in tensile or creep failure. It was found that nylon 66 fibres would fail in fatigue only if the maximum load was above about 60% of the nominal fibres breaking strength and that the minimum load was zero. Similar

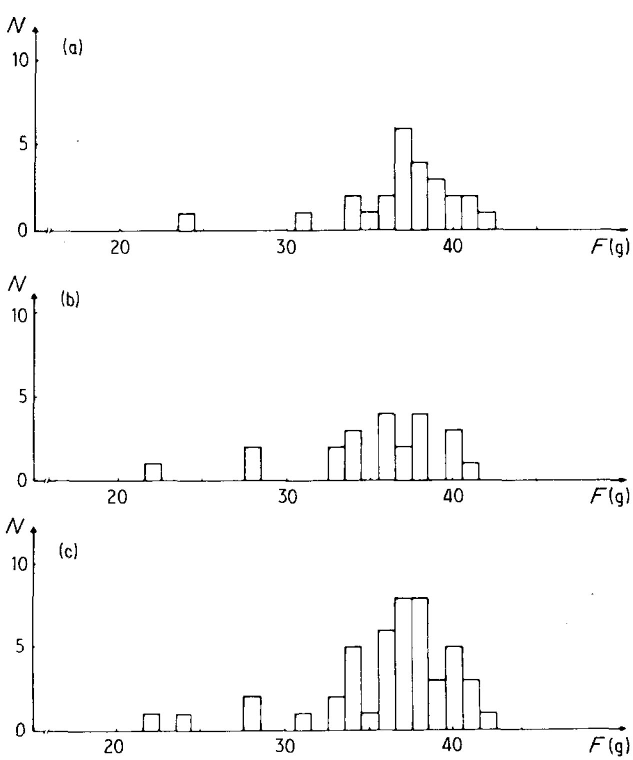

Figure 2 Distribution of fibre strengths of two lots of samples containing (a) twenty and (b) forty fibres together with (c) the result of combining the two.

behaviour was found in Nomex and polyester fibres [9]. Polyacrylonitrile fibres were found to fibrillate on cyclic loading due to their weak radial strength and it is thought that the effects of cyclic loading are different for PAN fibres from those in the other fibres mentioned [10]. The high modulus form of Kevlar-49 was tested under cyclic load conditions and found to fibrillate in a way not dissimilar to that of PAN fibres [11]. Kevlar-49 was found to be resistant to cyclic loads and did not fail unless the maximum applied load was greater than 80 % of the tensile strength. A zero minimum load was not found to be a criterion for fatigue failure although the fatigue lifetime fell as the load amplitude increased: Kevlar-49 was found to quickly stabilize under creep conditions. A study by Konopasek and Hearle [12] suggested that cyclic loading led to even greater fibrillation of the fibre at failure.

Kevlar-29 has the same strength but only half the modulus by Kevlar-49 and is increasingly being used for high performance cables [13].

2. Experimental procedure

In this present study all tests were conducted at room temperatures (20° C) and at a frequency of 50 Hz. The specimen gauge length was 50 mm and the fibre was glued onto a cardboard frame which acted as support before the test and which was cut for the test. A length of the fibre to be tested was retained for diameter measurements using a Watson image shearing eyepiece.

The fatigue apparatus was a version of one described elsewhere [7]. The fibre was gripped between two sets of jaws. One set was connected to a vibrator capable of operating at frequencies between 0 and 10 kHz and having a movement of ± 3 mm at 50 Hz. The upper jaws were connected to a piezoelectric transducer and a cantilever beam onto which was glued a Wheatsone bridge. In this way electrical signals were obtained which were proportional to the cyclic and mean loads on the fibre. Associated electrical circuits summed the two values and an electrical signal was obtained proportional to the maximum load. This signal was used in a servo system which operated a motor controlling the distance between the jaws. Any variation of the maximum load started the motor and the load in this way was controlled to within 0.1 g.

Creep tests were conducted in order to determine the effects of steady loading on the fibre and these tests were carried out on a modified version of the fatigue apparatus. The vibrator was replaced by a fixed jaw and only the signal from the strain gauge bridge was used to control the applied load. As for the fatigue tests, a displacement transducer was used to measure deformation, and time to failure was recorded by an automatic counter which was switched off when the load on the fibre fell to zero.

Due to the scatter in properties amongst individual fibre samples it was necessary to conduct a large number of tests in order to obtain an average value under each testing condition. In order to determine just how many tests were necessary for each value a comparison was made between two lots of fibres, one contained twenty specimens, the other forty. It was found that under creep conditions the same spread in results was seen with the two lots and the median lifetime to failure for each lot was the same. It was therefore decided to use twenty specimens in order to obtain each average point.

3. Experimental results and discussion

Fig. 2 shows the spread of tensile properties obtained by a simple tensile test to failure at a speed of 2% strain mm^{-1}. Sixty fibres were broken and a mean breaking strength of 36 g was determined.

TABLE II Constant load amplitude conditions used in the tests with different maximum applied loads

Load amplitude (g)	Maximum load (g)	% of ultimate strength	$R = \frac{\sigma_{min}}{\sigma_{max}}$
12.5	32	90	0.22
	30	83	0.17
	28	77	0.11
	25	70	0.00
10	30	83	0.33
	28	77	0.28
	25	70	0.20
	20	56	0.00

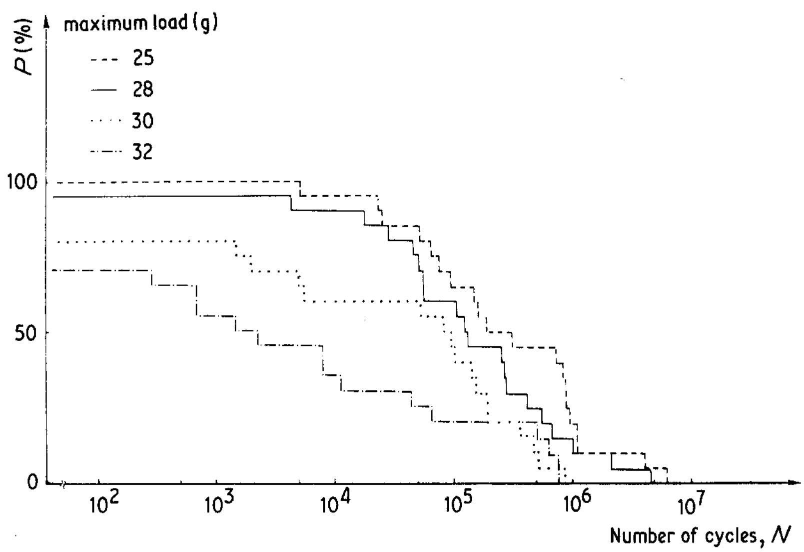

Figure 3 Lifetimes of Kevlar-29 fibres subjected to load cycling with an amplitude of 12.5 g and different maximum loads.

In order to study the effects of cyclic loading two types of tests were conducted. The first involved keeping the load amplitude constant but varying to maximum applied load, the second consisted of maintaining the maximum load constant and varying the load amplitude. Steady loading and creep deformation made up part of the second type of test in order that the possibility of failure under cyclic loading by a purely creep process could be examined.

Table II shows the conditions of loading used under constant load amplitude conditions and Figs 3 and 4 show that the lifetimes obtained were reduced as the maximum load was increased. This is as would be expected if the fibres were failing due to creep but it can be noted that the mean lifetimes with a maximum applied loads of 25 g and 20 g were equivalent when a load amplitude of 10 g was used. Failure solely by a creep mechanism seems an unlikely explanation for this observation.

After the first few cycles the fibre was seen to behave in a nearly elastic manner with little energy dissipated as was shown by an almost non-existent load–displacement hysteresis loop. We are entitled to conclude therefore that little heating of the fibre occurred and that it had no accelerating effect on failure in these tests.

Table III shows the conditions of loading used in constant maximum load tests and Fig. 5 shows the range of lifetimes obtained. Fig. 5a shows that there was an influence of the load amplitude for a given maximum load. As the load amplitude increased so the lifetime decreased indicating an

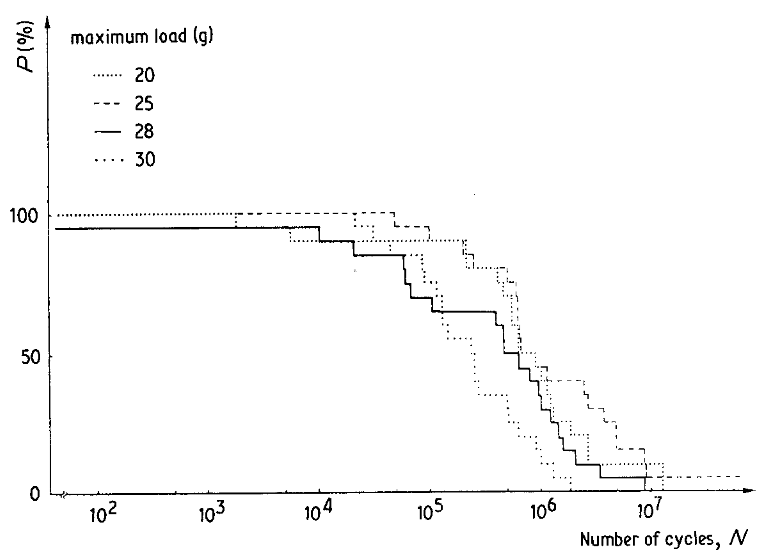

Figure 4 Lifetimes of Kevlar-29 fibres subjected to load cycling with an amplitude of 10 g and various maximum loads.

TABLE III Loading conditions in which different load amplitudes were used with one of two maximum applied loads

Maximum load (g)	Load amplitude (g)	Minimal load (g)	$R = \frac{\sigma_{min}}{\sigma_{max}}$
25*	12.5	0	0.0
	10	5	0.2
	0	25	1.0
28†	12.5	3	0.11
	10	8	0.28
	0	28	1.00

*70 % of nominal breaking load
†78 % of nominal breaking load

acceleration of damage. Fig. 6 shows that with a maximum load of 28 g both longer and shorter mean lifetimes than found under steady loads were obtained depending on the load amplitude. A load amplitude of 10 g produced longer lifetimes, indicating creep dominated behaviour whereas an amplitude of 12.5 g produced shorter lifetimes which suggests a fatigue effect. It can also be noted that under cyclic loading with a maximum load of 25 g and a zero minimum load, all fibres failed before 10^7 cycles. Under creep conditions with the steady load of 25 g, 25 % of the specimens remained intact after a period of time equivalent to 10^7 cycles. This observation lends support to the possibility of the existence of a fatigue damage accelerating process.

Fig. 7 shows the effect of load amplitude and of the maximum applied load. A zero amplitude is the same as a creep test and it can be ssen that under these steady conditions the relationship between lifetime and maximum load σ_{max} is given by

$$\frac{\sigma_{max}}{\sigma_R} = A \log t + B, \qquad (1)$$

in which t is time. A and B are constants and σ_R is the nominal breaking load.

It can be seen from Fig. 7 that two domains of failure were found to exist. Those points above the line of creep failure correspond to cyclic tests which produced longer lifetimes than a creep test at a steady load equal to the maximum cyclic load applied. Those below correspond to accelerated failure due to the cyclic loading and so can be termed fatigue failure.

The fracture morphology obtained under these fatigue conditions was considered to be indistinguishable from that obtained in simple tensile tests.

4. Discussion

The wide scatter in tensile properties of Kevlar fibres must be considered as a material property.

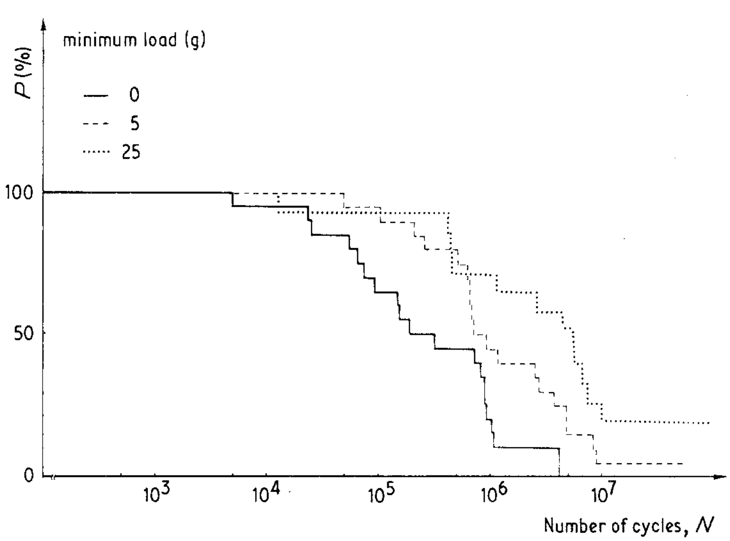

Figure 5 Failure distributions of Kevlar-29 fibres subjected to load cycling with various load amplitudes which are given in Table III.

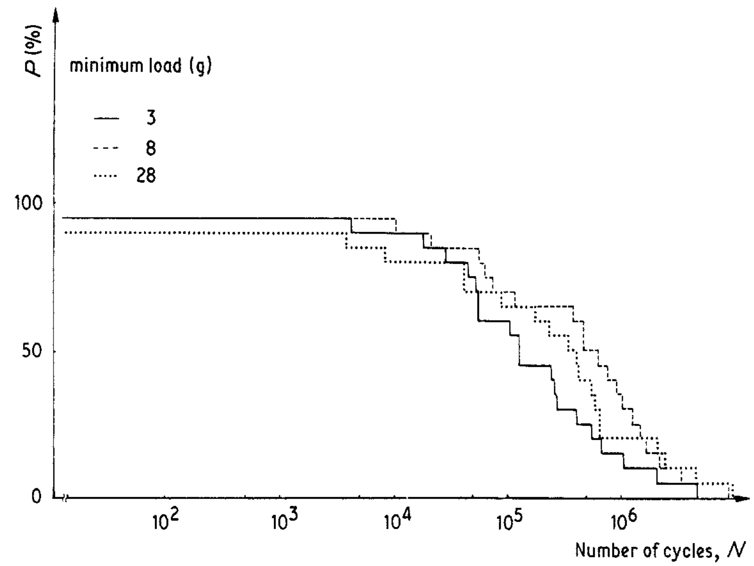

Figure 6 Failure distribution of Kevlar-29 fibres subjected to load cycling with various load amplitudes given in Table III and a maximum applied load of 28 g.

A considerable scatter in properties of all fibres is only to be expected, however Kevlar fibres contain defects of all sizes from those which can be seen with the naked eye presumably down to the molecular level. The scatter which has been observed was found not to be due to variations in fibre diameters in the bundle tested. This was shown by selecting several long fibre specimens and removing from each of them 10 tensile specimens. The same scatter in results was obtained as if the fibres had been selected randomly from the bundle showing that the scatter was due to the distribution of faults on the fibre.

The structure of the fibre is highly anisotropic with a low transverse strength leading to splitting upon failure under tensile loading conditions. One simple exception to this is a failure produced in tension after kinking of the fibre [3]. Cyclic loading can lead to failure and the mechanism which dominates may be creep. In this case the lifetime is longer than that obtained under steady loading at the maximum load level. This is because under cyclic conditions the fibre is not subjected continuously to the maximum load. At greater load amplitudes the median lifetimes obtained were found to be shorter than those found under creep conditions indicating an accelerating process. This process could be internal heating of the fibre although given the small mechanical hysteresis which is observed this seems unlikely. The conclusion therefore is that the type of loading has an influence and the fatigue degradation is occurring. The influence of the loads applied is not as simple as in the case of, say, nylong fibres where a zero minimum load is a criterion for fatigue failure.

The absence of a distinct failure fracture mor-

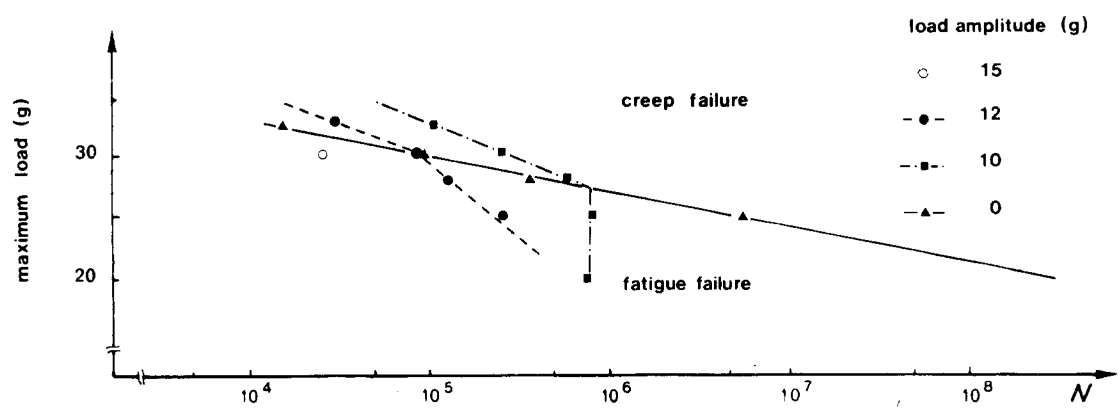

Figure 7 Effect of load amplitude and maximum applied load on lifetimes. The solid line represents creep failure under equivalent length of time.

phology is not surprising as the fibre fibrillates to a great extent even under simple tensile conditions. This type of failure seems similar to that found with polyacrylonitrile and Kevlar-49 fibres and may involve the production of internal cracks in the fibre in contrast to the surface initiated fatigue failures found with nylon and polyester fibres [10, 14].

5. Conclusion

Kevlar-29 fibres show considerable scatter in their mechanical behaviour under both steady and cyclic loading conditions. Failure of these fibres under cyclic conditions may be induced by a creep mechanism or a fatigue mechanism which becomes predominant. The fracture morphologies under tensile, creep and fatigue condition are indistinguishable due to the splitting of the structure. The origin of the splitting may be at a defect on the surface or inside the fibres.

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