Fatigue in Fibres and Plastics (A Review)

J. W. S. HEARLE
Department of Textile Technology, The University of Manchester Institute of Science and Technology, Manchester 1, UK

A review is presented of studies of fatigue in fibres and plastics. The nature of fatigue in visco-elastic systems is discussed, and the reasons for the use of cumulative extension testing are given. A model is described showing the importance of imperfect elastic recovery and of time-dependent effects in determining behaviour in a fatigue test. Superimposed on this, there may be some true fatigue effects. Using this model, a more rational explanation of experimental results, which are otherwise confusing, is attempted.

1. Introduction

The word *fatigue* is rather loosely used as a description of behaviour in polymeric materials; the first necessity is to clarify its meaning. This is more than a mere matter of terminology: it is necessary to study the subject in detail to discover what phenomena are involved – to discover, indeed, whether there is anything that can properly be called fatigue. An interesting distinction is made by Frank and Singleton [1] between *fatigue-testing*, covering a variety of experimental procedures, and *fatigue-failure*, implying a specific mechanism of rupture.

Fatigue-testing can be defined as the subjection of specimens to cyclically varying stress or strain leading ultimately to breakage. This definition eliminates the inclusion of dynamic tests which do not cause break, and also eliminates the failure of a specimen after some time under a constant load. The latter type of test is sometimes referred to as static fatigue, but is better regarded as a creep test leading ultimately to the breaking extension, with the possibility that the breaking extension and the nature of the break may depend on the type of test and may be a function of the time to break.

Table I describes the basic structural features of fibres and plastics. We shall not be concerned in this paper with rubber-like amorphous polymers, or with any composite systems such as textile fabrics containing many fibres in particular structural arrangements, tyres containing rubber and cord, or fibre-reinforced plastics.

In metals, "fatigue" commonly implies failure after a large number of applications of stress at a level below the elastic limit of the material: the strains are very small. In many fibres and plastics, the problem is different because there is no clear division between elastic and plastic regions of deformation, because the strains are often much larger, and because these materials are visco-elastic and so their properties are strongly time-dependent. Table II gives a comparison between the results of typical fatigue tests on metal and fibre. The term "fatigue" can also be used for failure of metals after a few reversals at large strains, above the yield point; and this effect is closer to the behaviour of visco-elastic materials, especially for pure, soft metals of low melting point.

The subject of fatigue in fibres and plastics also differs from the subject of fatigue in metals in that much less work has been done on it. There is much less experimental information, and the theoretical approaches to the best methods of test procedure, the best ways of expressing results, and the explanation of the phenomena are less highly advanced.

The deformation and damage which an imperfectly elastic material suffers during fatigue-testing is of two sorts. Firstly, there are effects which are incidental to fatigue-testing in the sense that they can, in principle, be predicted from a knowledge of the stress/strain/time and recovery properties obtained in other simple tests. These effects include: (i) continuing deformation, resulting from imperfect recovery in successive cycles if the slack is taken up during the test; (ii) continuing creep and stress relaxation effects; (iii) rise in temperature, and its effects, resulting from the loss of energy in

TABLE I Classification of plastics and fibres.

Type	Molecular nature	Character	Examples
Thermo-set plastic	Irregular three-dimensional network	Hard, rigid, infusible	Ebonite, Bakelite
Glassy thermoplastic	Linear, amorphous, rigid network	Hard, rigid; softening to visco-elastic with large energy losses, and then to elastic rubber	Perspex, polystyrene
Tough plastic	Linear, partially crystalline, unoriented	Moderately extensible, tough, reasonably elastic, fusible	Polythene, bulk nylon
Fibre or film	Linear, partially crystalline, oriented	Moderately extensible, high strength and elasticity in preferred direction, fusible	Cotton, nylon, Cellophane

TABLE II Typical conditions for fatigue-failure.

	Copper	Nylon
Type of test	Cycles of constant stress	Cumulative extension cycling
Number of cycles to failure	10^5	10^5
Maximum stress (kg/mm^2)	20	20
Extension	0.2%	10%
Type of deformation of bulk of material	Elastic	Visco-elastic + plastic

cyclic deformation. Secondly, there may be effects which are specifically due to the fact that stress is repeatedly applied and removed. These may include: (i) true fatigue-failure, due to some form of crack growth, often limited to regions of high localised deformation; (ii) general weakening of the material, due to structural damage or chemical degradation.

If composite specimens are used, there is also the possibility of damage due to forces between the individual components: thus there may be frictional wear between the individual fibres in a textile yarn.

It is important in studying fatigue to try and sort out which of these various factors are effective, and not to require all the results to be explained by a single mechanism. Our first task must therefore be to see how the first group of effects can be recognised: we shall then be in a position to examine experimental data and see whether any effects from the second group remain.

Note on units Results in the literature are reported in a variety of stress units. Studies on plastics use the usual physical definition of stress as *force per unit area*; the possible units include newton/m^2, dyn/cm^2, kgf/mm^2 or kg/mm^2, and lb/in.^{2} or psi. The choice of units depends on how far an author wishes to conform to modern academic preference or to older practical usage.

In fibre and textile studies, there are several strong reasons for replacing the above definition of stress by *specific stress* defined as *force per unit linear density*. Indeed, this practice can be commended for wider use, since the mass is a more basic property of a specimen than its volume. Linear density (or mass per unit length) is commonly expressed in *denier*, namely gramme per 9000 m; but there is a strong movement to replace this by a proper metric unit: *tex*, namely gramme per 1000 m. Specific stress thus has units of gf/denier or gf/tex, usually abbreviated to g/den or g/tex. The unit gf/tex is identical with the unit kmf or km, namely the force exerted by the weight of a given length of the material. The relation between stress and specific stress involves the density of the material.

The following are conversion relations for some of these units:

$$1 \text{ kgf/mm}^2 = 9.81 \times 10^6 \text{ newton/m}^2 = 1422 \text{ lb/in.}^2$$

$$1 \text{ gf/den} = 9 \text{ gf/tex}$$

If f = stress in kgf/mm^2, σ = specific stress in gf/tex, and ρ = density in g/cm^3, then:

$$f = \rho\sigma$$

2. The Nature of Fatigue-Testing of Fibres

2.1. Experimental Methods

There are a number of problems connected with the choice of experimental method for the study of fatigue in fibres. Because the material is not elastic, it is not possible to regard a given, imposed, constant strain variation as equivalent to a constant stress variation. Furthermore, in the simplest form of deformation, namely holding a fibre specimen at each end and changing the length, negative stresses are not possible because the fibre buckles. We are thus limited to the positive quadrant of the stress/strain diagram.

Rejecting any empirical method which gives an ill-defined combination of stress and strain variation, we are left with the possibilities of cyclically varying the tension or extension of the specimen between fixed limits. The first alternative is experimentally difficult, because of the need to maintain a reproducible load variation in a specimen which is both changing considerably in length during each cycle and steadily increasing in mean length (or length under zero load). The behaviour of fibres under long periods of load-cycling has consequently been little studied; it is, however, a method which ought to be examined and attempted more.

Simple extension cycling is the easiest method. The specimen is held between two clamps and one of them is subjected to a cyclic change of position. The difficulty with this method, as we shall see, is that the specimen becomes slack owing to imperfect recovery and is not under tension during a large part of each cycle. Unless the imposed extensions are very large, it is difficult to get failure.

In order to get failure, most investigators have adopted the technique of removing the slack at the end of each cycle, and then imposing the given extension stroke on the specimen which is once again just taut. This is known as cumulative extension testing. A typical form of apparatus used by Booth and Hearle [2] is illustrated schematically in fig. 1. The specimens

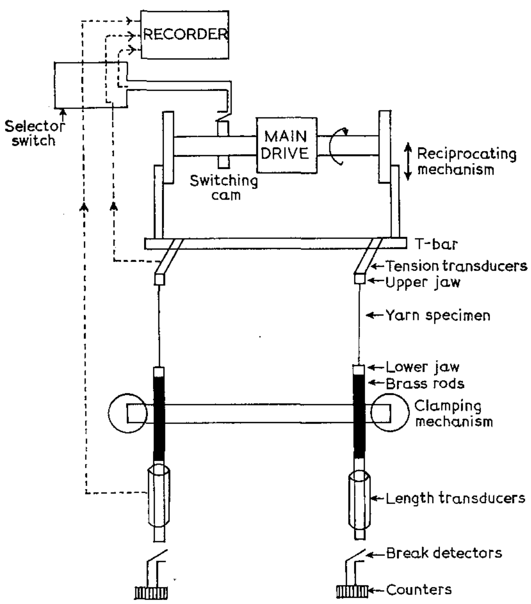

Figure 1 Schematic view of cumulative extension tester (Booth and Hearle [2]).

are clamped between pairs of jaws arranged in vertical alignment. The upper jaws are subjected to a reciprocating motion from the main drive, to which they are connected through phosphor bronze strips mounted with strain gauges in order to allow variation in tension to be followed. The lower jaws are held clamped electromagnetically during the extension, but at the lower part of each stroke the clamps release and the slack is taken up by the action of the small weight of the lower jaw assembly. Below the lower jaws are soft iron rods projecting into mutual inductance coils, allowing changes in length to be followed. Counters record the number of cycles and are cut off by a break detector when a sample fails. In the next section, the behaviour in cumulative testing will be discussed in detail.

Other forms of deformation which can easily be used on fibres are torsion and bending. With these, it is possible to go through the origin and to subject the fibre to alternating positive and negative stresses and strains. An interesting biaxial-rotation method was used by Lyons and Prevorsek [3]. The fibre specimen was held in two chucks with axes at 90°, as shown in fig. 2. The fibre is thus in tension on the outside and in compression on the inside of the bend. On rotation, the material is subject to alternating tension and compression, but there is no torsional deformation if the two chucks are driven in synchronism.

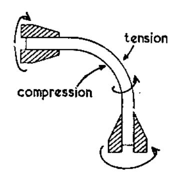

Figure 2 Biaxial-rotation method.

2.2. Cyclic Deformation of Plastic and Visco-elastic Materials

The effects of imperfect recovery in a cumulative extension test have been discussed in terms of a simple model, illustrated in fig. 3, by Booth, Hearle, and Plonsker [2, 4]. If the extension in the n^{th} cycle is ϵ_n, the elastic recovery (i.e. the fraction of the total extension which is recovered) from this extension is r_n, and, if the extension stroke is ϵ_1, then the extension ϵ_{n+1} in the $(n+1)^{\text{th}}$ cycle will be given by:

$$\epsilon_{n+1} = \epsilon_n(1 - r_n) + \epsilon_1 \qquad (1)$$

If it can be assumed that elastic recovery is a function only of the maximum strain reached,

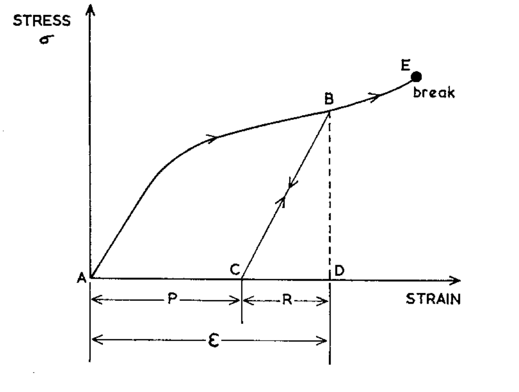

Figure 3 Basis of simple model of recovery behaviour: $R = r\epsilon$; $P = (1 - r)\epsilon$.

and is independent of the time or number of cycles, it is then possible to use equation 1 to calculate the gradual increase of extension in a cumulative extension test in which the slack is removed after each cycle of a given imposed extension.

It also follows from equation 1 that, if $\epsilon_n r_n = \epsilon_1$, then $\epsilon_{n+1} = \epsilon_n$, and no further extension occurs. Depending on the elastic-recovery properties of the material and the magnitude of the imposed stroke, we can then expect to observe two possible forms of behaviour: (i) the specimen may extend in successive cycles until it reaches its breaking extension and breaks; or (ii) the specimen may extend over a number of cycles, finally reaching a limiting extension which remains constant.

The simple behaviour may be modified if the materials show either primary creep (i.e. a time-dependent deformation recoverable in time) or secondary creep (i.e. a non-recoverable deformation with time under stress). If there is secondary creep, then, even in fixed extension cycling, the proportion of the total extension which is non-recoverable will increase as time goes on. In a cumulative extension test, this means that the amount of slack to be removed will gradually increase as time goes on, and so, instead of reaching a constant limiting extension, there will be a slow increase of the maximum extension achieved.

2.3. Comparison of Ideal and Experimental Behaviour

Fig. 4 shows the behaviour of idealised specimens, in which elastic recovery is a function only of the maximum strain, under three different forms of cyclic deformation. In fixed extension cycling, the pattern of all cycles, after the first, is elastic extension up to a given stress level, in what is now a mechanically conditioned specimen, but with the specimen slack during a substantial part of each cycle. Cycling between given stress limits gives a pattern differing only in the absence of the slack period. Cumulative extension cycling, on the other hand, leads to a steady increase of the maximum stress reached.

Fig. 5 shows comparable experimental data. The pattern is generally similar to that of fig. 4, except that there is marked non-linearity and that the effects of secondary creep appear as a

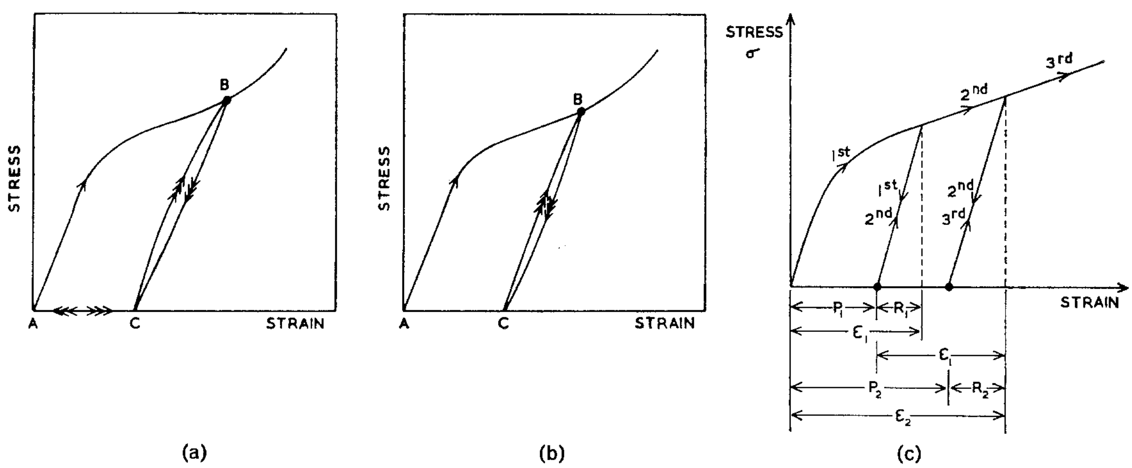

Figure 4 Behaviour of specimens showing idealised recovery behaviour: (a) in fixed extension cycling; (b) in load cycling; (c) in cumulative extension cycling.

gradual reduction of stress in fixed extension cycling and a gradual increase of maximum extension in constant stress cycling. The cumulative extension test shows an approach in a few cycles to the breaking extension of the specimen: this demonstrates the first type of behaviour discussed in the previous section.

Fig. 6 shows a comparison of experimental results during cumulative extension testing with the change in extension predicted by equation 1 using experimental elastic-recovery values. At large, imposed extensions, the specimen extends rapidly and there is good agreement between experiment and theory, particularly if elastic-recovery values after a number of cycles are used in evaluating the equation. At small, imposed strokes, there is evidence of approach to a limit as predicted by theory, though at a higher value of total extension and with some continuing increase which can be attributed to the visco-elastic effects.

2.4. A Possible Pattern of Failure in Cumulative Extension Fatigue-Testing

Final failure is always subject to a large statistical variation between individual specimens, since it is due to the occurrence of some point of exceptional weakness. Failure is always dominated by the extreme values of a frequency distribution where uncertainty is greatest. The gradual extension in cumulative extension tests will thus lead up to a distribution of breaking-extension values, and hence to a distribution of fatigue lives, even if there is no variability in the deformation behaviour. Fig. 7 is a representation of this behaviour, drawn in a linear fashion for the sake of clarity and ease in calculation, and because any attempt to put in smooth curves

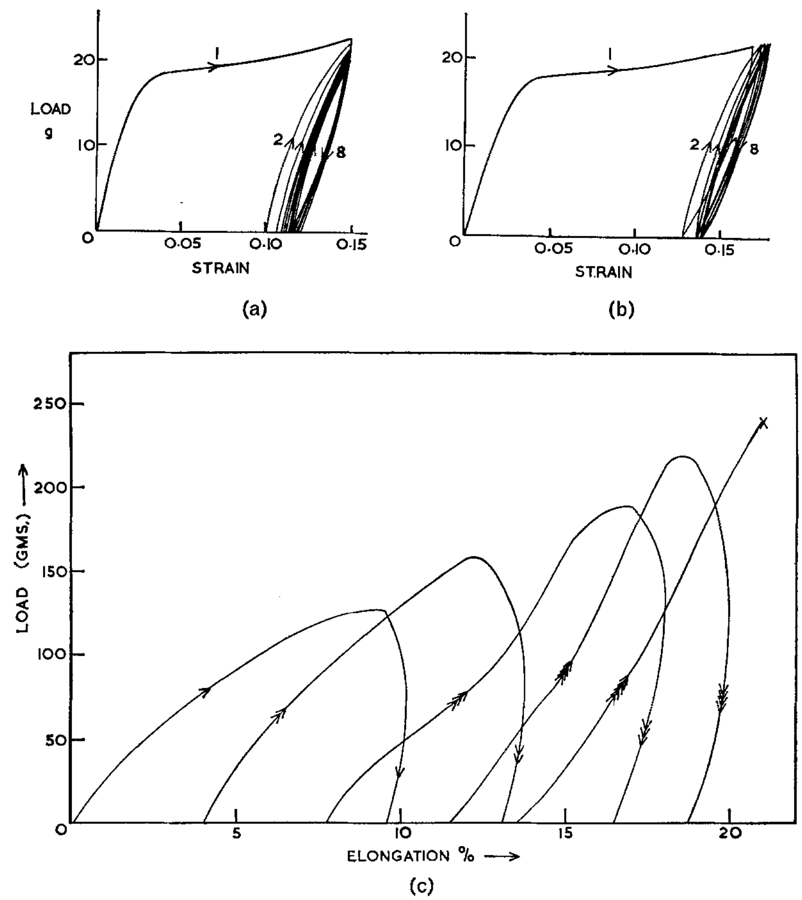

Figure 5 Actual experimental behaviour: (a) cellulose acetate fibre, in fixed extension cycling (Hearle and Plonsker [4]); (b) cellulose acetate fibre, in load cycling (Hearle and Plonsker [4]); (c) viscose rayon yarn, in cumulative extension cycling (Booth and Hearle [2]).

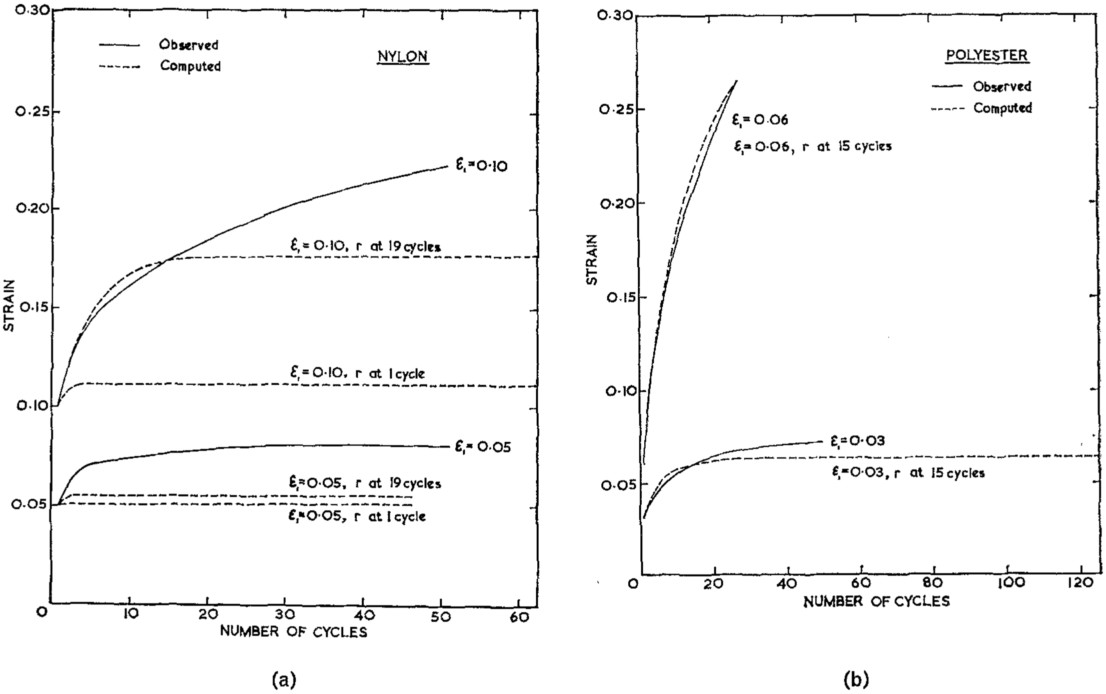

Figure 6 Cumulative extension testing – comparison of theory and experiment (Hearle and Plonsker [4]): (a) nylon fibre; (b) polyester fibre.

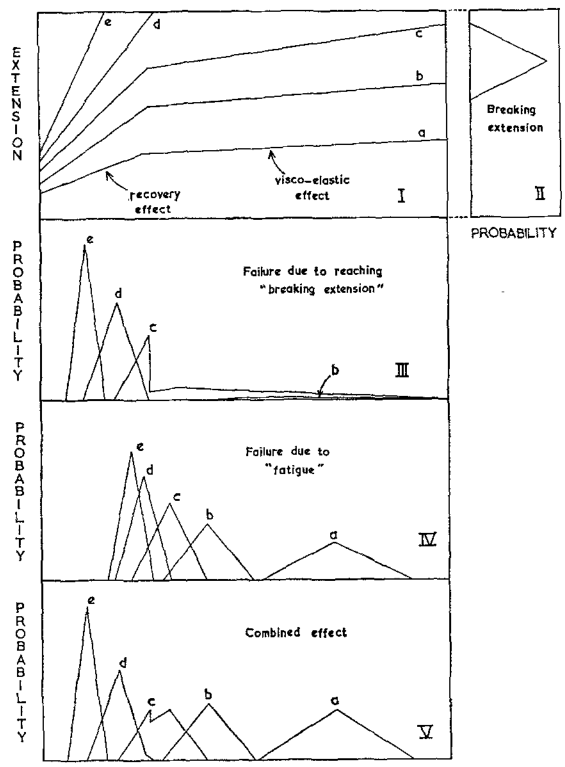

Figure 7 Schematic representation of failure mechanism in cumulative extension testing.

would merely give a spurious air of exact validity to what is only intended to be a schematic indication of the mechanisms involved. The diagram I shows the combination of the elastic-recovery effects of equation 1 leading into a slowly increasing extension due to visco-elastic effects, at increasing stroke levels, a to e. This deformation will interact with the breaking-extension distribution (II) to give the failure distribution shown in diagram III. At large strokes, all the specimens will fail, owing to the elastic-recovery effects; at intermediate strokes, some will; at low strokes, none will. In addition, some specimens, which survive the elastic-recovery sequence, may fail owing to the visco-elastic effects leading to the breaking extension.

We now postulate that failure may also occur owing to fatigue effects specifically associated with the repeated application of stress. In the absence of failure due to other causes, the frequency distributions for fatigue-failure are indicated in diagram IV. This will compete with failure due to reaching breaking extension (III), and the combined distributions are shown in diagram V. At high strokes and short life, elastic-recovery effects dominate; while at low strokes and long lives, we have fatigue-failure. At intermediate strokes, both effects contribute and, with the particular values used, a bimodal distribution occurs.

It must be emphasised that fig. 7 is purely schematic. Real behaviour will depend on the exact form and placing of the deformation curves and the frequency distributions. Thus the visco-elastic effects which do not have much effect on diagram V could, if the fatigue distributions were displaced to longer times, have more effect. There are also many other parameters, such as frequency, temperature, and so on, which may modify the curves. The breaking-extension distribution may be affected by the history leading to break. Nevertheless, we shall find that fig. 7 does give us a useful framework for the discussion of fatigue in fibres.

3. Results of Fatigue Studies

3.1. Behaviour of Yarns in Load-Cycling

Kelly [5] has recently published a set of results in which he investigated the failure of continuous filament yarns subjected to up to 2000 repeated applications of load on an Instron tester. Table III gives a typical set of results.

TABLE III Comparison of Kelly's [5] experimental results with prediction from time to break.

Number of	Relative breaking load ($100F_2/F_1$)	
cycles	Observed	Predicted
1	100	100
100	86	84
1000	72	76

Hearle [6] has pointed out that these measurements can be explained to a considerable extent in terms of breaking-times. For fibres and yarns subject to simple tensile tests over a very wide range of rates of extension, Meredith [7] found agreement with the empirical equation:

$$F_2 - F_1 = k \log_{10} (t_2/t_1)$$

where F_1 and F_2 are the breaking-loads in times t_1 and t_2 respectively, and k (which is negative) is the strength/time coefficient.

Treating a repeated loading test in the same way, with t_1 put equal to the period of one cycle, and F_1 as the load to break in one cycle, we have $t_2/t_1 = N =$ the number of cycles to failure under a load F_2. The relative breaking strength as a percentage plotted by Kelly will thus be given by:

$$100F_2/F_1 = 100(1 + k \log N)$$

With $k = -0.08$, as found for nylon by Meredith, we obtained the theoretical values given in table III. These agree reasonably with Kelly's experimental values and indicate that the major effect in his tests is the same as is found in tensile tests at different rates. He does, however, find some effect of rate of cycling – for instance, a Fortisan yarn shows an expected failure after 1000 cycles at 79% of breaking strength at 11 c/min and at 69% of breaking strength at 26 c/min – and this suggests that the intermittent character of the loading does have some influence on behaviour.

3.2. Behaviour of Yarns in Fixed Extension Cycling

Booth and Hearle [2] report some studies of yarns subject to fixed extension cycling. The general pattern of behaviour is illustrated in fig. 8: as the test proceeds, the amount of slack

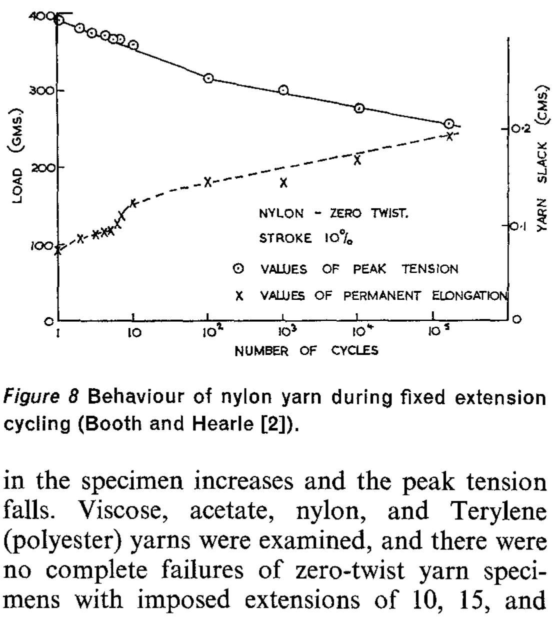

Figure 8 Behaviour of nylon yarn during fixed extension cycling (Booth and Hearle [2]).

in the specimen increases and the peak tension falls. Viscose, acetate, nylon, and Terylene (polyester) yarns were examined, and there were no complete failures of zero-twist yarn specimens with imposed extensions of 10, 15, and 20% carried on to 1.9×10^5 cycles, although there was some breakage of individual filaments. Some twisted yarns did fail at the higher strokes. In general, these tests demonstrated the difficulty of achieving failure in a simple, fixed-extension fatigue test.

3.3. The Cumulative Extension Studies of Booth and Hearle

When the same yarns were tested by Booth and Hearle [2] in a cumulative extension test, there was a gradual increase of length, and at large strokes failure occurred. The survivor diagrams for tests on twenty individual specimens are shown in fig. 9.

At the largest strokes applied to viscose rayon yarns, as shown in fig. 10, the increase in length agrees with that predicted from elastic-recovery values and leads rapidly to the ordinary breaking extension of the specimen: the result of the test is thus explained solely in terms of elastic-recovery effects. With smaller strokes, and in nylon yarns, where the elastic-recovery analysis predicts a stable limit, the extension does continue, and break eventually occurs after a large number of cycles. This will partly be due to the visco-elastic effects. However, there are two pieces of evidence which suggest that the nature of the break is different. Firstly, the breaking extension is less when failure occurs after a large number of cycles. Secondly, the appearance of the broken fibre ends is quite different from that in a simple tensile test. One example is shown in fig. 11. The end is jagged, and there is a partial break some distance away from the actual point of failure. The work of Booth and Hearle [2] was on multifilament yarns, so that some of the effects might be attributed to inter-fibre forces. However, we have observed similar jagged breaks on fatigued single-fibre specimens [8].

A comparison of the various materials tested by Booth and Hearle is shown by the median number of cycles to break given in table IV. Viscose rayon and acetate fail at much lower strokes than nylon or Terylene. It may be noted that there is only a very narrow range of strokes between those which do not give failure in a measurable number of cycles and those

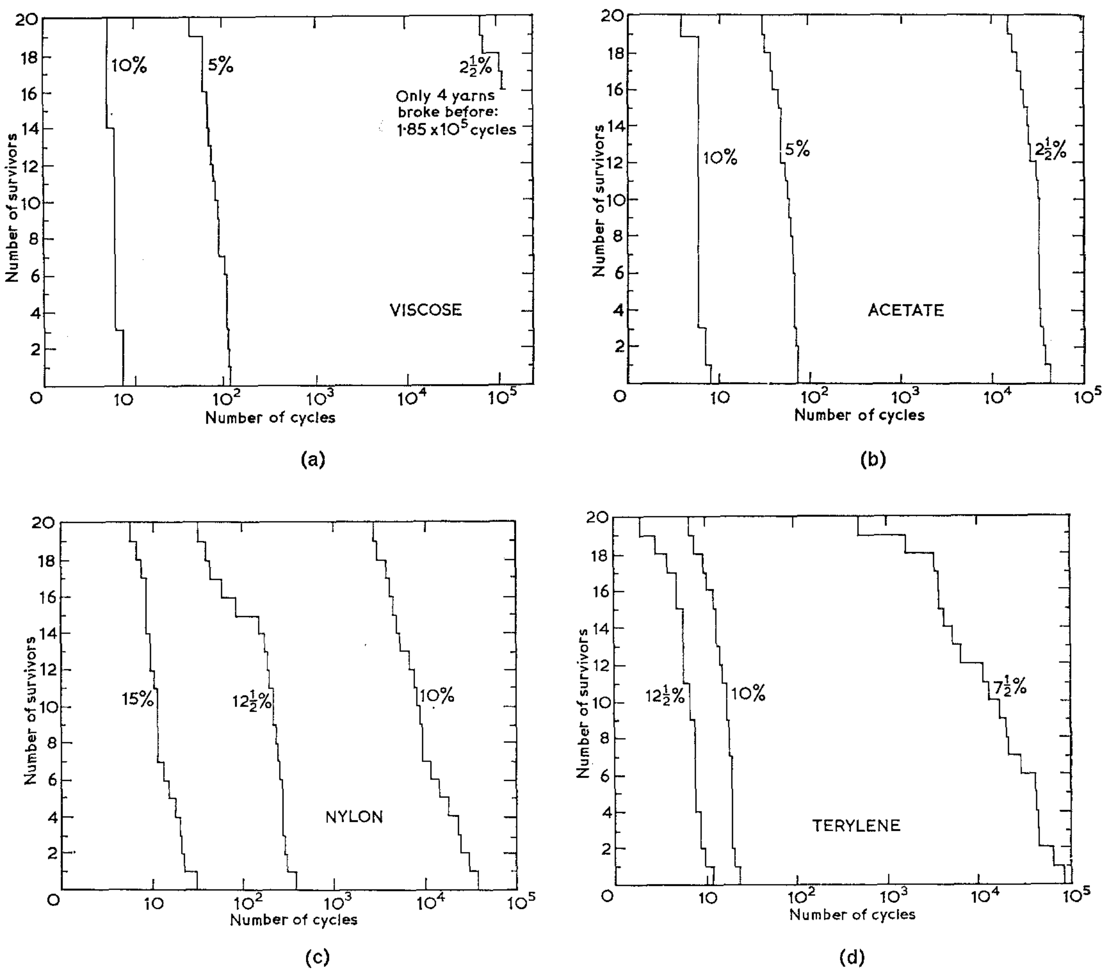

Figure 9 Survivor diagrams for yarns in cumulative extension test at various imposed extensions (Booth and Hearle [2]): (a) viscose rayon; (b) cellulose acetate; (c) nylon; (d) polyester (Terylene).

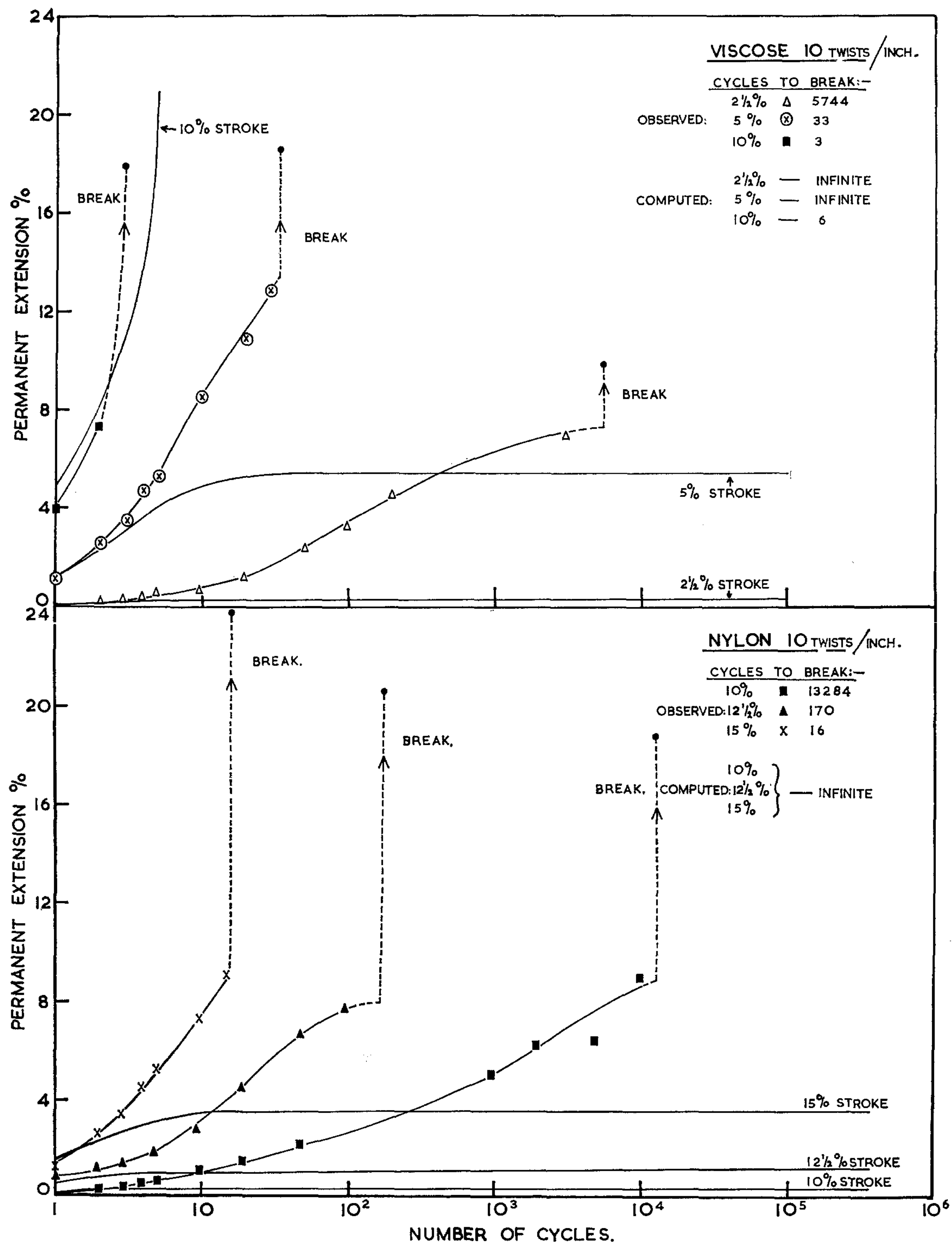

Figure 10 Comparison of observed **extension** during cumulative extension tests **with predictions from recovery** behaviour (Booth and Hearle [2]).

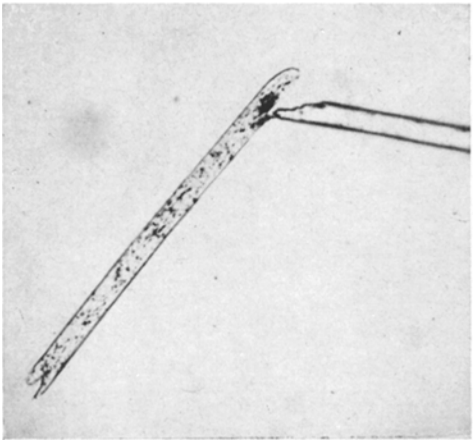

Figure 11 Fibre from a fatigued nylon yarn (Booth and Hearle [2]) (×150).

TABLE IV Median number of cycles to break for various yarns, in cumulative extension testing (Booth and Hearle [2]).

	Stroke (%)					
	$2\frac{1}{2}$	5	$7\frac{1}{2}$	10	$12\frac{1}{2}$	15
Viscose rayon	(a)	79		6		
Acetate	32 348	58		6		
Nylon			(b)	11469	220	12
Polyester		(b)	15 715	18	7	

(a) Only four samples out of ten broke up to 5×10^5 cycles.
(b) Preliminary experiment showed no breaks up to 5×10^5 cycles.

which are so large that break occurs in very few cycles. True fatigue, if it exists, needs rather carefully selected conditions for its observation.

3.4. The Work of Lyons and Prevorsek

Another extensive series of tests using a cumulative extension method has been reported by Lyons and Prevorsek [9]. A selection of their results will be included here.

Several of their observations fit in with the view presented earlier in this paper. Fig. 12a shows frequency distributions of lifetimes of an experimental acrylic fibre. At low strokes, all specimens last for a long period, but as the stroke is increased a second peak appears at a shorter life and gradually becomes more important: this behaviour would be explained by the two mechanisms of failure indicated in fig. 7. A cumulative frequency distribution for nylon fibres (fig. 12b) also shows a change in pattern, with the results for a stroke of 8% divided between the two forms. In another test, on a Dacron polyester fibre (fig. 12c), a similar split between two lines on a plot of cumulative frequency distribution is shown at certain frequencies. Finally, fig. 12d shows a collected plot of average lifetime versus relative stroke for several types of fibre, with two distinct portions: one covering strokes down to a certain fraction of the breaking extension, giving lifetimes up to 100 cycles, and the other at lower strokes carrying on to very long lifes.

The effect of frequency of cycling was found, in one series of tests on an acrylic fibre, to give the relation:

$$N_m = a\nu^{0.28}$$

where: N_m is the number of cycles to break; a, a constant; and ν, the frequency in cycles per second.

This is a special case of a general law proposed by Waller and Roseveare [10], of the form $N = a\nu^m$, and found to fit results for viscose rayon tyre cords with $m = \frac{1}{2}$. Obviously a law of this form would not fit when the mechanism of failure is changing, as it appears to for the results in fig. 12c.

The statistics of failure have been analysed by Lyons and Prevorsek using the Weibull distribution:

$$P(N) = \exp\left(-\left[(N - N_0)/(N_v - N_0)\right]^k\right)$$

where: $P(N)$ is the probability of survival for N cycles; N_0, the minimum life; N_v, the characteristic extreme, given by $P(N_v) = e^{-1}$; and k, the shape parameter.

They find that a simple fitting of this equation gives a negative value of N_0; but, as this is not allowable, they put N_0 equal to zero. The results for several series, of about twenty specimens each, then show a fairly reasonable fit to a straight line when plotted on Weibull paper. However, Booth and Hearle [2] have pointed out that, although their results show a reasonable fit to a Weibull distribution, they also fit other distributions, such as a normal distribution for $\sqrt{N}$. In order to test the validity of a particular distribution, it is necessary to examine a very large population. While demonstrating its usefulness empirically as a method of presenting the data, the work of Lyons and Prevorsek does not establish the basic validity of the Weibull distribution, or give confidence that it could safely be extrapolated much beyond the range of the available data.

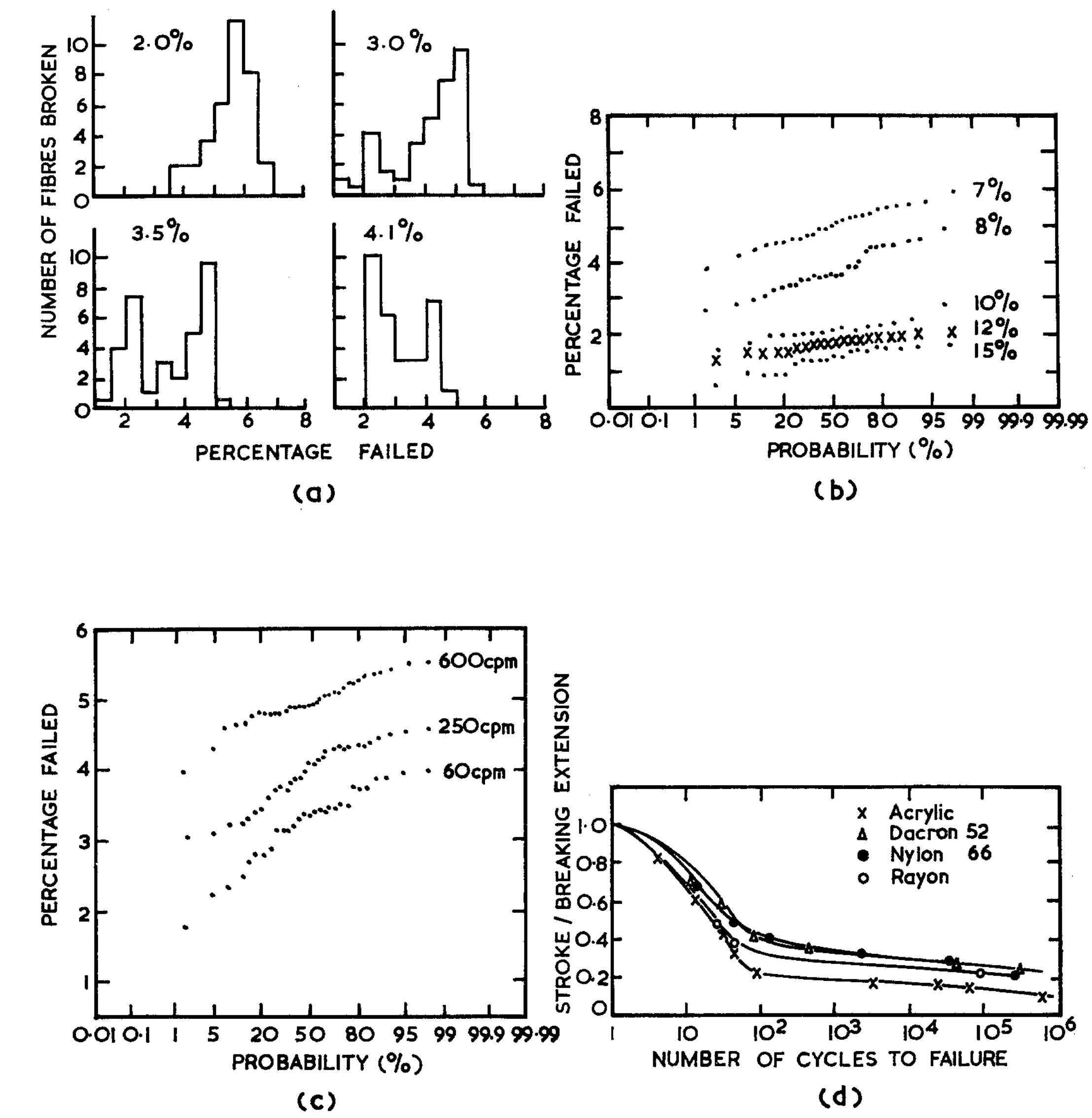

Figure 12 Some results of cumulative extension tests (Lyons and Prevorsek [9]): (a) distribution curves for cycles to failure in an experimental acrylic fibre at strokes of 2.0, 3.0, 3.5, and 4.1%; (b) cumulative distribution curves for a nylon 6 fibre, plotted on normal probability coordinates; (c) effect of frequency on cumulative distribution curves for a Dacron polyester fibre; (d) effect of relative stroke on number of cycles to failure.

Lyons and Prevorsek also made some interesting studies on the general damage occurring during testing, though with rather conflicting results. The stress/strain curves of broken portions of acrylic fibres (fig. 13) show a general stiffening. However, as indicated in table V, subsequent fatigue tests on these broken portions showed lifetimes as long as in the first test: this suggests that there is no progressive damage and that failure is rapid and localised. In another paper, they consider the law of cumulative damage proposed by Miner [11]. This law states that, if, under condition i, failure occurs in N_i cycles, then the application of n_i cycles causes a fractional damage of n_i/N_i. Failure occurs after a miscellaneous history when $\Sigma n_i/N_i = 1$. Table VI shows that the behaviour of a Dacron polyester fibre was consistent with this law.

An indication of the importance of the

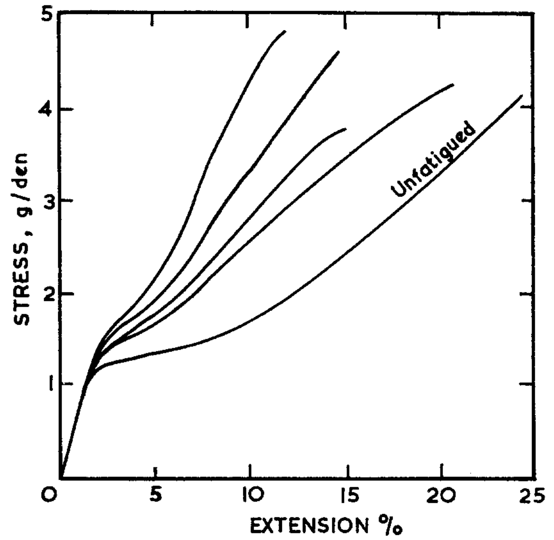

Figure 13 Stress/strain curves for original and fatigued specimens of an acrylic fibre (Lyons and Prevorsek [9]).

TABLE V Effect of second fatigue test on a broken specimen, acrylic fibre (Lyons and Prevorsek [9]).

Fatigue life (h)	
1st test	2nd test
0.92	1.07
7.71	0.00
7.29	3.67
2.54	9.84
12.73	0.00
3.28	14.47

TABLE VI Test of law of cumulative damage on a polyester fibre (Lyons and Prevorsek [9]).

Stroke (%)	4.0	4.3	4.6	5.0	5.3	5.6
Life in 10^3 cycles in simple test (N_i)	316	204	64	81	58	44
Period in 10^3 cycles in sequential test (n_i)	12	8	6	3	3	31
Damage ratio (n_i/N_i)	0.04	0.04	0.095	0.04	0.05	0.70
$\Sigma\ (n_i/N_i) = 0.97$						

TABLE VII Fatigue performance of two polyester types (Lyons and Prevorsek [9]).

	Dacron 52	Dacron 420
Median number of cycles to failure		
6% stroke, 60 c/min	110	2493
600 c/min	551	106 280
Modulus (g/den)	92	123
Tenacity (g/den)	7.9	10.2
Breaking extension (%)	17	15
Work of rupture (g/den)	0.8	0.9
Molecular weight (number average)	20 200	29 000
Density	1.378	1.384
Creep extension (%) after 100 cycles at 6% stroke,		
60 c/min	6.2	4.2
600 c/min	—	0.8

physical structure of the fibre is shown by the comparison of two Dacron polyester fibres given in table VII. It might be expected that, in a fatigue test carried out at a given level of extension, the fibre with the highest breaking extension would show the longest life; but this is not so – clearly some other structural feature must be playing an important part.

Finally, in their biaxial-rotation studies of monofilaments, Lyons and Prevorsek made interesting observations of the growth of cracks during fatiguing. Cracks started at the surface of the monofilament, and penetrated in further as the test proceeded. Tenacity values of specimens removed after some period gradually decreased, until finally they reached zero.

3.5. Studies of Fatigue in Plastics

With the exception of work on composite systems such as fibre-reinforced plastics, falling outside the scope of this paper, there appears to have been even less study of fatigue in plastics. For instance, Neilsen's [12] standard work on mechanical properties of polymers contains only a brief note on the subject.

The availability of plastics in large solid shapes means that conventional fatigue-testing equipment and methods can be used: there are no difficulties about alternating positive and negative loads. There are three investigations of particular interest.

Findley [13] studied the behaviour of cellulose acetate twenty-five years ago, using a cantilever test at strains of less than 1%, which is within the elastic region. He found a typical fatigue relation with the life of the specimen increasing as the applied stress decreased, and a well-defined stress below which the specimen lasted indefinitely. For stresses just above this endurance limit, the lifetimes were about 10^6 cycles. Table VIII shows the effect of various factors on the endurance limit.

Throop [14] found generally similar results for polystyrene fatigued under axial alternating load on a Sonntag machine, as illustrated in fig. 14. The endurance limit was of the order of ($\frac{1}{3}\times$ tensile strength) and corresponded to the stress at which the first crack appeared: the strain under this stress was 0.35%. The first small cracks perpendicular to the axis merged to inclined cracks at 45°; increasing in number and depth until fracture occurred on an inclined surface.

Polymethyl methacrylate has been examined by Zarek [15], using dead-weight loading to cause bending stresses on a rotating specimen. The appearance of the break suggested that it was initiated by crack development. At high stresses, when break occurred in a low number of cycles, the area of multiple cracking was small, with the remainder of the broken surface being smooth and suggesting a sharp completion of the break. As the stress was reduced, the life lengthened, and the area of multiple cracking

TABLE VIII Cantilever bending fatigue test on cellulose acetate (Findley [13]).

Endurance limit for rectangular specimen, aged for 15 months = 1380 lb/in.^{2}* (alternating stress at medium speed)

Effect of other factors	Endurance limits (lb/in.^{2})
Not aged	1100
Circular specimen	1760
Machined surface	1410
Cooled to room temperature by air blast	1540
Slow speed, 40 c/min	2000
High speed, 3000 c/min	1400
Superimposed on mean stress of 4500 lb/in.^{2}	950

*1 lb/in.^{2} = 7 × 10^{-2} kg/cm^2

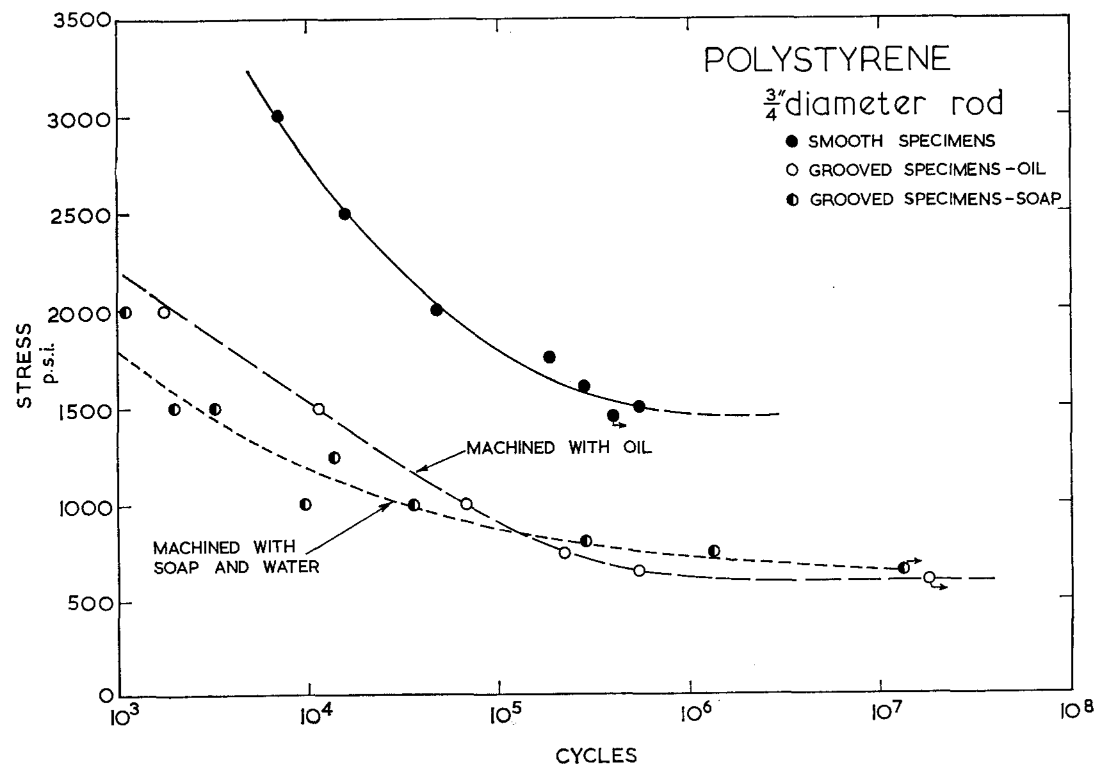

Figure 14 Stress-life/fatigue curve for a polystyrene rod under axial alternating load (Throop [14]).

increased until, near the endurance limit, it covered a large area of the cross-section.

All these studies on amorphous polymers in the glassy state show a behaviour generally similar to metals, and can be explained with the view that, above a certain stress level, crack growth can be started in a fatigue test and continues until break occurs.

There is an interesting example of the use of a partially crystalline polymer, polypropylene, in an application demanding good fatigue life [16]. A strip of this material can act as an integral hinge. As a result, it is possible to produce, as one item in a single moulding, a container, its lid, and the hinge: the separate mouldings and the assembly operations are eliminated. The hinge may withstand flexing for indefinitely long periods: in laboratory tests, correctly designed and moulded hinges have exceeded 23 million flexes without failure. On the other hand, a badly designed or moulded hinge may crack within the first few flexes. It is not possible to design a cheaper hinge to stand up to a few hundred flexes, as the behaviour of such a hinge would be unpredictable, and it might fail immediately. It is believed that, during flexing, some orientation occurs within the material leading to greater strength in the required directions. It may be noted that the operation of a hinge is a cumulative test in the sense used in this paper: at each opening, a fresh extension or energy shock is imposed on the specimen which already contains any residual deformation from previous openings. Correct design clearly demands that the hinge should rapidly settle down to a stable limiting state with a minimum of distortion.

4. Theories of Fatigue Behaviour

The discussion given earlier in this paper shows that, when dealing with imperfectly elastic materials, it is necessary to separate out effects attributable to poor elastic recovery or to time-dependent deformation before seeing whether any special fatigue effects remain. Where this separation is not understood, experimental results can be confusing, as the pattern of failure changes. Dischka [7] has described the first form of failure mentioned above as exhausting the capacity for deformation of the material.

Under some conditions which are not too severe, and which in glassy polymers would be within the elastic range, there is evidence of other mechanisms of failure, probably associated with crack growth and probably following lines of maximum shear stress. A number of detailed theories have been proposed.

Kargin and Slonimiski [18] have suggested a mechano-chemical mechanism: the application of tension leads to polymer chain rupture, and hence to free-radical formation and to chemical degradation.

Alternative purely physical mechanisms may be suggested. Eyring's general reaction rate theory, which can be used to predict the rate of bond breakage, has been modified by Lyons [19] to bring in a periodic stress factor and to calculate the time for all the bonds to break. This leads to a prediction of the frequency relation $N = a\nu^m$, found in some experiments. Other developments of Eyring's theory have been made by Coleman [20], who includes a discussion of the statistics of failure.

More recently, Prevorsek and Lyons [21] have given a treatment based on the theory of nucleation and growth of cracks.

It seems likely that all the mechanisms indicated above – and others – do play a part in fatigue behaviour. More experimental work is needed to clarify the subject further.

References

1. F. FRANK and R. W. SINGLETON, *Textile Res. J.* **34** (1964) 11.
2. A. J. BOOTH and J. W. S. HEARLE, "Proceedings of Fourth International Congress on Rheology (1963)", vol. III (Wiley, 1965), p. 203.
3. W. J. LYONS, *Textile Res. J.* **32** (1962) 750.
4. J. W. S. HEARLE and H. PLONSKER, *J. Appl. Polymer Sci.* **10** (1966) 1949.
5. W. T. KELLY, *Textile Res. J.* **35** (1965) 852.
6. J. W. S. HEARLE, *ibid* **36** (1966) 591.
7. R. MEREDITH, *J. Textile Inst.* **45** (1954) T30.
8. J. W. S. HEARLE and A. D. NATH, work in progress.
9. W. J. LYONS, *Textile Res. J.* **32** (1962) 448, 553, 750; W. J. LYONS and D. C. PREVORSEK, *ibid* **35** (1965), 73, 110, 217, 1048, 1106; *idem, ibid* **34** (1964) 271, 881, 1040; D. C. PREVORSEK, W. J. LYONS, and J. C. WHITWELL, *ibid* **33** (1963) 963.
10. R. C. WALLER and W. E. ROSEVEARE, *J. Appl. Phys.* **17** (1964) 482.
11. M. A. MINER, *J. Appl. Mech. Trans. ASME* **67** (1945) A-159.
12. L. E. NIELSEN, "Mechanical Properties of Polymers" (Reinhold, 1962).
13. W. N. FINDLEY, *Proc. ASTM* **41** (1941) 1231.
14. J. F. THROOP, M.Sc. thesis, Rensselaer Polytechnic Institute (1949).
15. J. M. ZAREK, *British Plastics* **30** (1957) 399.

16. " 'Propathene' for Integral Hinges", pamphlet issued by ICI (Plastics Division) Ltd (1965).
17. G. DISCHKA, *Acta Tech. Acad. Sci. Hungary* **14** (1956) 79.
18. V. A. KARGIN and G. L. SLONIMISKI, *Doklady Akad. Nauk USSR* **105** (1955) 751.
19. W. J. LYONS, *Textile Res. J.* **28** (1958) 127.
20. B. D. COLEMAN, *J. Appl. Phys.* **27** (1956) 862; **29** (1958) 968; B. D. COLEMAN and A. G. KNOX, *Textile Res. J.* **27** (1957) 393.
21. D. C. PREVORSEK and W. J. LYONS, *J. Appl. Phys.* **35** (1964) 3152.