13
Tensile properties

13.1 General introduction

The mechanical properties of textile fibres, the responses to applied forces and deformations, are probably their most important properties technically, contributing both to the behaviour of fibres in processing and to the performance of the final product. The properties of a textile structure such as a yarn or a fabric depend on a complex interrelation between fibre arrangement and fibre properties, so that, although a knowledge of fibre properties is essential to an understanding of the properties of yarns and fabrics, it is not in itself sufficient. There will be some effects that are due to the inherent properties of the structural arrangement, and the fibre properties may be modified by the presence of neighbouring fibres. The fibre properties in themselves do, however, give a limit to what is possible in a yarn or fabric. For example, except for minor effects due to mutual support of variable fibres, the strength of a yarn cannot be greater than the sum of the strengths of its component fibres.

The mechanical properties of a fibre cover a large number of effects, all of which combine to determine the particular character of the fibre. In using fibres, it is necessary to find that fibre whose character best suits the needs of the particular job. These needs vary widely in the manifold applications of textile materials.

Because of their shape, the most studied and, in many applications, the most important mechanical properties of fibres are their tensile properties, namely their behaviour under forces and deformations applied along the fibre axis. Of these, the simplest to study experimentally is the elongation, and finally the break, under a gradually increasing load. Experiments of this sort form the subject of the present chapter, but, to avoid giving a false impression, it will first be necessary to describe the various factors that affect the results of such experiments. These factors will be considered in greater detail later.

13.2 Factors determining the results of tensile experiments

13.2.1 The material and its condition

The behaviour of a material depends on the nature and arrangement of the molecules of which it is composed, and these will vary not only from one type of fibre to

another, but also from one fibre to another in a given sample, and from one condition of the material to another. These latter effects must be taken into account in considering the results of a test. The different behaviour of individual fibres must be investigated. On some occasions, the variability of the results may be more important than the mean value, as, for example, it would be if we wished to know the chance that the strength of a fibre would fall below a certain critical value. The condition of the material depends on its previous history, including the processes to which it has been subjected and the mechanical treatment that it has received, on the amount of moisture that it contains, and on the temperature. All of these must be specified if the results of tests are to be of value.

13.2.2 The arrangement and dimensions of the specimen

The dimensions of the specimen will, of course, have a direct effect on the results of tests. For example, other things being equal, the breaking load of a fibre will increase in proportion to its area of cross-section, and its elongation will increase in proportion to its length. It is, however, with the indirect effects that we are more concerned here.

In a variable material, there is a greater chance of the occurrence of a very weak place in a long length than in a short one, and, since a fibre breaks at its weakest place, the mean breaking load of long lengths will be less than that of short ones (see Section 14.2.1). For this reason, the length tested should be stated.

If composite specimens, made up of a number of fibres, are used in a test, then not all the fibres will necessarily bear the same proportion of the load, and they may not all break at the same time. For these reasons, the properties of a composite specimen are affected by the particular arrangement of fibres in the specimen and are not given by a simple combination of the properties of the individual fibres.

13.2.3 The nature and timing of the test

The elongation of a textile fibre is not a single-valued function of the applied load, for it depends on the length of time for which the load and any previous loads have been applied. If a constant load is applied to a fibre, it will, after its instantaneous extension, continue to extend for a considerable time and, if the load is great enough, it will eventually break. The load necessary to cause breakage will vary with the speed of the test, a rapid test requiring a greater breaking load than a slow one. Thus the results of experiments will be affected by the time allowed and by the way in which the load is applied, whether it is by constant rate of loading, constant rate of elongation, reduction from a higher load or any other sequence of events.

A limitation on the value of experimental results may be noted here. In use, textile fibres are subject to complex, variable and probably unknown loading histories. In assessing the practical behaviour of fibres, therefore, attempts must be made to predict the results under the actual conditions of use from experimental results obtained under different conditions. This can best be done if the experimental conditions are as simple as possible.

13.3 Expressing the results: quantities and units

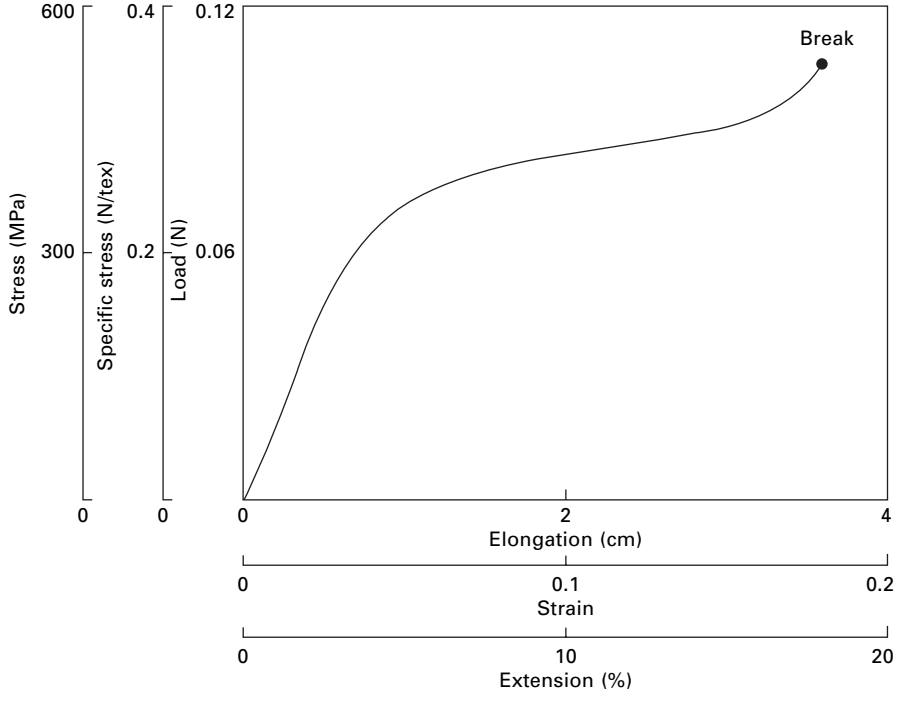
13.3.1 Load–elongation and stress–strain curves

The behaviour of an individual fibre under a gradually increasing applied force is completely expressed by the load–elongation curve with its end-point breakage, as is shown in Fig. 13.1. The load may be measured in newtons or grams force and the elongation in centimetres, but, if we wish to compare different types of fibre, independently of the direct effect of their dimensions, we must use other quantities. Elongation is easily normalised as fractional strain or percentage extension. However, as described in Appendix I, which contains a conversion table, the normalisation of force has produced great diversity dependent on the choice of quantity and units.

In most physical and engineering applications, load is replaced by *stress*, defined as:

$$\text{stress} = \frac{\text{load}}{\text{area of cross-section}}$$

The SI unit of stress is newton per square metre (N/m^2), which is also called a pascal (Pa). The convenient units for strength and modulus are megapascal (MPa) or gigapascal (GPa). Other commonly found units are kg/mm^2 and pounds per square inch (psi).



13.1 Hypothetical load–elongation curve for 20 cm specimen of 0.3 tex fibre with density of 1.5 g/cm^3.

In textile technology, however, we are more often interested in materials in terms of their weight, rather than in terms of their bulk. In addition, the area of cross-section of textile yarns and fabrics is not well defined, since it is confused by the space between fibres. For single fibres, the area is definitive, but is more easily obtained indirectly from the mass and density of the specimen than by direct measurement. The primary definition of fineness is the linear density (mass per unit length). It is therefore more convenient to use mass-based quantities based on the linear density, which give consistent information from the molecular to the macroscopic level. The normalised force is termed the *specific stress*[1] and is defined as:

$$\text{specific stress} = \frac{\text{load}}{\text{linear density}}$$

The consistent SI unit for specific stress would be N m/kg. However, in order to fit in with the tex system for linear density, it is better to use newton per tex (N/tex), which is 10^6 times as large as N m/kg. For smaller stresses, millinewton per tex (mN/tex) may be a more convenient size. When manufactured fibres were introduced in the first half of the 20th century, the unit chosen was gram force per denier, usually written as g/den, and this unit is still widely used. In order to get a unit of similar size to g/den, cN/dtex is often found.

In consistent units, we have the following relation between stress f, specific stress σ and density ρ:

$$f = \rho\,\sigma \tag{13.1}$$

The same equation is correct with f in GPa, σ in N/tex and ρ in g/cm^3. Conversion relations in other units are given in Appendix I. When engineers who are used to working with conventional stress wish to change to a mass basis, they often think of specific stress as (f/ρ) and use units such as GPa/(g/cm^3), which is equal to N/tex, or even the hybrid unit psi/(g/cm^3).

The distinction between stress and specific stress becomes significant only when we wish to compare materials of different density, for example silk and nylon, and more particularly between organic and inorganic high-performance fibres. Usually, we should want to do this on the basis of equal weights, but in some special cases, for example if material had to be packed into a small space, bulk might be important, and the conventional stress should be used. In composites, linear dimensions are used in engineering design, though weight can be important, and stresses are commonly used.

There are other related quantities. Specific stress is dimensionally equivalent to energy per unit mass, which is relevant to some applications. N/tex equals kJ/g. Another quantity, which was often quoted as a measure of strength, is the breaking length in kilometres, or more correctly kilometre-force. This is the length of material that would break under its own weight. 1 kmf equals 1 gf/tex or 9.8 mN/tex. The usage of older units is more common in the United States than in the rest of the world, and an extreme example was the uses of inches, strictly inch-force, for strength in manufacturer's literature for the Spectra HMPE fibre.

[1]When the context is clear, *stress* is often used.

To take account of the length of the specimen, the elongation is expressed as *tensile strain* or *percentage extension*:

$$\text{tensile strain} = \frac{\text{elongation}}{\text{initial length}}$$

Load–elongation curves become stress–strain curves by a change of units, without affecting the shape of the curve, as is indicated in Fig. 13.1.

Although stress–extension curves completely express the results of this type of test, there are some features of the curve that it is useful to define separately. These refer either to the shape of the curve or to the position of its end point, that is, breakage.

13.3.2 Strength

We first consider strength, which is a measure of the steady force necessary to break a fibre and is given experimentally by the maximum load developed in a tensile test. (See Section 14.6 for a discussion of some complications.) For an individual fibre, the strength is given by the breaking load. For comparing different fibres, the value of the specific stress at break is used and is called *tenacity* or *specific strength*. As noted above, *breaking length* may also be used. For use in comparing strengths on the basis of area of cross-section, the stress at break is termed the *ultimate tensile stress*.

13.3.3 Elongation at break

The elongation necessary to break a fibre is a useful quantity. It may be expressed by the actual, the fractional or the percentage increase in length, and is termed the *breaking extension* or *break extension*.

13.3.4 Work of rupture

For an individual fibre, the work of rupture, sometimes called the *toughness*, is defined as the energy needed to break the fibre. The units for this are joules. If we consider a fibre under a load F, increasing in length by an amount $\mathrm{d}l$, we have:

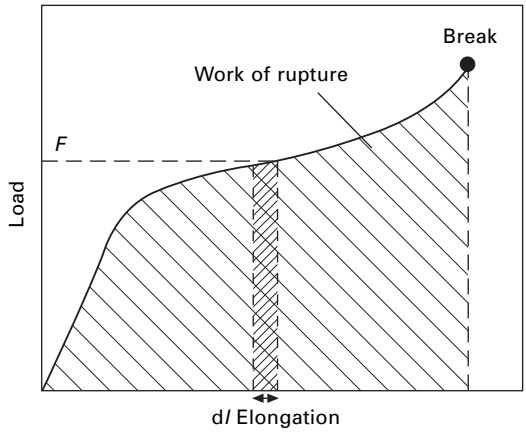
$$\text{work done} = \text{force} \times \text{displacement} = F \cdot \mathrm{d}l \tag{13.2}$$

$$\text{total work done in breaking the fibre} = \text{work of rupture} = \int_0^{\text{break}} F \cdot \mathrm{d}l \tag{13.3}$$

This equals the area under the load–elongation curve, as shown in Fig. 13.2.

Other things being equal, the work of rupture of a fibre will be proportional to its linear density (because of the effect on the load needed) and to its length (because of the effect on the elongation). To compare different materials, we may use the term, *specific work of rupture*[2], defined as:

[2] *Specific* may be dropped when the context is clear.



13.2 Work of rupture.

$$\text{specific work of rupture} = \frac{\text{work of rupture}}{\text{linear density} \times \text{initial length}}$$

As indicated above, specific work of rupture may be expressed in units of N/tex or kJ/g, and is given by the area under the curve of specific stress against strain. This represents the energy in joules needed to break a 1 tex filament, 1 m long. The total work of rupture of any particular specimen is proportional to its mass, independent of the actual values of linear density and length which determine that mass.

13.3.5 Comparison of methods of specifying breakage

We have now described three ways of specifying breakage, or resistance to breakage: by the force, elongation or energy necessary. Whenever breakage occurs, the values of each of these appropriate to the conditions of test must be reached, but usually the limiting value of only one of the three will be inherent in the conditions causing breakage, while the other two follow automatically. It is useful to compare the three quantities from this point of view.

Strength, or tenacity, gives a measure of the resistance to steady forces. It will thus be the correct quantity to consider when a specimen is subject to a steady pull, as, for example, in a rope used for slow hoisting of heavy weights.

The breaking elongation gives a measure of the resistance of the material to elongation. It is thus important when a specimen is subject to stretching, for example the neck of a garment being pulled over the head, or the warp extension in weaving.

The work of rupture, which is the energy needed to break a fibre, gives a measure of the ability of the material to withstand sudden shocks of given energy. When a mass m, attached to a textile specimen, is dropped from a height h, it acquires a kinetic energy, equal to mgh, and, if this energy is greater than the work of rupture, breakage will occur, whereas if it is less the specimen will withstand the shock. Thus the work of rupture is the appropriate quantity to consider in such events as the opening of a parachute, a falling climber being stopped by a rope and all the occasions

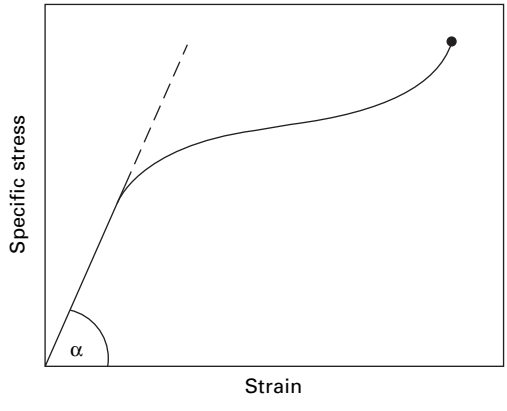
when sudden shocks are liable to cause breakage. It should be noted that the significant feature in the application of the work of rupture is that the shock contains a given amount of energy; the fact that it occurs rapidly is not directly relevant, though the rate of loading will affect the value of the work of rupture.

In comparing materials to see which is least likely to break, it is important to consider the conditions under which breakage would occur and then to decide which quantity is the appropriate one to use. For instance, it is no use for a climbing rope to have a high tenacity if its work of rupture is low. In actual practice, more complicated tensile conditions may occur, for example a sudden shock may be applied to a specimen already carrying a steady load. It should also be remembered that breakage may occur as a result of the repeated applications of forces, not necessarily along the fibre axis, as discussed in Chapter 19.

13.3.6 Initial modulus and other moduli

The first of several quantities related to the shape of the tensile stress–strain curve is the *initial modulus*, which is equal to the slope of the stress–strain curve at the origin (after the removal of any crimp). This slope usually remains constant over the initial portion of the curve, as in Fig. 13.3. The modulus is measured in units of stress or specific stress. Note that fractional strain is always used, even though the data may be given in percentage extension. The corresponding absolute quantity is the spring constant, equal to force/elongation.

It may be noted that the value of the initial modulus equals the value of the stress that would be necessary to double the length of the specimen if the conditions at the origin persisted. It is a measure of the resistance to extension for small extensions. An easily extensible fibre will have a low modulus. The modulus is important in situations where the amount of extension has to be limited, for example in the magnitude of offset allowable for an oilrig subject to environmental forces. It also gives a measure of force developed when a given displacement is imposed, as when an oilrig rises and falls under wave action.



13.3 Initial modulus = tan α.

Two other moduli may be reported. The *tangent modulus* is the slope of the stress–strain curve at any given position. It is relevant when materials are subject to cyclic loading. Plots of tangent modulus against strain are another useful way of showing the changes in extensibility as fibres are increasingly strained, as described by van Miltenburg [1]. The *secant modulus* is stress/strain at any position on the stress–strain curve. Dynamic moduli are covered in Chapters 16 and 18. The reciprocal of modulus is called the *compliance*.

13.3.7 Work factor

If the fibre obeyed Hooke's law, the load–elongation curve would be a straight line, and the work of rupture would be given by:

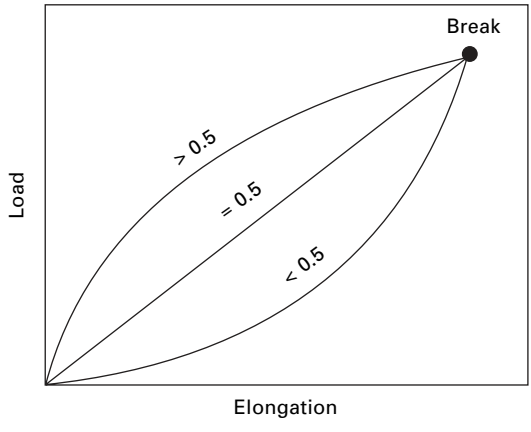
$$\text{work of rupture} = {}^{1}/_{2}\ (\text{breaking load} \times \text{breaking elongation})$$

It is convenient to define a quantity, the work factor, dependent on the difference from this ideal state:

$$\text{work factor} = \frac{\text{work of rupture}}{\text{breaking load} \times \text{breaking elongation}}$$

In the ideal state, the work factor will be 0.5. If the load–elongation curve lies mainly above the straight line, the work factor will be more than 0.5; if below, it will be less than 0.5. This is illustrated in Fig. 13.4.

For materials breaking at the same point, the work of rupture will be greater the higher the work factor. Since the work factor will not vary much in different specimens of the same material, the values given later (in Table 13.1) or other available values may be used to estimate the work of rupture from measurements of the breaking load and elongation.

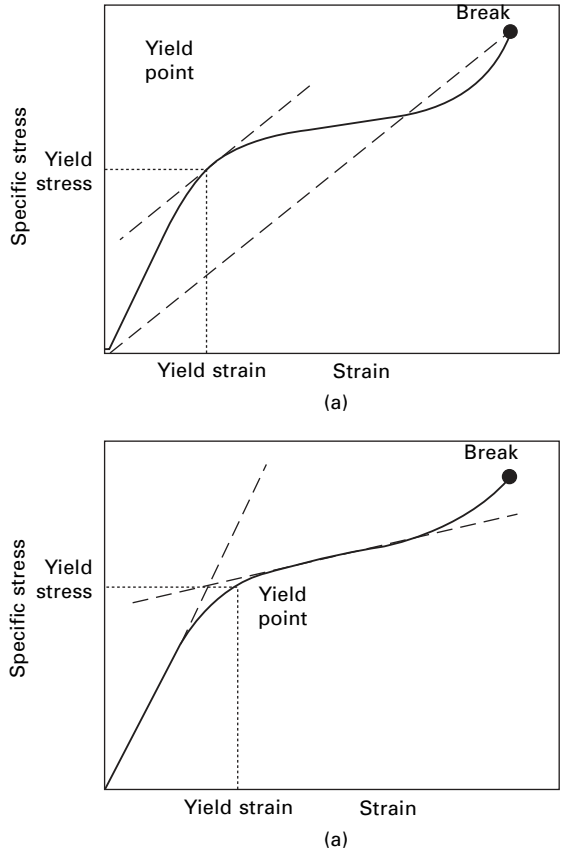


13.4 Work factor.

13.3.8 Yield point

Many stress–strain curves have a shape similar to that in Fig. 13.5. After an initial period with a steep slope, extension suddenly becomes much easier. It is in this region that the *yield point* occurs. In order to locate a precise position, Meredith [2] has suggested defining the yield point as the point at which the tangent to the curve is parallel to the line joining the origin to the breaking point, as in Fig. 13.5(a). This point is then characterised by its stress and strain as the *yield stress* and *yield strain*. Coplan [3] used a different construction and defined the yield point as occurring at the stress given by the intersection of the tangent at the origin with the tangent having the least slope. This is shown in Fig. 13.5(b). Alternatively, particularly when there are considerable linear regions both above and below the yield region, the point of intersection of the tangents may be taken as the yield point. Since the stress–strain curve is approximately linear up to the yield point, the work to the yield point will be almost equal to $^1/_2$ (yield stress × yield strain).

Apart from its indication of the shape of the curve, the yield point is important because for most materials, elastic recovery, which is good up to the yield point,



13.5 Yield point: (a) Meredith's construction; (b) Coplan's construction.

becomes less complete for higher strains. In practice, the point at which permanent deformation starts to take place may be just as important as the point at which breakage occurs. Recovery behaviour is discussed in greater detail in Chapter 15.

The actual amount of bending over of the stress–strain curve may be important. Where there is a marked flattening of the curve, it means that the fibre will firmly resist small loads but will yield under high loads. This will have an influence on the handle of fabrics made from the fibres.

13.3.9 Crimp

In the discussion so far, it has tacitly been assumed that the fibre is initially straight. However, many fibres are crimped. The crimp is normally pulled out by a suitable small tension in measuring linear density, and it can be removed by a pre-tension at the start of a tensile test.

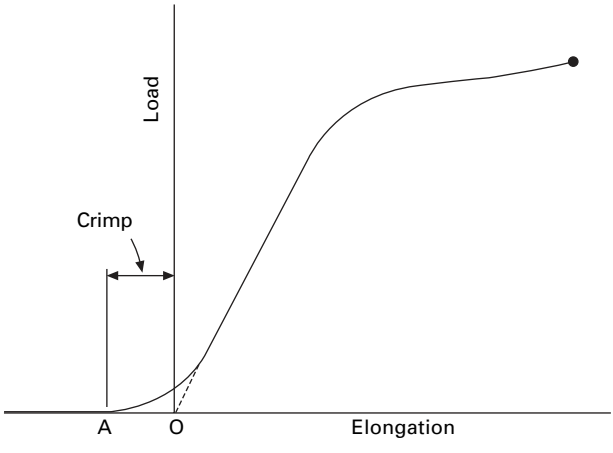
If a crimped fibre is inserted in the tester without any initial tension, the load–elongation curve will have the form shown in Fig. 13.6. The origin of the curve may be put at A, where it diverges from the zero line, but this point is difficult to locate precisely. A better procedure is to put the origin at O, the extrapolated point corresponding to a hypothetical straight fibre. The crimp is given by AO and may be expressed as a percentage of the initial length, again probably best taken as at O, though the value based on the crimped state at A may be used.

Studies of the methods of measuring and defining crimp have been made by Alexander *et al*. [4–6] and more recently by Bauer-Kurz *et al*. [7].

13.4 Experimental methods

13.4.1 General

The load–elongation curve of a textile fibre may be obtained by gradually extending it and measuring the tension corresponding to each increase in length. The essential

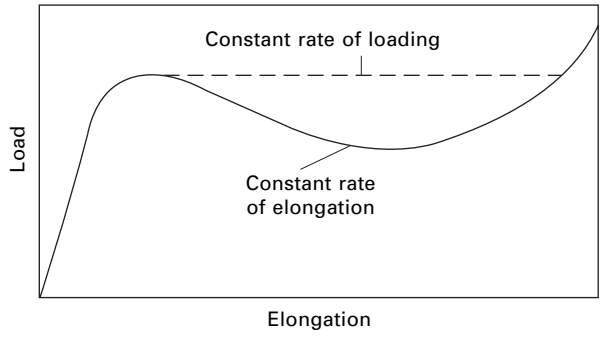


13.6 Load–elongation curve of a crimped fibre.

features of any method consist of the jaws in which the ends of the specimen are held, the type of specimen used, the method of varying the load and elongation, and the means of recording their values to give the load–elongation curve. Prior to the middle of the 20th century, a variety of mechanical testers were used for this purpose and were followed by early electronic testers. However since the research of Hindman and Burr [8] at MIT, which led to commercialisation of Instron[3] testers, the almost universal method has been the imposition of a controlled elongation with force measured on a load cell. The next section describes this type of tester. Brief comments follow on other testers. More information is given in books on textile testing [9–11] and in manufacturers' literature. Some relevant standards for test methods are listed in Appendix III. Special methods for high-speed testing are covered in Chapter 16.

For continuous filament materials, tests are usually carried out on yarns. A small amount of twist may be inserted to cause all fibres to break at the same point. Single fibre tests and individual yarn tests are appropriate for research purposes, but are time-consuming. For routine testing of cotton, either in laboratory testers or in HVI lines, bundle tests are used. Because of the influence of variability, these are discussed in Chapter 14. For yarns, automated testers can pull yarn off a package and make a large number of repeated tests.

Because of the way in which the elongation and the breaking point of textile fibres vary with time, the method of extending the specimen is a factor in determining the results of the test. In *constant rate of elongation* (CRE) tests, the specimen is extended at a constant rate and the force is a dependent quantity; in *constant rate of loading* (CRL) tests, the specimen is loaded at a constant rate and the elongation is a dependent quantity. For the usual non-linear fibre stress–strain relations, the load–time relation is different in the two procedures. Hence differences in creep will cause differences in the shape of the curve. Another consequence is that in a constant rate of elongation test it is possible for the load to decrease while the elongation increases, but this is not possible in constant rate of loading tests, where the load must increase throughout the test, giving the difference shown in Fig. 13.7. The pendulum tester[4], which was



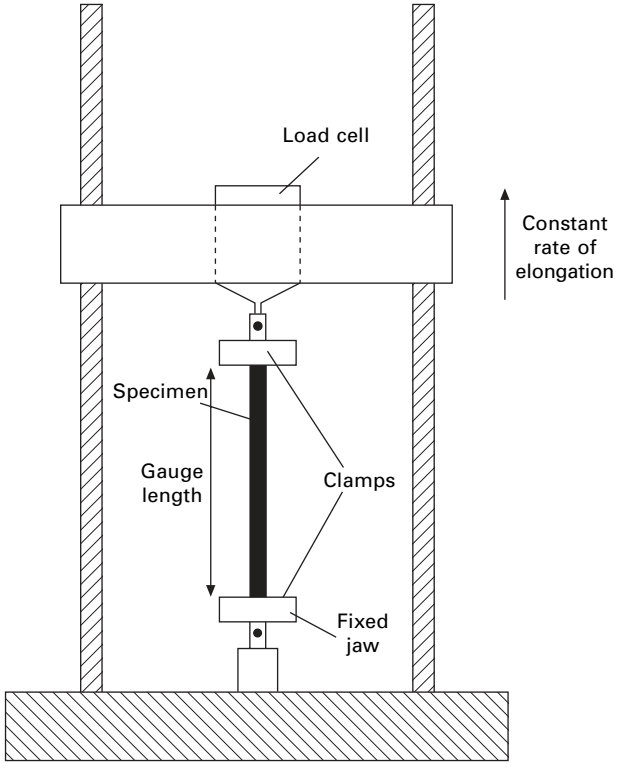
13.7 Constant rate of elongation and constant rate of loading results.

[3]Like Hoover and Google, Instron is often used as a generic description.
[4]The pendulum tester was extensively described in the first edition of this book.

once widely used for strength tests, is described as constant rate of traverse; the controlled jaw moves at a constant rate, as in CRE; the dependent jaw is attached to the pendulum, which rises to record the load. It is not CRE, because there is a substantial displacement of the dependent jaw as the pendulum rises, which influences the elongation; it is not CRL, because the movement of the pendulum depends on the non-linearity of increase of tension with elongation.

13.4.2 Instron-type tests

The Instron tensile tester and others acting on the same principles are constant rate of elongation instruments. The essential feature of these instruments, illustrated in Fig. 13.8, is that one end of the specimen is clamped in jaws, which are mounted on a cross-head that is traversed at a constant rate by a mechanical drive. The drive may come from a constant speed motor, with interchangeable gears to vary rate of elongation, or from a computer-controlled stepper motor. The other end is clamped in jaws, which are mounted on a stiff load cell containing a strain-gauge or other form of transducer. In early versions of the testers, the drive is connected to the recorder drive, and the electronic circuits of the load cell lead to deflection of the recorder pen. A paper record of the load–elongation curve is thus obtained. In modern versions, the



13.8 Instron-type tester.

load and elongation are digitally transferred to a computer, so that the data can be plotted or analysed as required. Instruments of this type are usually very versatile in load ranges, traverse rates, chart-drive rates, testing sequences and auxiliary facilities. Stress relaxation can be measured by holding the elongation constant. Servo-control is used to give constant rate of loading or to hold load constant for creep testing.

A finite, but small, deflection is, of course, necessary in order to measure load. For reasonable lengths of most fibres, the resulting error in elongation values is negligible. For stiff high-performance fibres or when it is necessary to test short lengths, corrections must be applied. If an inextensible specimen, e.g. a thick strip of metal, is tested, the extension will solely be due to the deformation of the load cell and can be used as a correction. Alternatively, specimens of different length can be tested and one elongation subtracted from the other to give the elongation of the difference in length.

Another type of Instron tester employs pneumatic loading, which enables higher-speed and cyclic tests to be carried out under electronic control.

Medium and large Instron-type testers cater for a wide range of specimens, from single fibres and yarns to large cords, but smaller instruments have been introduced for specialist investigations of single fibres or fine yarns. The tensile fatigue tester [12], described in Section 19.3, can be used as a tensile tester if the vibrator is not activated. It has been redesigned as a Universal Fibre Tester (UFT) [13]. Mwaisengela [14] discusses its operation in detail, and describes the addition of a temperature-controlled chamber. An updated version of the UFT also allows for temperature control [15]. Sikorski *et al*. [16] describe a flexible thermomechanical analyser, which treats elongation and tension as described above. The instrument, which is computer controlled, has facilities for twist insertion and torque measurement, but its most notable feature is that the test specimen is enclosed in a chamber which can subject to rapid programmes of temperature change [17]. Fudge *et al*. [18], in a paper on hagfish slime threads, describe a micromechanical tester, which measures tension by the deflection of a fine glass micro-beam. The test thread was extended by a constant speed motor and the deflection of the beam was monitored by a video-camera mounted on a low-power microscope. Data was recorded and analysed by LabView collection software. Kawabata [19] describes a sensitive tester for single fibres.

The SIFAN tester (see Section 3.7.1) enables tensile tests to be combined with observations of fineness along the length of a fibre, thus enabling the stress at the point of break to be found.

13.4.3 Other testers

In the mechanical era, there were several ingenious methods for securing constant rate of loading. The simplest method is direct loading, which was used, for example, by Leonardo da Vinci in the 15th century in measuring the strength of wire. Water or shot can be fed into a bucket attached to the specimen. The load on the specimen is controlled by the flow of water in the Krais instrument [20]. Alternatively load can be increased by the movement of a rider on a balance, as described by Saxl [21], or by electromagnetic methods, as described by Barratt [22]. Unwinding a chain does

not, in its simplest form give constant rate of loading, since the elongation of the specimen alters the load. However, de Meulemeester and Nicoloff [23, 24] described an ingenious way of overcoming the difficulty in a chainomatic tester. A widely used method was the inclined-plane tester. The test specimen is fixed to a carriage on a planar track. As the track is inclined the load on the specimen increases at a constant rate. Since the loading is by dead weight, inertia errors may occur and lead to an oscillation, with the elongation lagging initially behind the load. There may also be an error due to centrifugal force if the carriage moves down too rapidly. The Scott IP testers were examples of this type of instrument. Raes, *et al.* [25] have described an inclined-plane instrument that is mounted on the stage of a polarising microscope in order to permit cotton fibres to be mounted at positions related to reversals.

One old form of tester is worth mention because it was used by Meredith in his classical researches (see Table 13.1), which provide the most comprehensive comparative data on a variety of fibres. The tester designed by Cliff [26] secures constant rate of loading by the use of a very soft loading system, which can be activated by a suitable drive with a negligible error due to extension of the specimen. The tester uses a spring in torsion, as shown in Fig. 13.9. The rotation of the free end of the spring through an angle ϕ applies a load F to the specimen, given by:

$$FR = K(\phi - \theta) \tag{13.4}$$

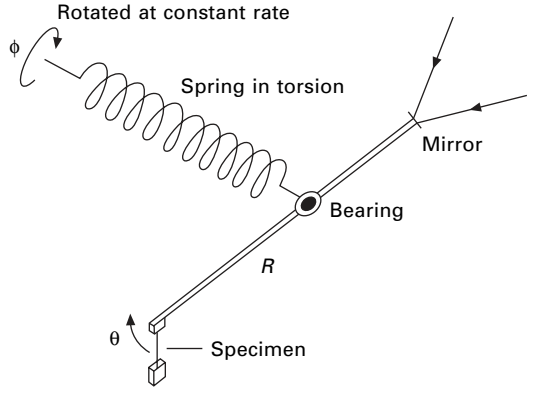
where R = radius of arm connected to specimen, K = torque per unit angle of rotation of spring, and θ = angle of rotation of rod due to elongation of specimen.

With a weak spring and a long rod, $\theta << \phi$, so that we can put:

$$F = \frac{K\phi}{R} \tag{13.5}$$

A constant rate of rotation gives a constant rate of loading.

Another tester which was widely used before Instron testers became available was the Cambridge Textile Extensometer, which could be used for constant rate of loading or constant rate of elongation tests. This type of tester was used for another set of comparative tests (see Table 13.1). The test specimen is mounted between a spring,



13.9 Cliff tester.

which can be extended at a controlled rate to apply tension, and a drive to give controlled elongation. Between the spring and the specimen, an electrode is located between two other fixed electrodes. For CRL tests, the spring is driven at a constant rate which causes contact with the electrode on the spring side; the elongation motor is then driven to maintain a balance of tensions. Conversely, for CRE, the elongation motor is driven at a constant and the spring motor is activated by the electrical contacts. The two motors are linked to a paper recorder to provide a load–elongation curve. Creep and stress relaxation tests can be made by holding one side or the other constant.

13.4.4 Direct measurement of work of rupture

The work of rupture may be obtained from the load–elongation curve, but it can also be measured directly by the ballistic test. A pendulum (Fig. 13.10) is released from a given angle to the vertical and on its swing engages with one of the specimen jaws and breaks the specimen. The energy necessary to break the specimen is lost by the pendulum, and thus we have:

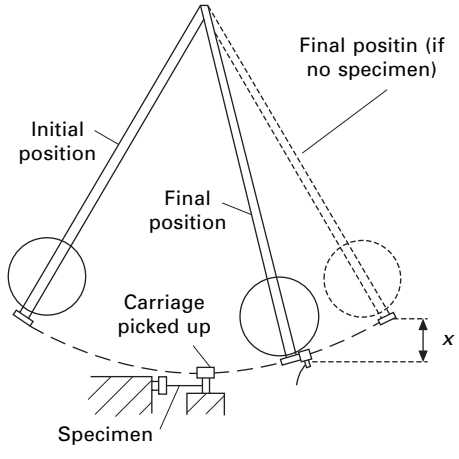
$$\text{work of rupture} = \text{loss of potential energy} = M\,g\,x \tag{13.6}$$

where M = mass of pendulum and x = difference in height of final positions of pendulum, with and without the specimen.

This method is more rapid than a normal load–elongation test, but the variation of load with time will depend on the properties of the specimen and the conditions of the experiment. The method has been discussed in detail by Lang [27].

13.4.5 Other experimental features

Some other experimental features that are common to the above methods may be mentioned here. Single-fibre specimens are best if it is required to investigate the



13.10 Ballistic tester.

properties of the fibres themselves, since the results for bundles of fibres will be affected by the form of the specimen and the variability of the material, as described in more detail later (see Section 14.4). The clamps holding the specimen must not damage it. If this happens, there will be an undue proportion of breaks at the jaw. But undue extension or slippage within the jaws must also be avoided. Care must be taken not to stretch the fibres during the operations preliminary to the test, since this will change the fibre properties. An adequate system of sampling must be used, to take account of the variation in behaviour from one fibre to another. Moisture-absorbing fibres should be in equilibrium with an atmosphere of controlled humidity and temperature, which should always be approached from the same side, preferably the dry side.

13.4.6 Meredith's experimental procedure

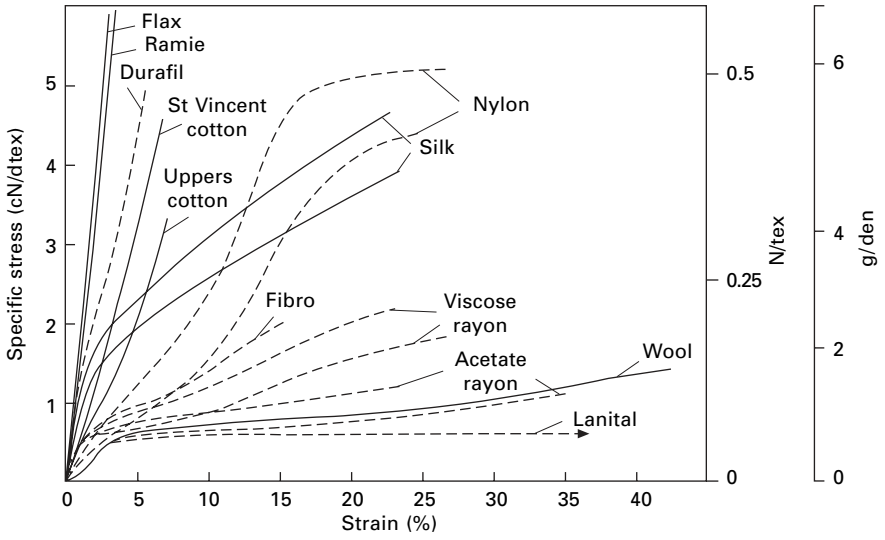
It is useful to study one particular experimental procedure in more detail, and the methods used by Meredith [2] have been chosen, since he made the best early comprehensive set of measurements of load–elongation curves of textile fibres. He tested single fibres, 1 cm long, at 65 ± 2% r.h. and 20 ± 2 °C. Unbiased samples of 25 or 50 fibres of each material were selected, and the fineness of each fibre was measured by weighing a 2 cm length on a micro-balance. The load–elongation curve was then obtained on a Cliff load–elongation recorder, at a constant rate of loading of 10 gf den^{-1} min^{-1} (0.15 mN tex^{-1} s^{-1}).

The method of drawing an average or typical stress–strain curve for a given material is interesting. It is important that the characteristic shape of the curves should be preserved, but straightforward averaging of all the curves would result in the transformation of a sharp bend to a smooth curve if it occurred in somewhat different points in different specimens. Meredith chose the five curves whose strength, breaking extension and yield point were nearest to the mean values of these quantities. From these curves, he took the loads corresponding to 20, 40, 60, 80 and 100% of the breaking elongation of the specimen and expressed them as percentages of the breaking load of the specimen. These percentages were then averaged for the five curves. Thus a series of related percentages of breaking load and breaking elongation was obtained. The mean breaking stress and breaking extension were then used to convert the percentages to absolute values of stress and extension. The typical stress–strain curve was drawn through these points, the yield point being put in at its average value.

13.5 Fibre properties

13.5.1 General

Meredith [2] carried out an extensive set of tests to give comparative data on the fibres available in the 1940s as described in Section 13.4.6. A selection of the results is given in Fig. 13.11 and Table 13.1. It should be remembered that these values apply only to the particular types of material tested and to the particular conditions of test. A later set of comparative data for manufactured fibres of the 1950s is given in Fig.



13.11 Stress–strain curves of various fibres tested at 65% r.h., 20 °C, 0.15 mN tex^{-1} s^{-1}. From Meredith's [2] 1945 data. Note: *Durafil* is Lilienfeld rayon; *Fibro* is staple viscose rayon; *Lanital* is a casein fibre; acetate rayon is secondary acetate.

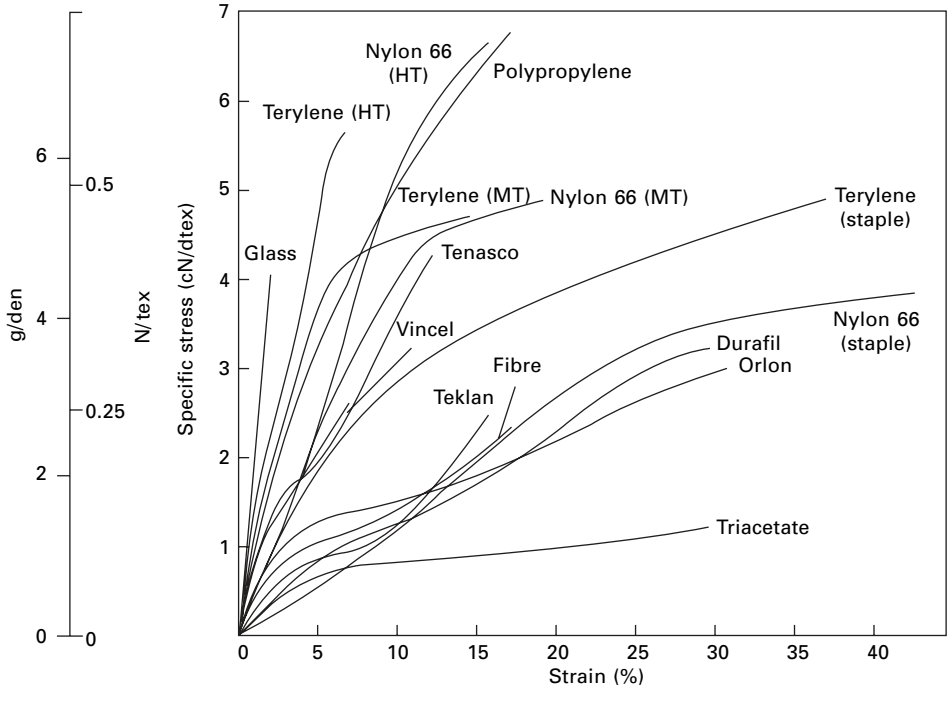
Table 13.1 Tensile properties of fibres at 65% r.h., 20 °C, 1 cm test length, 0.15 mN tex^{-1} s^{-1} [2]

Fibre	Tenacity (N/tex)	Breaking extension (%)	Work of rupture (mN/tex)	Initial modulus (N/tex)	Yield stress (mN/tex)	Yield strain (%)	Work factor
Cotton							
St Vincent	0.45	6.8	14.9	7.3	–	–	0.49
Upper	0.32	7.1	10.7	5.0	–	–	0.46
Bengals	0.19	5.6	5.1	3.9	–	–	0.49
Flax	0.54	3.0	8.0	18.0	–	–	0.50
Jute	0.31	1.8	2.7	17.2	–	–	0.50
Hemp	0.47	2.2	5.3	21.7	–	–	0.50
Ramie	0.59	3.7	10.6	14.6	–	–	0.47
Viscose rayon	0.18	27.2	30.6	4.8	57	2.0	0.62
Courtaulds continuous-filament							
Fibro	0.21	15.7	18.8	6.5	68	1.9	0.59
Tenasco	0.27	16.9	19.7	6.0	66	1.6	0.50
Acetate (Celanese)	0.13	23.7	21.6	3.6	75	3.2	0.72
Fortisan (cellulose)	0.59	6.4	19.1	16.1	113	0.8	0.51
Silk	0.38	23.4	59.7	7.3	156	3.3	0.66
Nylon	0.47	26.0	76.0	2.6	407	16.0	0.61
Wool							
Botany 64s	0.11	42.5	30.9	2.3	57	5.0	0.64
Crossbred 56s	0.14	42.9	37.5	2.1	62	5.1	0.62
Crossbred 36s	0.12	29.8	26.6	3.0	74	3.6	0.78
Glass	0.75	2.5	9.8	29.4	–	–	–
Steel wire	0.26	8.0	17.7	28.5	–	–	–

13.12 and Table 13.2. Another useful set of comparative data was published by du Pont [31] at this time.

For the second generation of synthetic fibres, the high-modulus, high-tenacity fibres (HM–HT), there is no comparative data for fibres tested in a single investigation. It is necessary to take data from a variety of sources, for which test conditions may not be the same. A set of stress–strain curves is shown in Fig. 13.13(a) and another set, which gives a comparison with nylon and polyester (PET) fibres in Fig. 13.13(b). Table 13.3 lists the tensile properties of a selection of HM–HT fibres. Table 13.4 gives values for some chemically and thermally resistant fibres.

The complete collection of fibres can be roughly divided mechanically into five groups, which are illustrated in Fig. 13.14. The weak inextensible fibres such as rock wool are of little interest. The natural and regenerated fibres and some synthetics have moderate strength and extensibility. The tough synthetic fibres have higher strength combined with extensibility. The HM–HT fibres have high strength and low extensibility. The elastomeric fibres have low tenacity, when related to their unstrained dimensions, and high extensibility.



13.12 Stress–strain curves of various fibres. From Farrow [28, 29] and Ford [30]. Note: viscose rayon variants are *Fibro* (regular staple), *Vincel* (high-wet modulus) and *Tenasco* (high-tenacity, industrial); *Terylene* is polyester fibre; *Orlon* is acrylic fibre.

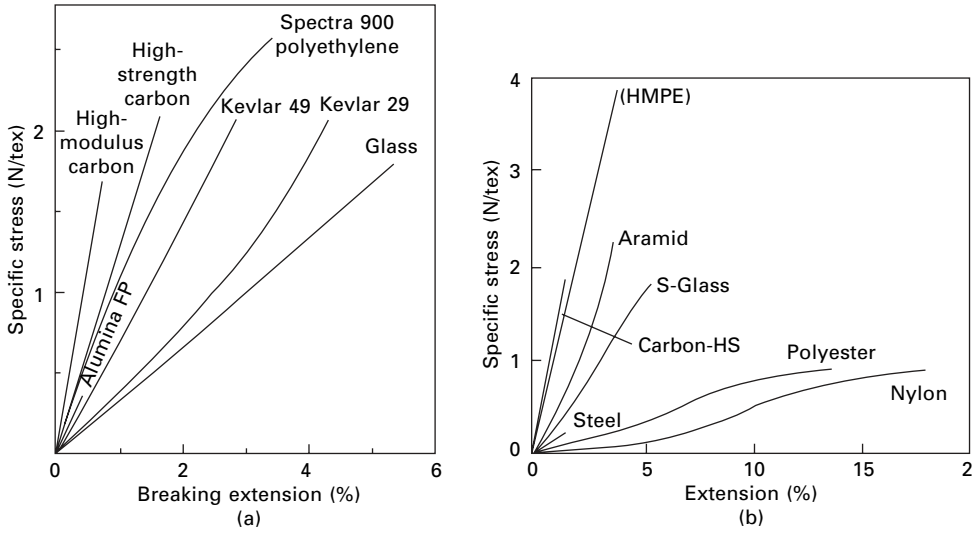
Table 13.2 Tensile properties of fibres at 65% r.h., 20 °C [28–30]

Fibre	Tenacity (N/tex)	Breaking extension (%)	Work of rupture (mN/tex)	Initial modulus (N/tex)
Viscose rayon				
high-tenacity	0.41	12	28	8.8
polynosic	0.26	7	11	13.2
Triacetate	0.12	30	18	3.1
Casein	0.10	63	44	3.5
Nylon 6.6				
medium-tenacity	0.48	20	63	3.0
high-tenacity	0.66	16	58	4.4
staple fibre	0.37	43	101	1.0
Nylon 6 (*Perlon*)	0.29	46	77	0.6
Polyester fibre (*Terylene*)				
medium-tenacity	0.47	15	53	10.6
high-tenacity	0.56	7	22	13.2
stape fibre	0.47	37	119	8.8
Acrylic (*Orlon* 42 staple-fibre)	0.27	25	47	6.2
Modacrylic (*Dynel*)	0.34	34	63	8.8
Poly(vinyl alcohol)	0.17	26	24	2.2
Poly(vinyl chloride)	0.24	17	23	3.5
Polyethylene				
Courlene (low-density)	0.08	20–40	11–26	0.9
Courlene X3 (high-density)	0.34	10	19	4.4
Polypropylene (*Ulstron*)	0.65	17	71	7.1
Glass	0.40	1.9	3.9	21.2
Elastomer				
polyurethane	0.0309	540	65	0.0071
rubber	0.008	520	14	0.0026

13.5.2 Cotton and the other natural cellulose fibres

The stress–strain curve for cotton is slightly concave to the extension axis, and there is no obvious yield point. Meredith [2] found considerable variation between different varieties of cotton. In general, the finer cottons showed a higher tenacity and a higher initial modulus than the coarser cottons. The breaking extension ranged from 5 to 10% but was not related to fineness. Figure 13.15 shows stress–strain curves of five cottons from the 1970s. The Punjab–American cotton is much stronger than the 1940s Bengals cotton in Table 13.1.

Meredith [34] later showed that there was a better correlation between tenacity and molecular orientation than there was between tenacity and fineness. The orientation may be measured by the birefringence of the fibre, that is, the difference $(n_{\parallel} - n_{\perp})$ between the refractive indices for light polarised parallel and perpendicular to the fibre axis. The orientation value decreases as the spiral angle in the cotton fibre increases (see Section 1.4.3). Figure 13.16 shows the correlation between tenacity and the difference in the refractive indices for 36 different samples of cotton of 26



13.13 Typical stress–strain curves of HM–HT fibres.

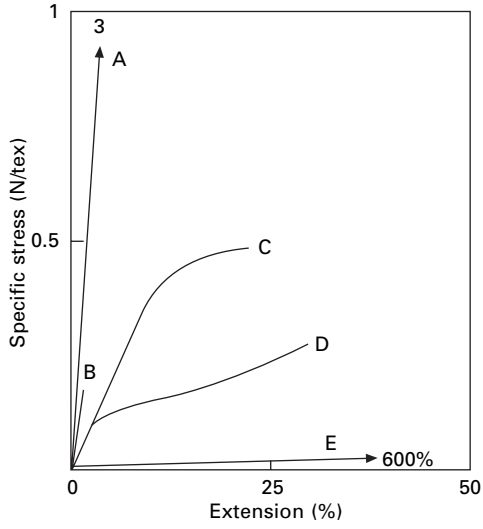
Table 13.3 Illustrative values of tensile properties of HM–HT fibres from manufacturers' literature

Fibre	Tenacity (N/tex)	Initial modulus (N/tex)	Breaking extension (%)	Tensile strength (GPa)	Initial modulus (GPa)
HMPE					
Spectra 900	2.6	124	3.5	2.5	120
Spectra 1000	3.1	177	2.7	3.0	172
Aramid					
Kevlar 29	2.1	58	4.4	3.0	83
Kevlar 49	2.1	80	2.9	3.0	115
Kevlar 149	1.6	98	2.5	2.3	141
Carbon (*Hysil Grafil*)					
XA	1.8	128	1.4	3.2	230
High-strain	2.1	128	1.7	3.7	230
High-modulus	1.3	183	0.7	2.5	340
Ultra-HM	1.7	218	0.8	3.1	405
Silica					
Enka LT	0.14	7	2.0	0.25	13
Enka HT	0.40	28	1.4	0.8	56
Tyranno	1.2	83	1.5	2.8	200
Glass–E	1.4	2.9	4.8	3.5	72
–S	1.8	35	5.4	4.6	87
Silicon carbide					
Niccalon	1.0	81	1.5	2.7	210
Whisker	3.2	220	1.2	8.4	580
Nextel	0.63	56	1.1	1.7	150
Alumina – FP	0.36	97	0.4	1.4	380
Alumina–zirconia					
PRD-166	0.50	90	0.6	2.1	380

These are illustrative examples, taken from manufacturers' literature.

Table 13.4 Tensile properties of chemically and thermally resistant fibres [32]

Fibre	Tenacity (N/tex)	Break extension (%)	Initial modulus (N tex)
Polyvinylidene chloride (PVDC)	0.20	15–30	0.44–0.68
Polytetrafluorethylene (PTFE) (*Teflon*)	0.14	20	–
Polyetheretherketone (PEEK)	0.65	20	4–5
Polyphenylenesulphide (PPS)	0.27–0.47	25–35	2.7–3.7
Melamine-formaldehyde (*Basofil*)	0.2–0.4	15–20	6
Novoloid phenolic resin (*Kynol*)	0.12–0.16	30–50	2.6–3.5
meta-Aramid (*Nomex*)	0.485	20	7.5
Polyimide (P84)	0.35–0.38	33–38	3–4
Polyamide-imide (*Kermel*)	0.25–0.59	8–20	4.9–9.4
Semi-carbon oxidised acrylic	0.14–0.21	15–21	5–8
Polybenzimidazole (PBI)	0.24	28.5	2.8

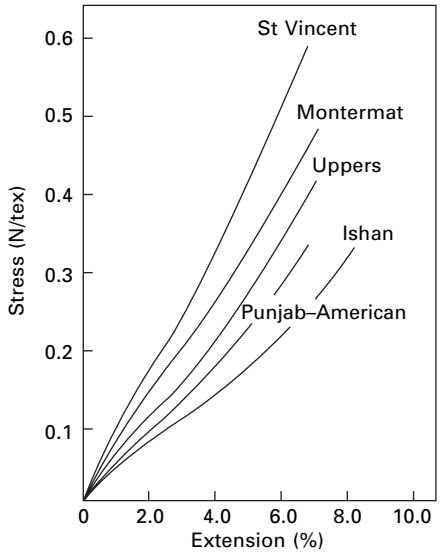


13.14 Mechanical classification of the fibre types: A, HM–HT fibre; B, weak inorganic fibre, e.g. rock wool; C, tough synthetic fibre; D, weaker textile fibre; E, elastomeric fibre.

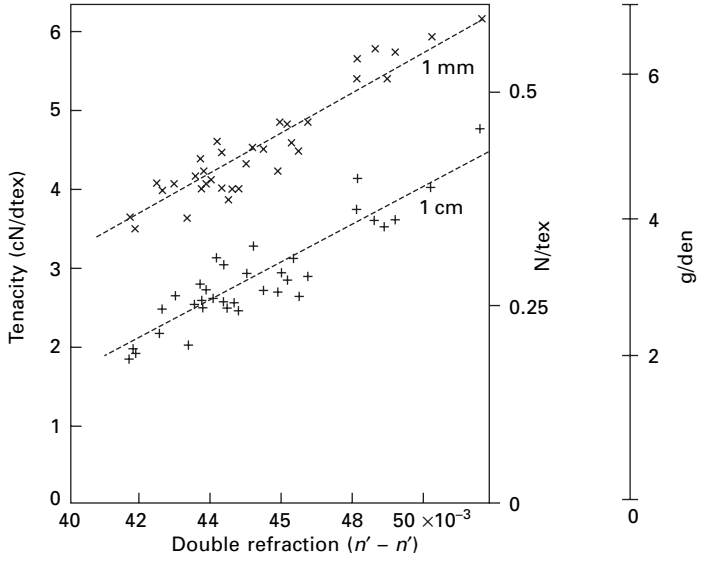
different varieties. Similar results are obtained by using X-ray methods to measure molecular orientation [35], and a correlation is also found between initial modulus and orientation. It must, however, be noted that it has been reported [36, 37] that the spiral angle of cotton fibres is constant within the range 20–23° and that the apparent differences are really due to the effect of convolutions.

Hessler *et al.* [38] investigated the effect of the length of chain molecules in the cotton and found that this also gave a good correlation with the tenacity of different types of cotton. Thus it is not clear which is the effective factor in determining the tenacity of different varieties of cotton.

Morlier *et al.* [39] investigated the difference between fibres *within* a given sample of cotton for six different varieties of cotton. In most cases, they found that tenacity

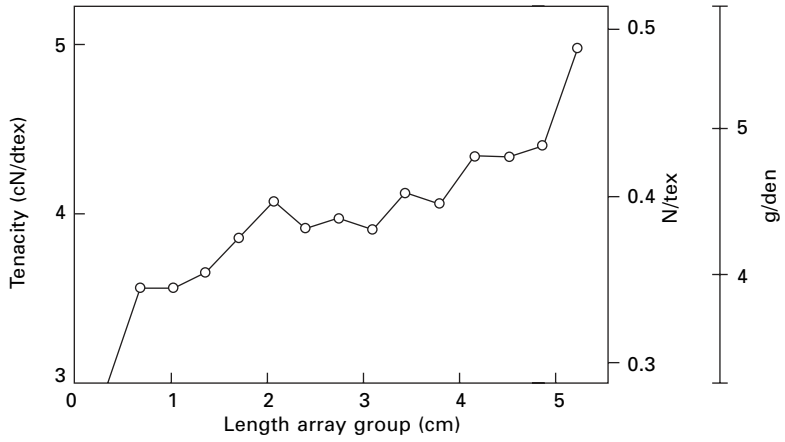


13.15 Stress–strain curves for various cottons. After Sparrow [33].



13.16 Correlation between tenacity and birefringence of cotton at test lengths of 1 mm and 1 cm. From Meredith [34].

and breaking extension increased with increasing length of fibre. An example of their results is given in Fig. 13.17. Meredith found no correlation between strength and fineness within a sample of cotton. Timpa and Ramey [40] found an increase of strength, measured in four laboratories according to HVI standards, from 0.2 to 0.3 N/tex with increasing length from 21.2 mm (staple length code: 26) to 32 mm (code: 40); they also found a significant increase of strength with molecular weight, albeit



13.17 Correlation between tenacity and length for a Sea Island cotton. From Morlier *et al.* [39].

Table 13.5 USDA descriptive designations for HVI tenacity values of cotton

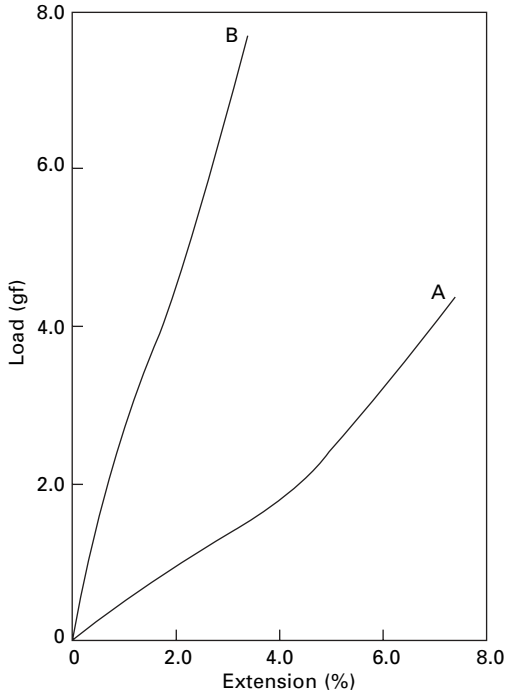
Designation	HVI tenacity	
	Specified grams per tex	Equivalent N/tex
Very weak	<20	<0.196
Weak	21–23	0.206–0.226
Average	24–26	0.235–0.255
Strong	27–29	0.265–0.284
Very strong	>30	>0.294

with considerable scatter. Foulk and McAlister [41] report an extensive study of the tensile properties of cottons with three micronaire values, each subdivided into seven length groups.

With the advent of HVI testing of cotton, the US Department of Agriculture (USDA) has given the designations of tenacity values in Table 13.5 as an indication of cotton fibre quality. The values are lower than those from Meredith's single fibre tests, reflecting the influence of bundle testing discussed in Chapter 14.

Hearle and Sparrow studied the effect of convolutions on the behaviour of cotton fibres [42]. If a fibre is stretched, the convolutions are pulled out. If the fibre is extended in the wet state and dried while held under tension, the extended form is temporarily set. Figure 13.18(a) shows the effect on the stress–strain curve at 65% r.h. The treated fibre is stiffer, and shows a higher tenacity and lower break extension.

The bast fibres, in which the molecules are very nearly parallel to the fibre axis, show a greater tenacity, a higher modulus, a lower breaking extension and a lower work of rupture. They constitute the strongest but least extensible of natural fibres. The jute tested by Meredith gave lower values of tenacity than the other bast fibres, but it has been shown by Mukherjee *et al.* [43] that a better-quality jute has a tenacity



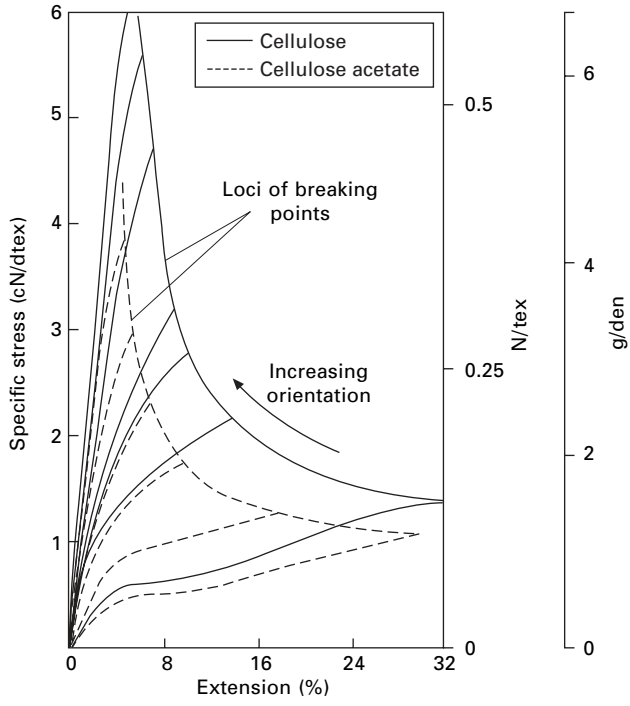
13.18 Load–extension curves of Acala cotton: A, normal fibre; B, after stretching wet and drying.

of 0.56 N/tex under similar conditions; this is as strong as flax or hemp. Franck [44] includes a large collection of reported values of mechanical properties of bast and other plant fibres. The values are generally similar to those for flax, jute, hemp and ramie in Table 13.1.

13.5.3 Regenerated cellulose and related fibres

The stress–strain curves of rayon and acetate fibres show an initial rapid rise with a marked yield point, followed by a nearly flat portion and a rise again as breakage approaches. The curves vary widely for different types of rayon and different manufacturing methods. Differences are due to the spinning method and the degree of stretch imposed. A highly stretched fibre, such as the formerly produced *Durafil*, has high molecular orientation, which gives high strength and low extensibility, similar to the bast fibres. Rayons used for apparel are weaker and more extensible. Tyre-cord rayons, such as *Tenasco*, are intermediate in value.

The effect of orientation is clearly shown in the set of curves in Fig. 13.19, for acetate of varying degrees of orientation. If cellulose yarns are regenerated from the acetate, as they were in *Fortisan*, the locus of strengths is somewhat higher. Acetate fibres are, in general, weaker and more extensible than viscose rayon fibres. The load–elongation curves of acetate fibres, measured at constant rate of elongation, often show a drop after the yield point.

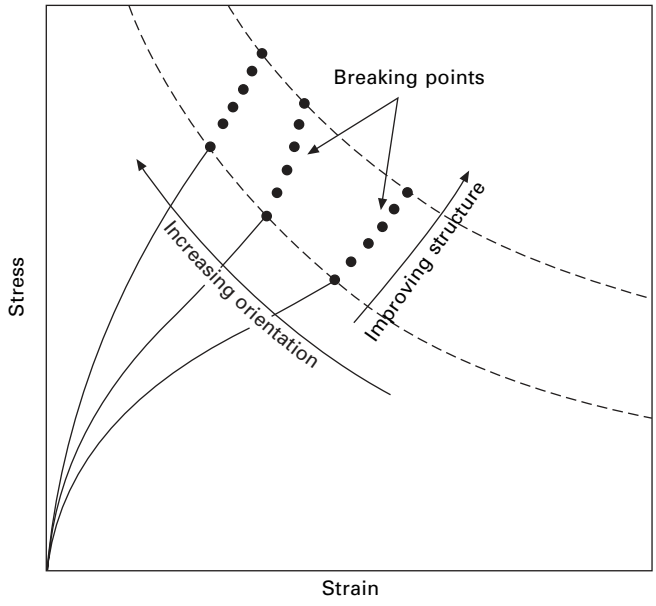


13.19 Stress–strain curves of filaments of varying degrees of orientation. The dotted curves are secondary cellulose acetate and the full curves are cellulose fibres regenerated from acetate. The lowest curve in each set is for unoriented material. From Work [45].

There are also important differences in the tensile properties of viscose rayon, depending on their fine structure. An improvement in structure will cause the whole locus of breaking points to be moved farther from the origin, so that strength is increased without the loss of extensibility that occurs when orientation is increased. This is illustrated in Fig. 13.20, and the great advances that were made in high-tenacity rayon tyre yarns in the 1950s are shown in Table 13.6. More extensible analogues of these fibres are used as high-strength staple fibres. Rayons made until the 1950s had a micellar structure, which results in a low-wet-modulus and a low strength as shown later in Fig. 13.26.

The modal rayons, which include polynosic fibres, are fibrillar in texture, and are stiffer, and closer to cotton in properties, than earlier rayon fibres (see Fig. 13.21). They have a high-wet-modulus and better wet strength. The reasons for this are discussed in Section 20.2.2. Lyocell fibres, such as *Tencel*, are similar in tensile properties, but somewhat stronger and stiffer. White *et al*. [47] give dry tenacities and break extensions of 0.38–0.42 N/tex at 14–16% dry and 0.34–0.38 N/tex at 16–18%.

Chamberlain and Khera [48] investigated the variation in the properties as the outer layers of viscose and cuprammonium rayon filaments are removed chemically. A typical result for viscose rayon is shown in Fig. 13.22. 1t appears from these results that the outermost layers are less extensible than the layers below the surface, but the



13.20 Load–extension curves for viscose rayon, showing changes produced by increasing orientation and improving structure.

Table 13.6 Properties of viscose rayon tyre cords. From Wilkinson [46]

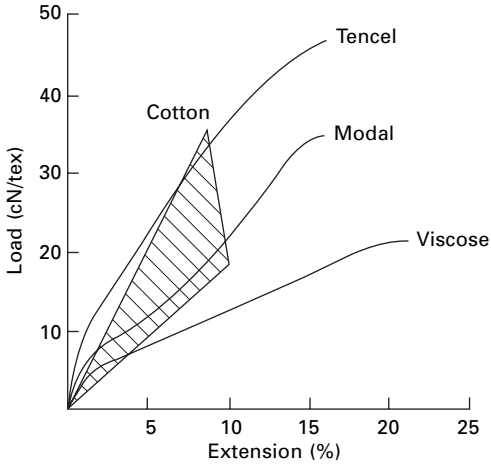
Type	Tenacity (N/tex)	Breaking extension (%)
Textile rayon	0.19	20
Tenasco	0.30	10
Tenasco 35	0.35	10.5
Tenasco 70	0.36	13.5
Tenasco Super 105	0.47	12.5

variation in tenacity cannot be worked out, since the stress would concentrate in the least extensible parts of the fibre. The results for cuprammonium rayon were different for the two samples of fibre tested.

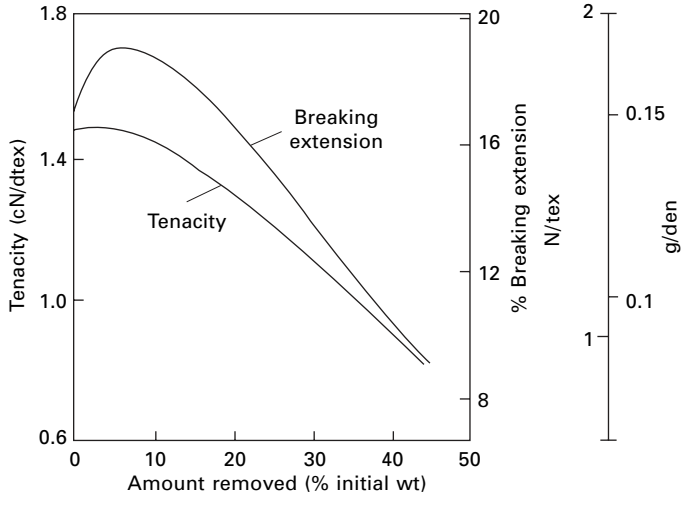
From reports by different workers, Muri and Brown include tenacities N/tex and break extensions of 0.154/14.5% and 0.183/ 6% for calcium alginate fibres and 0.204/10% for zinc alginate [49].

13.5.4 Protein fibres

Silk, like nylon, is characterised by fairly high strength and breaking extension, which combine to give a work of rupture very much greater than that of the other fibres tested by Meredith. The wide range of spider silks include fibres of very high



13.21 Stress–strain curves of lyocell (*Tencel*), modal and regular viscose rayon compared with cotton. From Courtaulds Lyocell Overview.



13.22 Change of tenacity and braking extension of viscose rayon as outer layers are removed. From Chamberlain and Khera [48].

strength combined with high extensibility, which leads to very high work of rupture [50, 51].

Wool and other hair fibres are characterised by low strength but great extensibility. Owing to the high breaking extension, and to the shape of the curve, the work of rupture is not low despite the low strength. Different types of wool give slightly different curves, but these are always characterised by an initial linear Hookean region up to 2% extension, a yield region of very low slope from 2 to 30% extension, and finally a post-yield region of greater slope, up to a breaking extension around 45%.

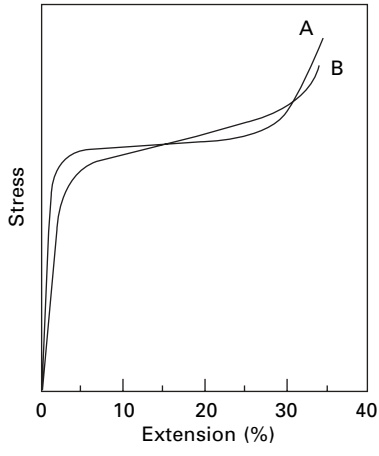
The very extensive experimental studies that have been carried out on wool have been reviewed by Chapman [52] and Feughelman [53]. Much of the work has been done on wet fibres, and Collins and Chaikin [54] have found, as illustrated in Fig. 13.23, that, if the effects of fibre irregularity are eliminated, the separate regions become even more distinct, with sharp turning points between them, and the yield slope becomes very small.

Anderson and Cox [55] have shown that although there was a very wide scatter of the results, the tenacity of wool fibres from a given lock of wool increased with the fibre diameter. There was a slight positive correlation between breaking extension and fibre diameter.

Regenerated protein fibres are weak and extensible and even weaker when wet. In addition to the fibres manufactured in the 1950s, this also applies to the attempts to produce fibres from spider silk proteins derived from genetically engineered sources.

13.5.5 Synthetic fibres

The general tendency in melt-spun synthetic fibres, as shown by Figs 13.11 and 13.12 and Tables 13.1 and 13.2, is for moderately high strength to be combined with moderately high breaking extension, which results in a tough fibre, though this is open to modification through the amount of drawing. The lower part of the stress–strain curve is very sensitive to the treatment of the fibre and may or may not show a yield point. There is commonly another yield point at a high stress, close to the breaking stress, though this may be cut off by premature rupture. Although their breaking points lie close together, polyester fibres have a markedly higher initial modulus than nylon and polypropylene fibres. This has a practical effect on the handle of fabrics. Differences in the shape of the stress–strain curves of commercial polyamide and polyester fibres can be attributed to changes in the annealing and drawing processes during manufacture.

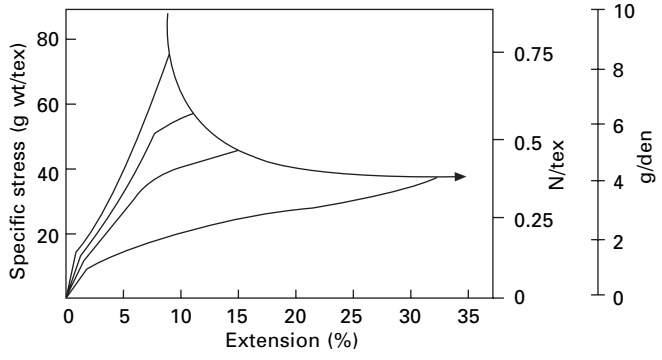


13.23 Stress–strain curves of wool fibres: A, with good uniformity; B, more irregular fibre. From Collins and Chaikin [54].

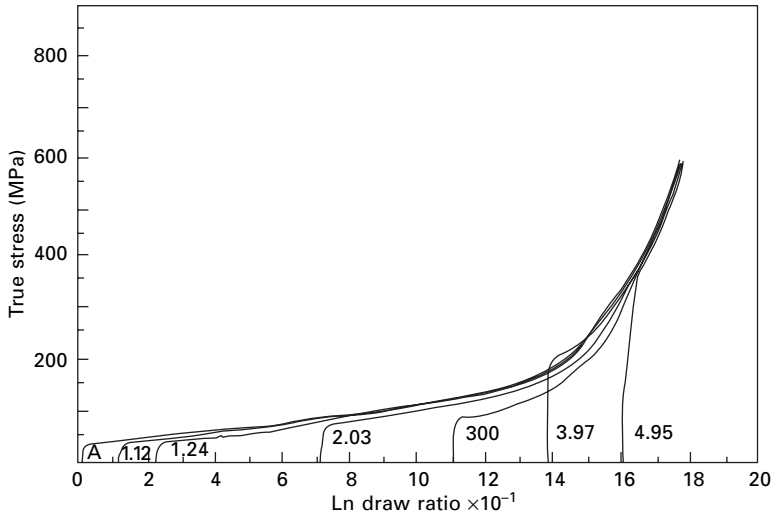
The tensile properties of synthetic fibres depend to a considerable extent on the molecular weight of the polymer and on the conditions of spinning and drawing. A good example of this is polyester fibre, which can have a variety of stress–strain curves, as shown in Fig. 13.24. As the degree of orientation is increased by drawing, strength and stiffness increase and breaking extension decreases. If the molecular weight increases, the locus of breaking points moves upwards, but the initial parts of the stress–strain curve are little altered.

The results in Fig. 13.24 are for an early *Terylene* polyester fibre produced by winding up an undrawn, low orientation fibre and then drawing it under different conditions. Ward [57], and Long and Ward, [58] have studied the drawing behaviour of polyester fibres, previously drawn to different degrees. After an initial stiff region, the fibre yields and joins a common curve to the break point (Fig. 13.25. Recovery from any point on the draw curves is approximately along lines parallel to the elongation curve of the fibre with the highest draw ratio. The yield at the end of the stress–strain curve of a drawn fibre is the final stage of the draw process. For practical operation, the maximum draw cannot be imposed, because a certain margin has to be left or there would be a risk of breakage during the drawing operation. In polybutylene terephthalate (PBT, 3GT) a crystaline phase transition and in polyethylene naphthalate (PEN) crystallisation effects complicate the relation between drawing and properties [57].

The early separation of spinning and drawing gave way to a continuous spin-draw operation, but this did not appreciably change the mechanical behaviour. A greater change when spinning at higher speed, *c*. 3000 m/min, gave partially oriented yarns (POY), for which drawing could be completed in subsequent draw-texturing or other processes. Figure 13.26 shows stress–strain curves for polyester fibres spun at different speeds. If the curves are translated to an equivalent draw ratio, then after the initial elongation, they fall on a master curve similar to Fig. 13.25. Polyester fibres spun at around 6000 m/min are sometimes referred to as fully oriented fibres (FOY). What this means is that they are oriented to a degree that allows them to be used directly in some textile fabrics without additional drawing. However, it can be seen from Fig.



13.24 Stress–strain curves of polyester fibre (Terylene) at varying orientations [56].



13.25 Stress–strain curves of polyester fibres previously drawn to different degrees. Note that the stress is a true stress, based on the changing area of cross-section. The numbers attached to the curves are the initial draw ratios. From Ward *et al.* [59].

13.26(a) that they are more extensible than conventional drawn fibres and they will have a lower tenacity based on the as-spun linear density.

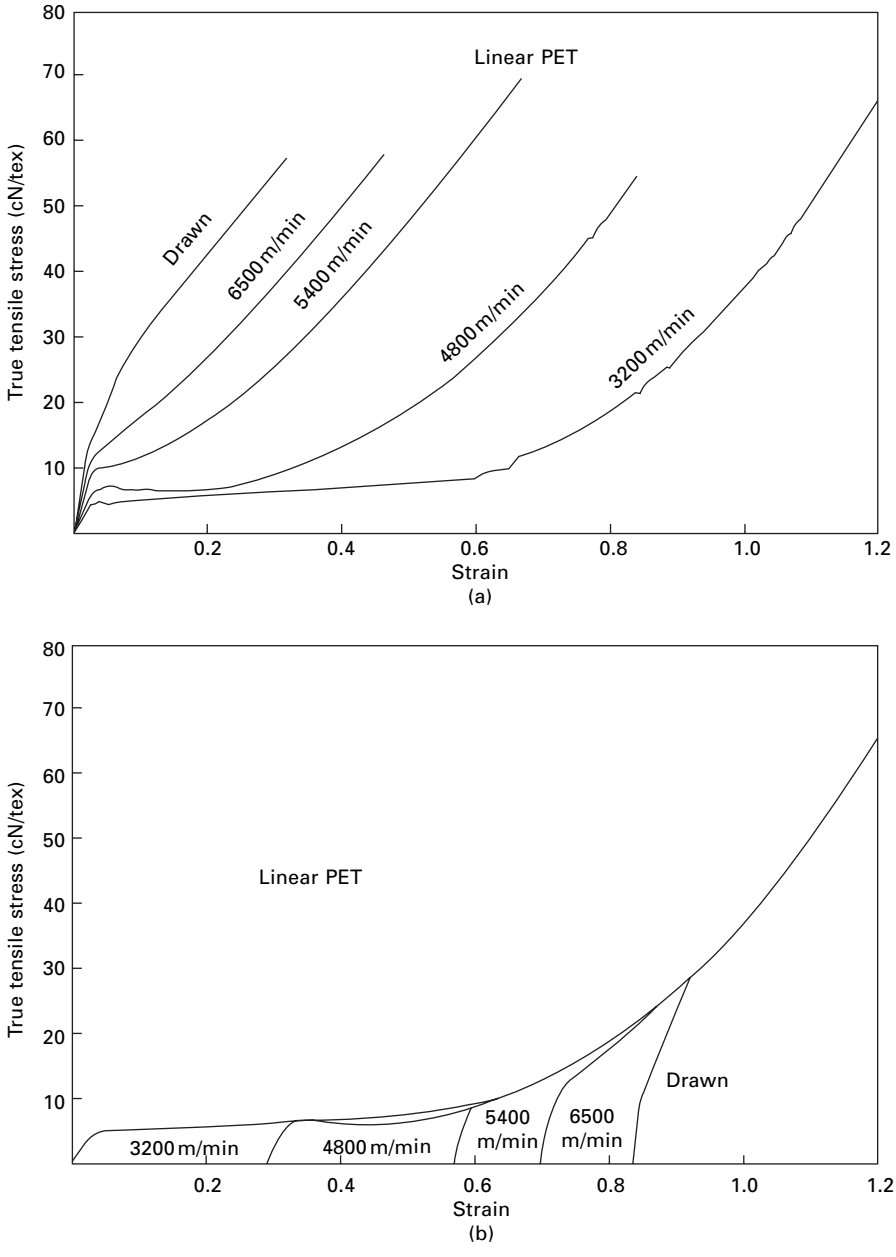
For maximum stiffness and strength, which naturally combine with low breaking extension, polyester fibres are subject to additional heat treatments under tension. These high-tenacity yarns were initially developed for tyre cords, but are also used in other technical textiles. Typical properties of a high-tenacity polyester yarn would be a tenacity of 0.8–0.85 N/tex with a breaking extension of 13–18%. This is considerably stronger than the early high-tenacity polyester listed in Table 13.1. The fact that both strength and break extension have increased means that the stress-strain curve has been extended to a higher locus without much change in stiffness.

PEN fibres have a higher modulus than PET fibres. Polytrimethylene terephthalate fibres have a lower modulus and are more similar to nylon in tensile properties.

The effect of draw ratio and spinning speed for nylon is broadly similar to that for polyester. Figure 13.27 shows stress–strain curves for nylon 66 fibres spun at different speeds. High-tenacity nylon yarns reach about 0.85 N/tex in tenacity, but have a breaking extension of 20%, which makes then tougher and more extensible than polyester yarns.

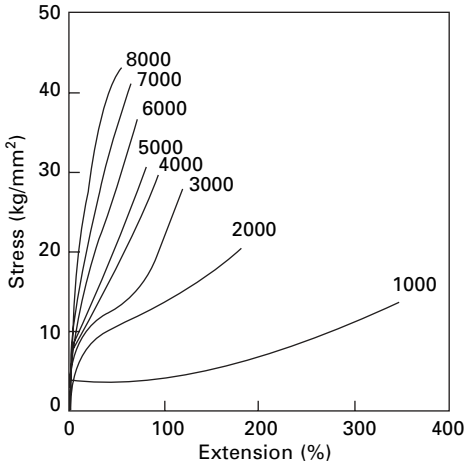
Much detailed information on the effect of spinning speed on mechanical properties and structure of polyester, nylon and polyolefin fibres is included in the book edited by Ziabicki and Kawai [62].

The shape of the stress–strain curve of both nylon and polyester fibres can be considerably altered by heat treatments under tension. Figure 13.28 shows a set of stress–strain curves, related to the original fibre dimensions, for nylon fibres subjected to heat treatments by Hearle *et al.* [63]. Another example of the influence of subsequent

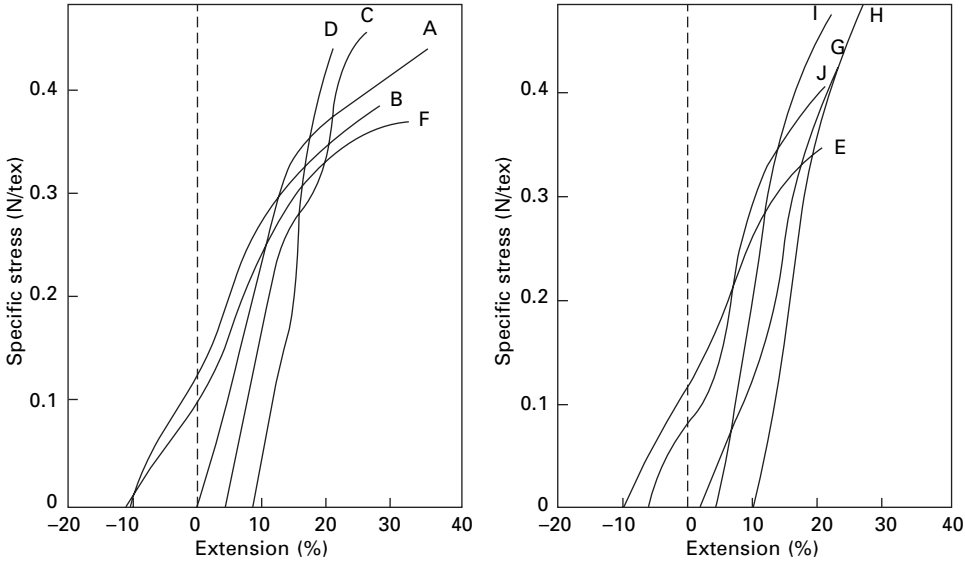


13.26 True stress–strain curves for polyester fibres spun at different speeds: (a) with strain based on as-spun length, (b) with curves translated to an equivalent initial draw-ratio. From Perez [60].

heat treatments is shown by Figure 13.29 for polyester fibres tested at 20 °C and 65% r.h. as received, and under the same conditions after exposure to water at 95 °C: the shape of the curve is markedly different in the two cases. Figure 13.30(a), from an extensive study by Mwaisengela [14] shows stress–strain curves after free annealing

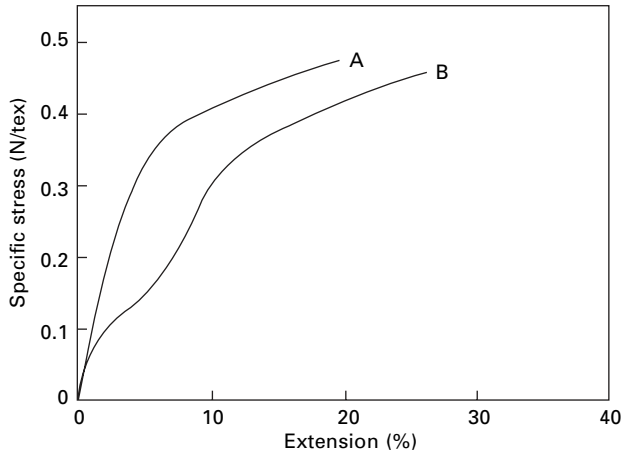


13.27 Stress–strain curves of nylon 66 fibres spun at different speeds. From Shimizu *et al.* [61].



13.28 Stress-strain curves of 70 denier (78 dtex) nylon yarns after various heat treatments: A, as received; B, 200 °C, zero tension; C, 200 °C, 0.3 N; D 200 °C, 0.75 N; E, relaxed in boiling water; F, 200 °C, zero tension, then relaxed; G, 200 °C, 0.75 N, then relaxed; H, 200 °C, 0.1 N, then 240 °C, 0.5 N; I, 200 °C, 0.5 N, then 160 °C, 0.1 N; J, 200 °C, 0.1 N, then 160 °C, 0.5 N, then relaxed [63].

for a moderately high-tenacity polyester yarn spun at 800 m/min, but drawn 4× and heat-set at 160 °C, as used for sewing thread. The low-stress yield has been eliminated by the heat setting, but reappears after annealing. When re-plotted using original dimensions, Fig. 13.30(b), the fibre shows shrinkage of up to 18% and all the curves come together at about 0.3 N/tex and 8% extension. The heat treatment causes a



13.29 Stress–strain curve of polyester fibre under standard conditions: A as received; B, after treatment in water at 95 °C [30].

small loss in strength. Commercially provided polyester yarns may be similar to this yarn in showing no low yield point and having low shrinkage or, if they have been processed differently, may have stress–strain curves with a low yield point like the stress–strain curve in Fig. 13.30(a) at 120 °C. Mwaisengela [14] found a similar behaviour in a high-tenacity nylon 66 yarn, as shown by the tangent modulus plot in Fig. 13.31. The initial stiff region leads to the low yield point, represented by the minimum in the modulus, which is followed by a gradual stiffening and then a lower modulus as break is approached.

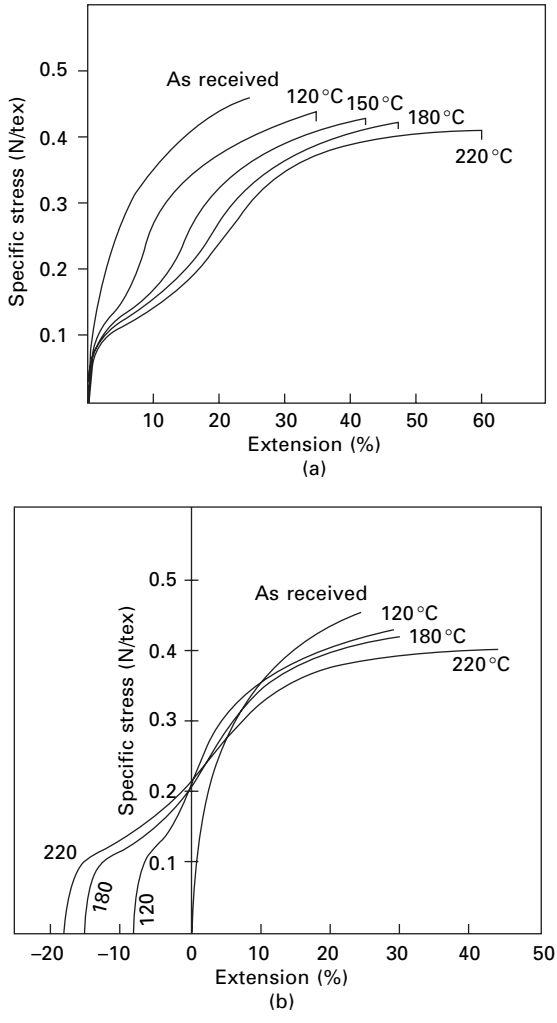
Wang *et al*. [64] report that the strength of polypropylene can be increased to 0.88 N/tex by a second stage drawing process at 140 °C, but some whitening of the fibre is observed. This is an indication of defects in the fibre and the breaking extension is 18.4%, compared with 22% for fibres drawn at lower temperatures.

Figure 13.32 shows the stress–strain curve of an acrylic fibre under standard conditions. As in all acrylic fibres, there is a yield point at around 2% extension. Although treatments can give higher strength and lower breaking extension, commercial acrylic fibres are usually at the lower strength and higher extension range for synthetic fibres. Acrylic fibres are not quite as tough as nylon, polyester or polypropylene fibres.

Staple polylactic acid (PLA) fibres have stress–strain curves in extension similar to wool, with tenacities of 0.32–0.36 N/tex and a break extension of 55% [65]. Elastic recovery is 99.2% form 2% extension and 92.6% from 5% extension, but is not as good as wool from higher extensions.

13.5.6 High-performance fibres

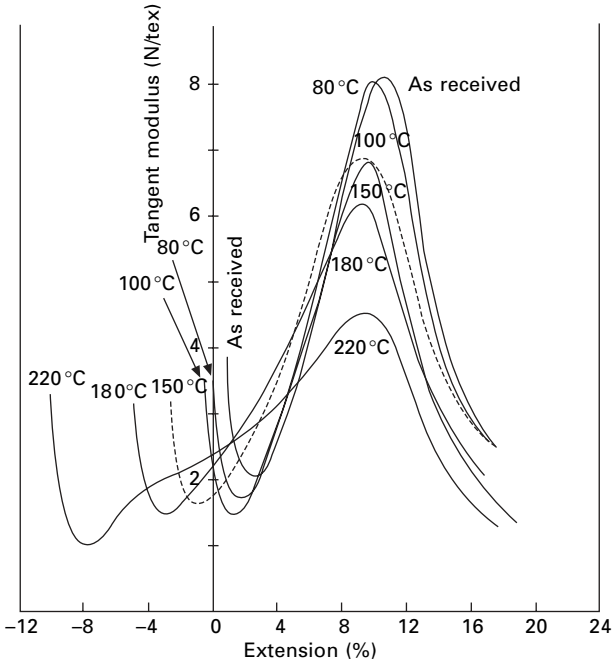
For the characterisation of the tensile stress–strain properties of HM–HT fibres, two aspects merit special mention. Experimentally, the high strength of the fibres makes the problem of securing a grip that holds but does not weaken the specimen more



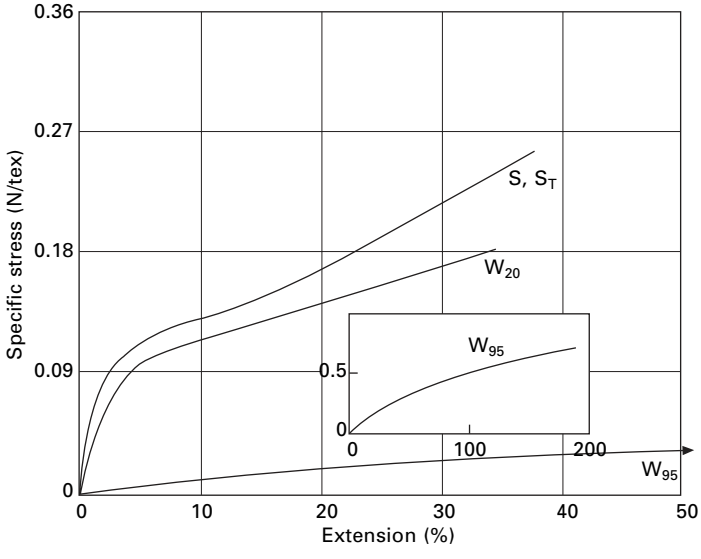
13.30 Stress–strain curves of polyester yarn annealed under zero tension at different temperatures: (a) based on length after annealing; (b) based on original length. From Mwaisengela [14].

acute; and, because of the high stiffness, any softness of the gripping system, including deformation of the jaws and the load cell, will cause greater errors in determination of fibre extension, especially for short samples. In interpretation, the large density differences cause large changes in relative values of strength and stiffness for different fibres, depending on whether specific stresses, normalised by linear density, or stresses, normalised by area, are quoted.

Some typical stress–strain curves of HM–HT fibres were shown in Fig. 13.13. Numerical data in Table 13.3 were given on both a mass and volume basis. It must be stressed: (1) that these are not like the data in Tables 13.1 and 13.2, obtained in single scientific comparisons of many fibre types, but are mostly from manufacturers'



13.31 Tangent modulus plot for nylon 66 yarn free annealed at different temperatures. From Mwaisengela [14].



13.32 Stress–strain curves of Courtelle acrylic fibre: S: 65% r.h., 20 °C, as received; S_T, 65% r.h., 20 °C, after water at 95 °C, W_{20}, in water at 20 °C, as received; W_{95}, in water at 95 °C, as received.

literature; (2) that process differences can cause substantial differences in properties; (3) that most of these fibres are in the first or second generation of development, and improved performance can be expected in future. The examples quoted in Table 13.3 are typical of the range found, but variants and fibres from other manufacturers may have somewhat different properties. For improved forms of HMPE fibres, van Dingenen [66] quotes values up to 3.7 N/tex at a break extension of 3.8% for *Dyneema* SK76. For its *Tenax* carbon fibres, Enka quoted moduli from 238 to 440 GPa, strengths from 2.15 to 4.7 GPa, and breaking extensions from 0.4 to 1.8%. Test methods can also cause differences: for example, Simon and Bunsell [67] report a reduction in mean strength of *Nicalon* SiC fibres from 2.04 GPa at a 15 mm test length to 1.29 GPa at a 220 mm length owing to coefficients of variation of around 30%; and similar effects would occur in other fibres.

To a first approximation, HM–HT fibres follow Hooke's Law, with stress proportional to strain, and break is sharp without any yield. There is no appreciable deviation from linearity in ceramic, glass and carbon fibres. The lower-modulus aramids, like *Kevlar* 29, show a stiffening with extension, but this is reduced in the higher-modulus forms, *Kevlar* 49 and 149, which have been subject to further processing. The HMPE fibres show a softening at high extension. The concave deviation of the aramids is most marked at low stresses, but the convex deviation of HMPE is most marked at high stresses.

A rough guide to comparative values of strength, stiffness (average modulus), and extensibility that can be expected from different sorts of HM–HT fibre is shown in Fig. 13.33, but, for any purposes needing precision, the actual properties should be checked or measured.

Table 13.4 listed tensile properties of fibres that are used for their thermal or chemical properties. Their mechanical properties are generally somewhat inferior to the corresponding general-purpose textile fibres.

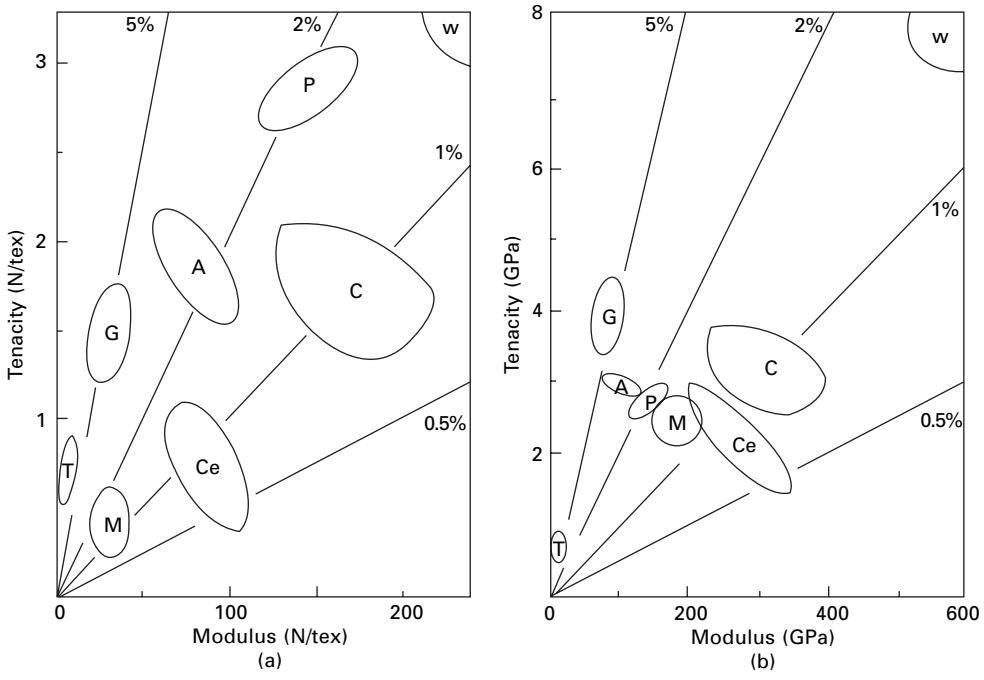
13.5.7 Elastomeric fibres

At the other end of the performance limits from HM–HT fibres, there are elastomeric fibres, which show good elastic recovery up to high extension. Natural rubber can be used, but the most important fine fibres are spandex, with *Lycra* as one example. Figure 13.34 shows a comparison of spandex and rubber fibres: their extensibilities are similar, but the spandex fibre is twice as strong. Based on the initial linear density, the strength appears low; but the true stress at break is about 0.5 N/tex, which is similar to that of nylon and polyester fibres.

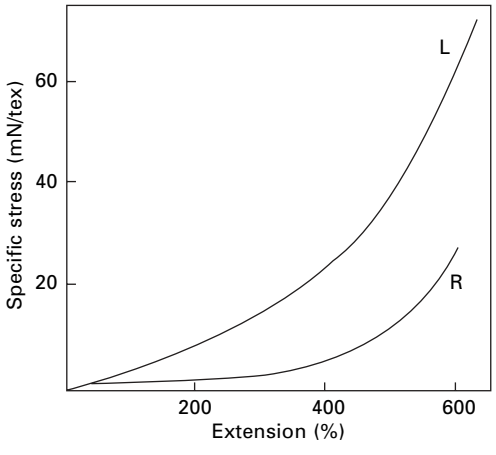
13.6 Other factors

13.6.1 Variability and time dependence

As discussed in the next chapter, particularly for natural fibres, variability must be taken into account in studying tensile properties. The weak link effect means that strengths may be much lower than expected.



13.33 Comparison of regions of mechanical properties approximately covered by different classes of fibres: (a) on weight basis; (b) on volume basis: A, aramid; C, carbon; Ce, ceramic; G, glass; M, metals; P, polyethylene (HMPE); T, textile fibres such as nylon or polyester; W, single-crystal whiskers. The radiating lines show breaking extensions, assuming Hooke's Law.



13.34 Stress–strain curves of *Lycra* spandex fibre (L) and natural rubber (R) [68].

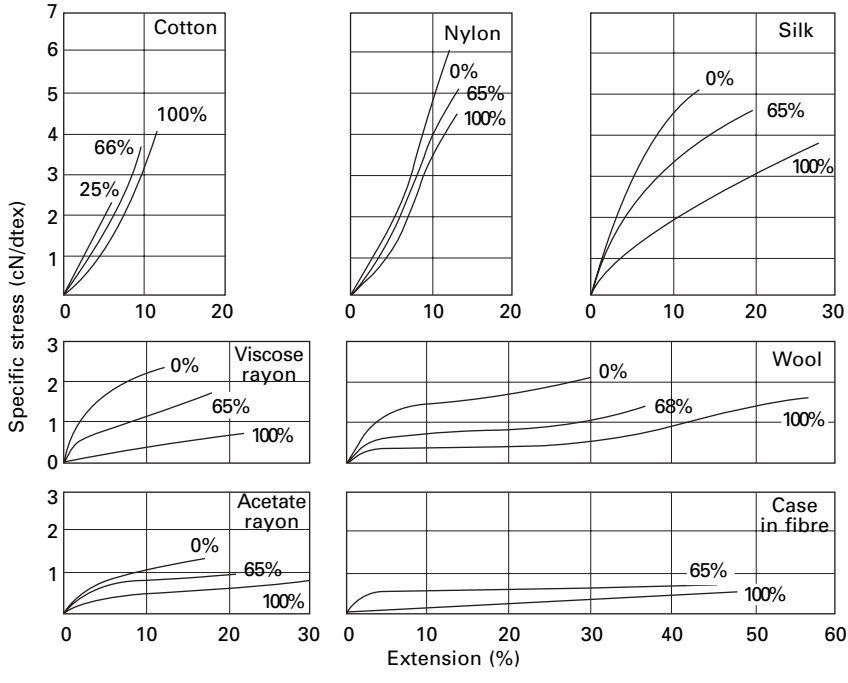
The rate of extension is another factor influencing tensile properties, but this is included in the consideration of rheology in Chapter 16. Generally an increase in rate of testing, often expressed as reduced time to break, leads to lower extensibility and greater strength.

13.6.2 Effect of moisture and temperature

Figure 13.35 shows stress–extension curves for various fibres at different relative humidities. All the fibres become more extensible at higher humidities, the modulus becoming smaller and the breaking extension greater, but, whereas cotton and other natural cellulose fibres become stronger, the rest of the fibres become weaker. Table 13.7 gives values of the tensile properties of a number of fibres expressed as a percentage of the values under standard conditions. The properties of those synthetic fibres which absorb little or no water would not be expected to vary with humidity.

As an example of a set of very detailed results, Fig. 13.36 shows the effect of relative humidity on the stress–strain curves of wool fibres. It will be noted that the major effect is to raise the yield point. This behaviour is also found in other fibres.

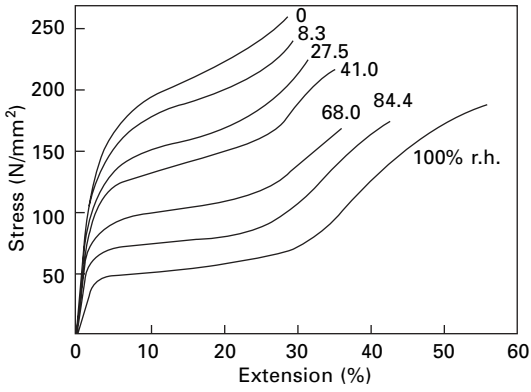
The mechanical properties of fibres also change with temperature. Table 13.7 illustrates the differences between the behaviour at 20 °C and that at 95 °C when wet. The tenacity and stiffness are lower at the higher temperature, but the breaking extension is usually higher. Prolonged exposure to high temperatures can lead to permanent degradation of fibres.



13.35 Stress–strain curves at various humidities [69].

Table 13.7 Effect of moisture and temperature on tensile properties [28, 30]

Fibre	Ratio of values: wet/65% r.h				Ratio of values: wet, 95 °C/wet, 20 °C			
	Tenacity	Breaking extension	Work of rupture	Initial modulus	Tenacity	Breaking extension	Work of rupture	Initial modulus
Cotton, Uppers	1.11	1.11	0.92	0.33	1.00	1.00	1.00	1.00
Viscose rayon								
high-tenacity	0.64	2.00	0.78	0.02	0.90	1.25	1.25	0.75
polynosic	0.70	1.21	0.62	0.08	0.95	1.06	1.00	0.83
normal	0.50	1.58	0.69	0.03	0.90	1.03	0.89	0.80
Acetate	0.54	1.41	0.63	0.17	0.43	1.98	0.75	0.07
Triacetate	0.62	1.27	1.10	0.57	0.56	1.79	0.91	0.30
Silk	0.92	1.63	1.31	0.25	0.71	0.96	0.67	0.67
Wool, merino	0.69	1.33	0.65	0.40	0.55	1.37	0.82	0.50
Fibrolane (casein)	0.32	0.95	0.18	0.05	0.29	0.67	0.33	1.00
Nylon	0.80	1.05	0.87	0.82	0.79	1.76	1.19	0.21
Terylene (polyester fibre)	1.00	1.00	1.00	1.00	0.72	1.40	0.85	0.42
Orlon (acrylic fibre)	0.84	1.08	0.98	1.00	0.35	4.26	1.04	0.02
Polyprpylene fibre	1.00	1.00	1.00	1.00	0.45	2.47	1.13	0.21
Fibreglass	0.80	0.78	0.63	1.00	0.68	0.78	0.53	0.86



13.36 Effect of relative humidity on stress–strain curves of wool at room temperature [52].

Du Pont [31] published data on the influence of temperature on the stress–strain curves of various fibres. Tests in water (Fig. 13.37) illustrate the effect of temperature alone; but those in air combine an effect of moisture, since at –57 °C the humidity would be close to 100 r.h., at 21 °C it was 65% r.h., and at the high temperatures it would be close to 0% r.h. The influence of temperature on the stress–strain properties of wet wool is shown in Fig. 13.38.

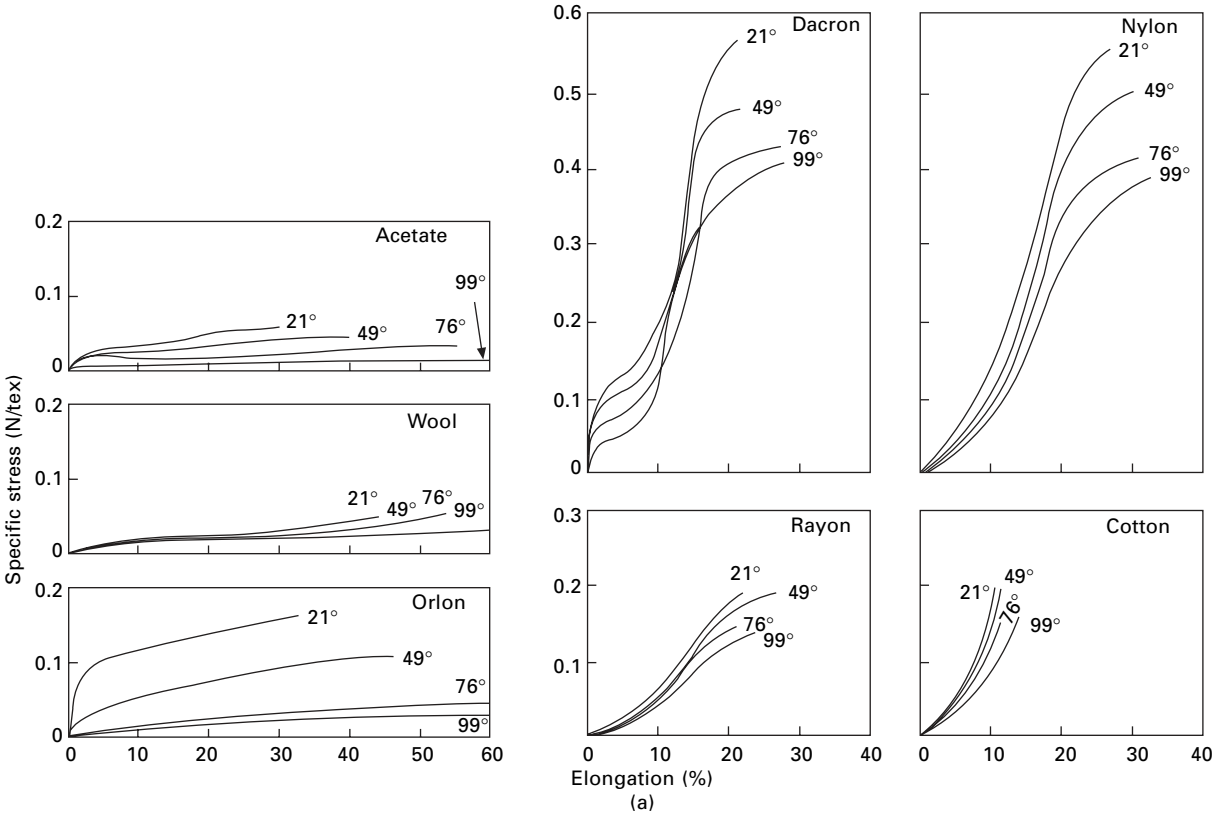
Daniels [71] has shown that the breaking extension of undrawn nylon fibres at –196 °C is only about 12%, but the value increases abruptly to 70% at a draw ratio of 2. The breaking extension then progressively decreases to a value of about 20% at a draw ratio of 4. Hall [72] found that, in drawn polypropylene monofilaments, the breaking extension decreased rapidly from 75% at 35 °C to 50% at 10 °C and 20% at –16 °C the final long yield region of the stress-strain curve was missing at lower temperatures.

Rosenbaum [73] gives stress–strain curves of acrylic fibres at various temperatures and shows that the resistance to extension at 100 °C or more is very small. The low resistance to extension of an acrylic fibre is also shown in Fig. 13.32.

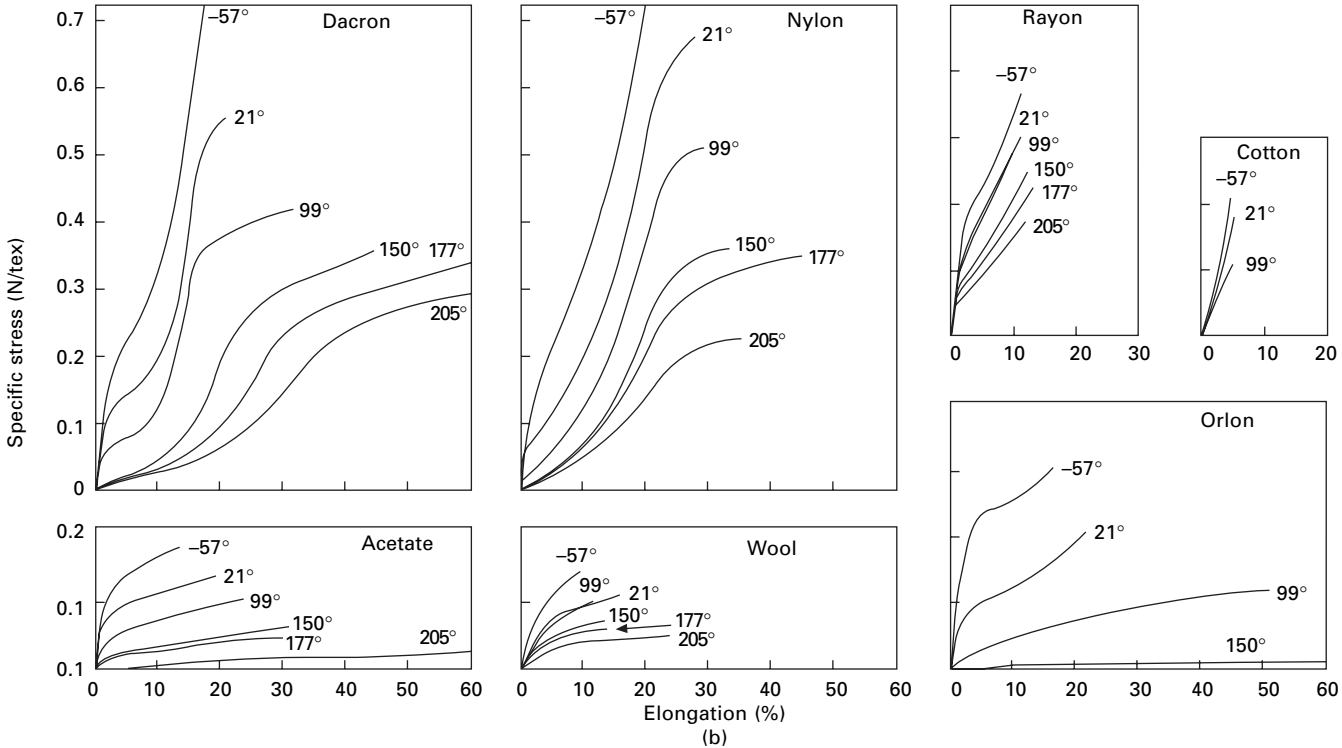
Measurements of the initial modulus of wet fibres at temperatures between 20 and 100 °C have been made by Guthrie [74], and some of his results are shown in Fig. 13.39. The presence of water reduces the modulus of viscose rayon to a low value, and temperature has little further effect; nylon is also little affected. Polyester, triacetate and acrylic fibres all show a very marked fall in modulus as the temperature is raised. This has technical consequences in dyeing, and other forms of hot wet processing, of these materials.

Other data on the effect of temperature on modulus are reported by Ross [75].

Ceramic and carbon fibres retain their strength well up to high temperatures; but glass will lose strength, especially for long times under load, as its softening point is approached. Para-aramid and other liquid crystal fibres retain their strength up to moderately high temperatures, *c*. 400 °C. HMPE suffers considerable strength loss when the temperature increases above about 50 °C, as shown in Fig. 13.40. Since the effect of an increase in temperature is to speed up deformation mechanisms, the



13.37 Comparative stress–strain curves of fibres at various temperatures: (a) in water; (b) in air [31]. *Dacron* is polyester; *Orlon* is acrylic.



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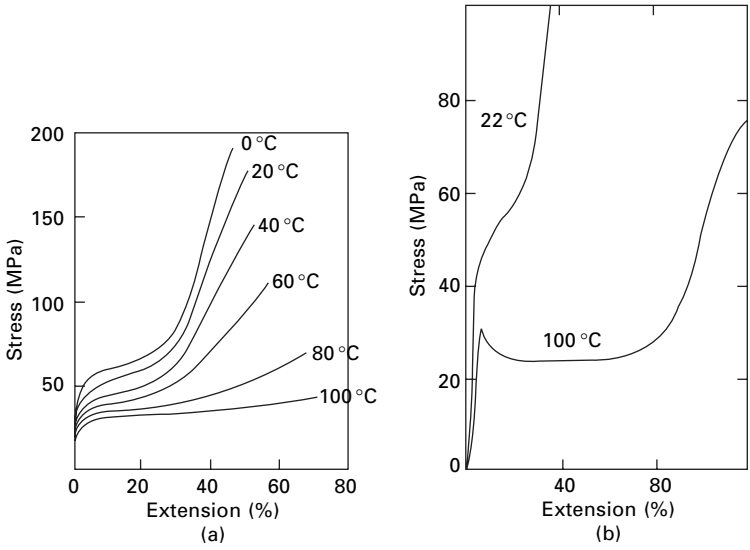
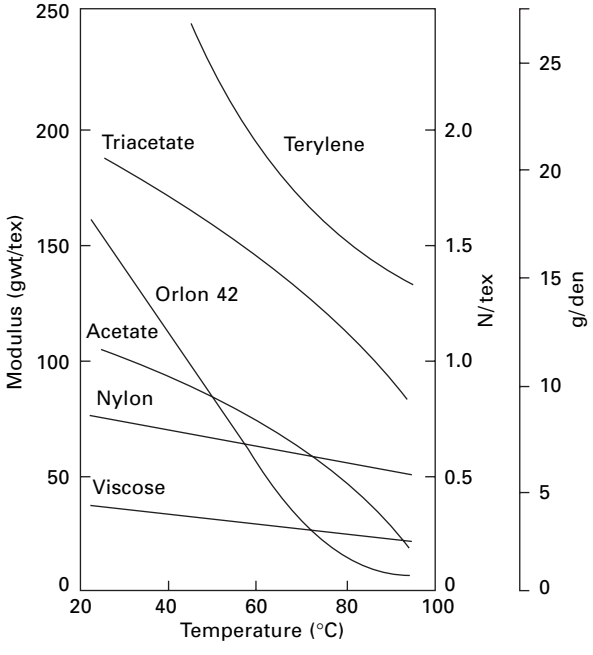
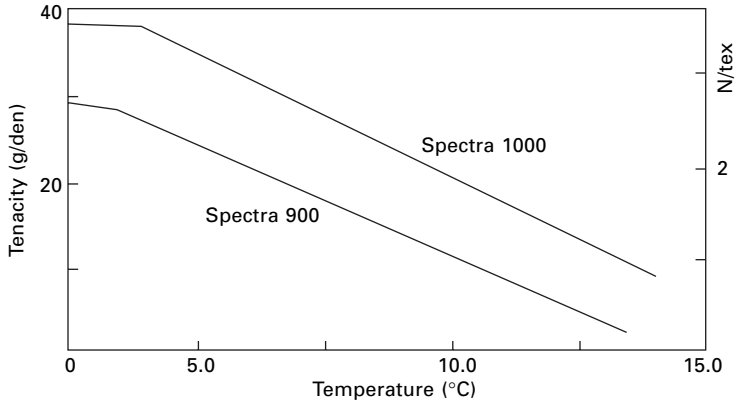


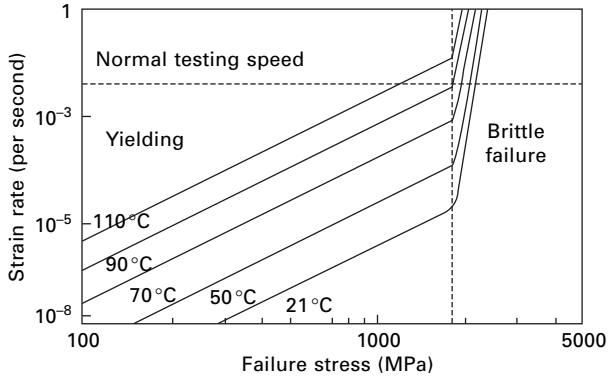
13.38 (a) Effect of temperature on stress–strain curves of wet wool [52]. (b) Stress–strain curves at 22 °C and 100 °C. From Peters and Woods [70].



13.39 Change in initial modulus of wet fibres with temperature. *Terylene* is *Polyester*; *Orlon* is acrylic. After Guthrie [74].



13.40 Effect of temperature on strength of Spectra 900 and 1000 [76].



13.41 Effect of strain rate and temperature on breakage of HMPE (Dyneema) yarn. From van Dingenen [66].

counterpart to this is strength loss with time, as shown in Fig. 13.41. Later improved forms of HMPE fibre have improved creep resistance, which implies lower strength loss with temperature.

13.6.3 Effect of light

When exposed to light, or to ultraviolet or infrared radiation, textile fibres may deteriorate and show a decrease in strength and breaking extension. The degree of deterioration depends on the type of fibre; on the fibre fineness, and the extent to which the fibres are protected by other neighbouring fibres; on whether any dyes, finishes or other agents are present on the fibre; and on the type and intensity of the radiation. The last-named factors are in turn affected by the type of exposure, for example, whether it is in full sunlight, partly shaded, behind glass, or in artificial light; and, for daylight exposure, by the geographical location and the time of year.

In testing materials for light resistance, it must be remembered that other factors, such as mildew, moulds, fungi, industrial fumes, smoke, flexing, abrasion and sand carried in the wind, may cause more deterioration than the sunlight.

Although there have been many *ad hoc* tests, little fundamental information is available. Table 13.8 gives the relative order of resistance to deterioration. Table 13.9 gives values for the loss in strength of undyed cotton and nylon fabrics exposed to sunlight and shows that if ultraviolet radiation is excluded, the damage is considerably reduced.

13.6.4 Effect of chemical environment

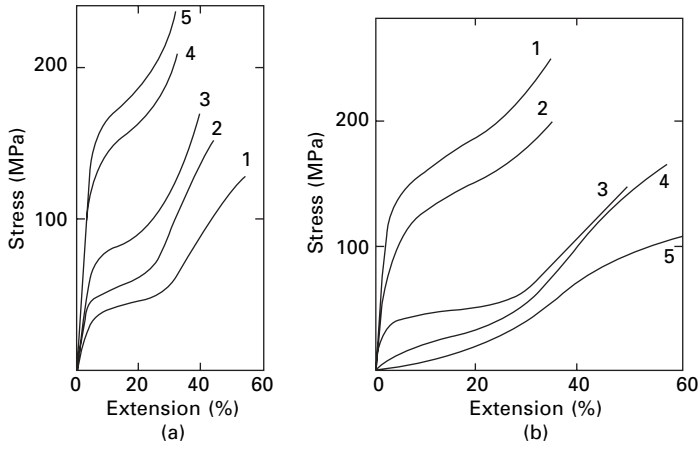
The tensile properties of fibres may also change with the chemical environment. For example, the properties of wool change remarkably in alcohol and in acid conditions, as illustrated in Fig. 13.42. and in salt solutions. Wool supercontracts in a first stage in a cold lithium bromide solution and in a second stage in a stronger hot solution. The resulting stress–strain curves are shown in Fig. 13.43. After the first stage, the initial Hookean and yield regions have been lost. After the second stage, the post-yield stress is lost. Other fibres are affected by different chemicals. More severe chemical treatments lead to permanent changes in mechanical properties.

Table 13.8 Relative loss in strength due to sunlight [77]

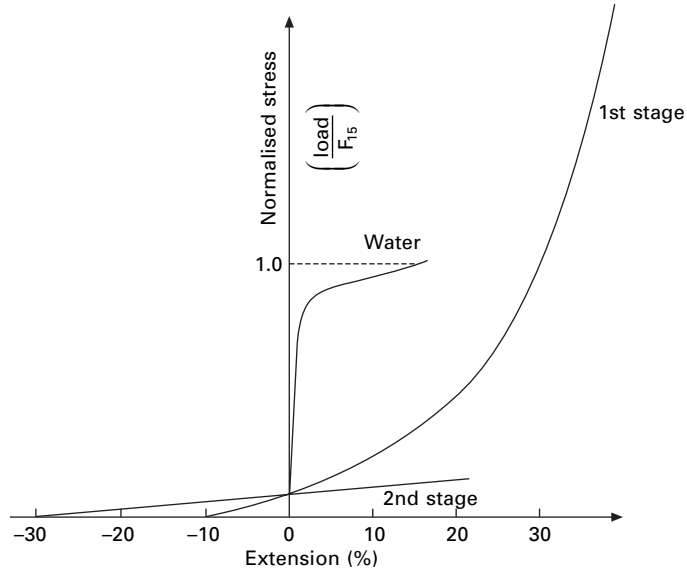
Exposed behind glass	Decreasing resistance	*Exposed outdoors*
Bright *Orlon* acrylic		Bright *Orlon* acrylic
Semi-dull *Orlon* acrylic		Semi-dull *Orlon* acrylic
Bright *Dacron* polyester		Bright acetate, bright *Dacron*, bright nylon, type 680 dull nylon, bright rayon, cotton
Semi-dull *Dacron* polyester		Semi-dull *Dacron* polyester
Bright acetate, bright nylon, type 680 dull nylon, bright rayon, cotton		Silk, and most other semi-dull fibres
Silk, and most other semi-dull fibres		Most dull fibres; excluding dull *Dacron*, or those with a light-degradation inhibor, such as type 680 nylon
Most dull fibres; excluding dull *Dacron*, or those with a light-degradation inhibitor, such as type 680 nylon		

Table 13.9 Loss in strength of nylon and cotton fabrics [78]

	Residual tensile strength (%)	
	Behind untreated film	Behind ultraviolet absorbing film
Cotton, after 4 months, in		
Florida	64	92
Arizona	48	85
Nylon, after 2 months, in		
Florida	15	60
Arizona	13	39



13.42 Effect of chemical environment on stress-strain curves of wool. (a) 1 water and alcohols, 2 methyl, 3 ethyl, 4 *n*-propyl, 5 *n*-butyl or *n*-amyl; (b) 3 water and acids, 1 *n* butyric, 2 propionic, 4 acetic, 5 formic. From Peters and Woods [70].



13.43 Stress–strain curves of wool after first and second stage supercontraction with stress normalised by stress at 15% extension in water. From Chapman [79].

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14

The effects of variability

14.1 Introduction

Textile fibres are not uniform: their composition and fineness vary both from one fibre to another in a sample and along the length of each fibre (see Fig. 3.6(a)). Consequently, their tensile properties are also variable. The variability is of direct interest, since it is just as important to know the range of values of a given quantity in a specimen that is being tested as it is to know the mean value. For example, the variation of properties from one fibre to another influences the distribution of load on fibres in a textile structure, so that a material may be more valuable if it is more uniform, even though it appears to be less satisfactory in terms of its average properties.

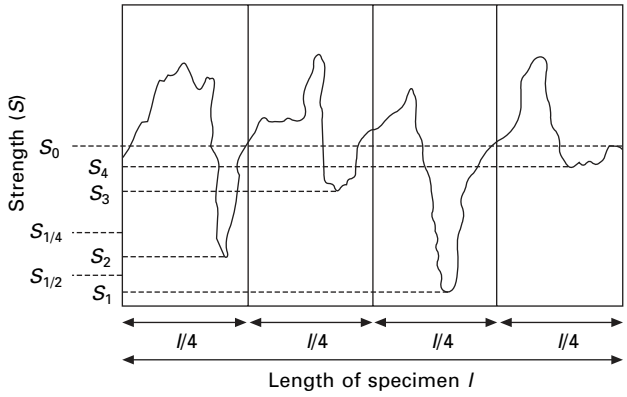
The variability also has important indirect effects on the results of measurements of mechanical properties. These may even result in a change in the order of ranking of specimens when the test conditions are changed.

The dimensions of a fibre also vary as a test is made. When a fibre is extended, it will become narrower. The extension and narrowing may not be uniform along the specimen. These changes during a test must not be neglected in the fundamental study of the behaviour of fibres.

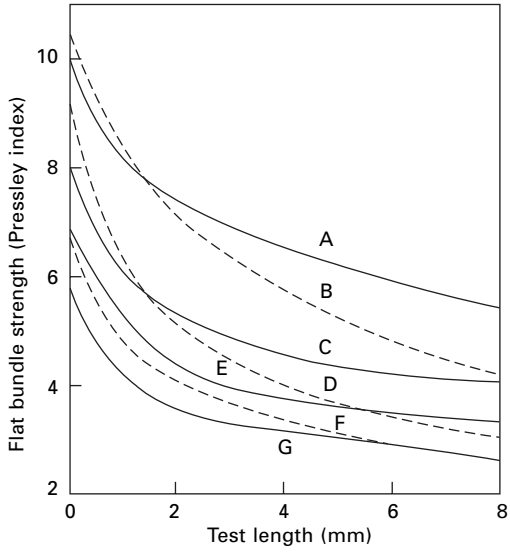
14.2 Variability, specimen length and strength

14.2.1 The weak-link effect

The weak-link effect in its simple form can be expressed as follows. Suppose that we could determine the strength at every point along the length of a fibre. We should find that it varied from point to point, as shown in Fig. 14.1. If a gradually increasing load is applied to this whole specimen, it will break at its weakest point, giving a strength S_1, but if the specimen is tested in two half-lengths, each will break at its own weakest place, one giving the value S_1, and the other a value S_2, which is necessarily greater than S_1. The mean strength $S_{1/2}$, measured on half-lengths, is the mean of S_1 and S_2, and must therefore be greater than the strength measured on the whole length. Similarly, going to quarter-lengths, we get the four values, S_1, S_2, S_3, S_4, and the mean strength $S_{1/4}$ is greater still. This increase will continue until at very short lengths the mean strength tends to the value S_0, which gives equal areas of the curve above and below the line $S = S_0$, since each small element will break at its own value of strength.



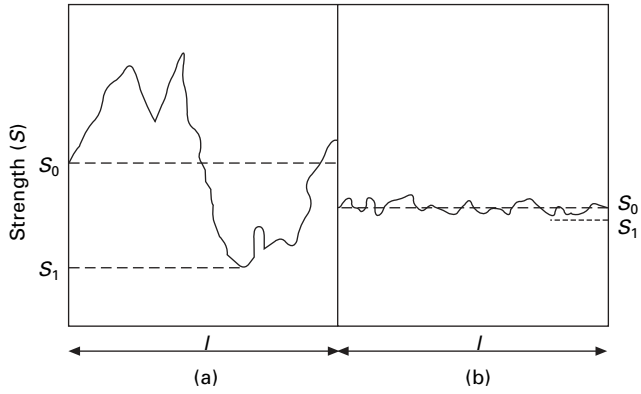
14.1 Weak-link effect.



14.2 Effect of specimen length on strength of cotton in flat bundle test [1]: A, Pima 32; B, THD-27; C, St Vincent; D, Bolshaw 1A; E, Deltapine; F, D and PL Fox; G, Watson Meban.

The weak-link effect described above has the following results:

- The mean measured strength of a specimen decreases as the test-length is increased. A typical example is shown in Fig. 14.2, which shows results from a commonly used bundle-breaking test, the Pressley test (see Section 14.4.2).
- The decrease in mean measured strength will be more rapid the more irregular the fibre is.
- The order of ranking of specimens may alter if the test-length is altered. Figure 14.3 illustrates this. At very short lengths, the fibre shown in (a) appears stronger, but at the length *l* the more uniform fibre in (b), appears stronger. As an example



14.3 Change in order of ranking of materials. S_0 is greater for (a) than for (b), but S_1 is greater for (b).

Table 14.1 Tenacity and length [2]

	Tenacity (N/tex) for test length of:		
	1 cm	1 mm	0.1 mm
Cotton	0.31	0.43	0.59
Nylon	0.47	0.50	0.54

Table 14.2 Estimating strength value

Strength values obtained with 1 cm length	4	5	3	4	6	4	5	3	6	4	Mean 4.4
Strength values selected for 2 cm lengths	4		3		4		3		4		3.6

of such a reversal in ranking, Meredith [2] quotes the values in Table 14.1 for cotton and nylon fibres.

The same effects occur in yarns as in fibres, and it is in relation to yarns that the weak-link effect has been most studied. In the absence of detailed results for fibres, some results for yarns will be included here, since the same ideas should be applicable to fibres.

If one wishes to estimate the strength that would be obtained at some greater test length than that actually used, the simplest method in principle is to group the results together in the appropriate numbers and to take the mean of the lowest value in each group. An example is given in Table 14.2. This method was tedious in practice, and several attempts at mathematical analysis have been made. However, with computers available, there is now no reason to avoid the direct numerical methods.

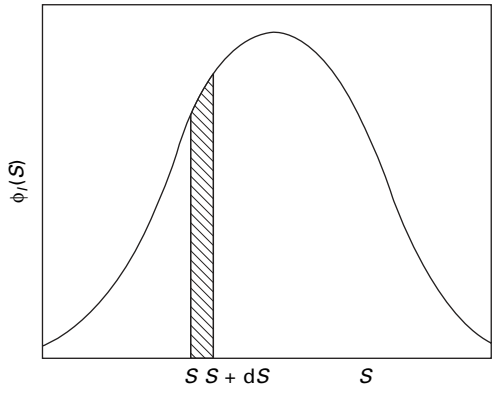
14.2.2 Peirce's theory [3]

Let $\phi_l(S) \cdot dS$ be the probability that the strength of a specimen of length l should lie between S and $(S + dS)$. The function $\phi_l(S)$, shown in Fig. 14.4, thus gives the distributions of breaking loads. It is assumed that this function does not vary significantly from one part of the batch of specimens to another. From the values of the distribution $\phi_l(S)$, one can work out the mean value S_l and the standard deviation σ_l by the usual methods.

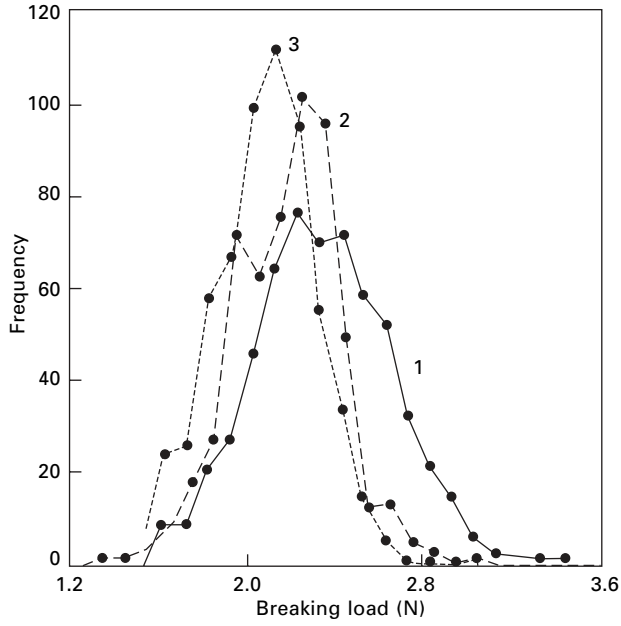
We now wish to find the distribution of breaking loads for specimens of length nl, that is, the probability, $\phi_{nl}(S) \cdot dS$, that the strength of a specimen of length nl lies between S and $(S + dS)$. The condition for this to occur is that the weakest of the n portions of length l of which the complete specimen of length nl is made up should have a strength lying between S and $(S + dS)$. In other words, any one of the n portions must have a strength between S and $(S + dS)$, and the other $(n - 1)$ portions must have a strength greater than S. The probability that any one of n lengths l has a strength between S and $(S + dS)$ is $n \cdot \phi_l(S) \cdot dS$. The probability that the strength of a length l shall be greater than S is $\int_S^\infty \phi_l(S) \cdot dS$; and thus the probability that all $(n-1)$ lengths shall have a strength greater than S is $\left[\int_S^\infty \phi_l(S) \cdot dS\right]^{(n-1)}$. The probability that the strength of a specimen of length nl lies between S and $(S + dS)$ will therefore be given by the product of these two terms, that is:

$$\phi_{nl}(S) = n\phi_l(S)\left[\int_S^\infty \phi_l(S) \cdot dS\right]^{(n-1)} \tag{14.1}$$

By using this relation, the frequency distribution can be worked out for any length of specimen. The relation is valid whether n is less than or greater than unity. Figure 14.5 shows an example of the application of this formula to cotton yarns.



14.4 Distribution of strengths.



14.5 Application of Peirce's theory to cotton yarn. Curves 1 and 2 are experimental curves for test-lengths of 9 and 27 inch (230 and 690 mm), respectively; curve 3 is the calculated curve for 686 mm (27 in.) test-lengths from the data in curve 1.

For further mathematical development, it is necessary to assume a form for the function $\phi_l(S)$. It is simplest to assume a normal distribution. This gives:

$$\phi_l(S) = \frac{1}{2\sigma_l\sqrt{\pi}}\, e^{-(S_l-\bar{S}_l)^2/4\sigma_l^2} \tag{14.2}$$

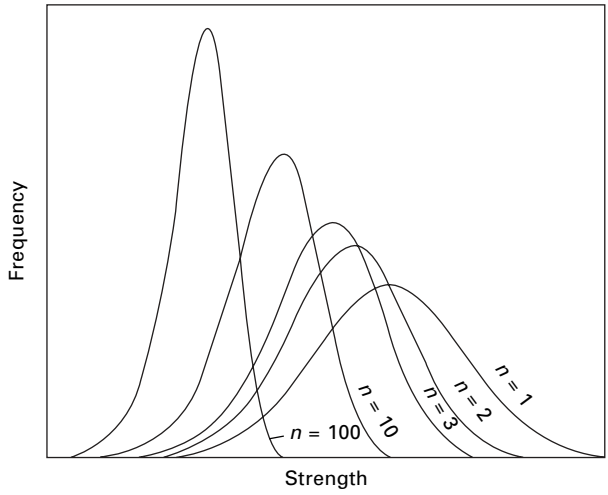
where $\bar{S}_l$ is the mean value of S_l, and σ_l is the standard deviation of S_l. This relation can be substituted in equation (14.1), and the new distribution is then defined. Figure 14.6 shows an example of this. It will be noticed that, even though we start with a symmetrical normal distribution, the derived distributions at other lengths are skew.

The distribution $\phi_{nl}(S)$ is thus known in terms of S_l, σ_l and n. Analysing this expression, and making some mathematical approximations, Peirce obtained equations giving the mean strength $\bar{S}_{nl}$ and standard deviation σ_{nl} for specimens of length nl. The relations are:

$$\bar{S}_l - \bar{S}_{nl} = 4.2(1 - n^{-1/5})\sigma_l \tag{14.3}$$

$$\frac{\sigma_{nl}}{\sigma_l} = n^{-1/5} \tag{14.4}$$

Table 14.3 shows a comparison of values obtained by using these relations with experimental results for cotton fibres. It will be seen that Peirce's relation gives too high a value for the shorter length. This is also found with results for yarns. It is



14.6 Application of Peirce's theory to a normal distribution. Curves for various test-lengths *nl*, calculated from the normal distribution at $n = 1$.

Table 14.3 Tenacity in N/tex and test-length, cotton [4]

Cotton variety	*S* 1 cm	σ 1 cm	*S* 1 mm calc.	*S* 1 mm expt
St Vincent	0.473	0.136	0.688	0.609
Sakel	0.405	0.180	0.688	0.535
Uppers	0.288	0.136	0.503	0.477
Ishan	0.324	0.093	0.467	0.446

useful to summarise here the approximations in Peirce's theory that cause these deviations. They are:

- the assumption that the distribution of strength is independent of the part of the sample considered;
- the assumption of a normal frequency distribution;
- the mathematical approximations.

14.2.3 Other treatments

An improvement on Peirce's theory has been worked out and applied to yarns by Spencer-Smith [5]. It is first necessary to clear away the assumption, which has been implicit in the previous discussion, that breakage occurs at a point. In fact, the disturbance involved in a break will be spread over a certain length, which Spencer-Smith called the *fracture zone*. Any theory of the weak-link effect should therefore consider a succession of fracture zones.

Spencer-Smith further pointed out that the strengths of neighbouring fracture zones in yarns are related to one another. This will also hold for fibres, since the same

molecules will be passing through neighbouring zones, and the dimensions and composition of neighbouring zones cannot be very different. There will thus be a tendency for strong zones to group together and for weak zones to group together. This means that, in testing a number of specimens, most of the weak places will be concentrated in a few of them, and thus only a few will give breaking values. Instead, some higher values will be included, and the mean strength will appear higher. Table 14.4 shows a numerical example of this effect. It is in this respect that Spencer-Smith's theory is an advance on that of Peirce, where the values were, in effect, redistributed at random.

Spencer-Smith has worked out the theory in detail and obtained the relation

$$\bar{S}_f - \bar{S}_{nf} = W(n) \cdot F(n) \cdot \sigma_f \tag{14.5}$$

where f is the fracture-zone length, S_f and S_{nf} are the mean values for lengths f and nf, respectively, σ_f is the standard deviation for length f, $W(n)$ is a statistical function, tabulated by Tippett [6] for values of n, and $F(n)$ is the serial correlation function.

$$F(n) = \left\{ \frac{1}{n^2} [n(n-1) - 2(n-1)r_1 - 2(n-2)r_2 \ldots \right.$$
$$\left. - 2(n-m)r_m \ldots 2r_{n-1}] \right\}^{1/2} \tag{14.6}$$

where r_m = correlation coefficient for the strengths of zones a length mf apart.

In this expression, $W(n)$ is a numerical factor, $F(n)$ is a factor taking account of the correlation of strengths of neighbouring zones, and σ_f brings in the variability. The product $W(n) \cdot F(n)$ replaces 4.2 $(1 - n^{-1/5})$ in Peirce's expression.

Spencer-Smith's theory has been applied only to yarns, and examples are given in Fig. 14.7. The agreement with experiment is still not perfect.

In many studies of fracture, a Weibull distribution is found to give the best statistics and has been applied to weak link theory. The basic two and three parameter equations for the Weibull distribution and the change of mean strength with length are as

Table 14.4 Four-zone lengths with zones (a) perfectly grouped and at random

(a)

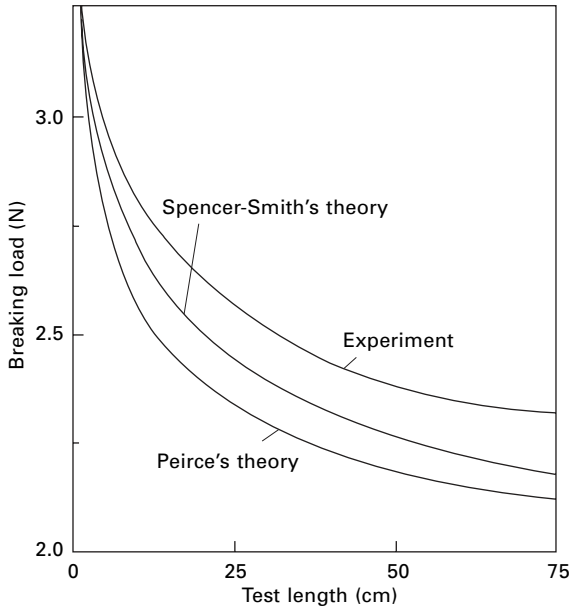
Zone strength	4 4 4 4	3 3 3 3	2 2 2 2	1 1 1 1
Four-zone strength	4	3	2	1

Mean for four-zone length = 2.5

(b)

Zone strength	4 1 2 1	2 3 1 2	4 4 2 1	3 2 3 4
Four-zone strength	1	1	1	2

Mean for four-zone length = 1.25



14.7 Comparison of theory and experiment for a spun-rayon yarn [7].

follows.

$$\phi_l(S) = 1 - \exp\left[-N\left(\frac{S}{S_0}\right)^m\right] \tag{14.7a}$$

$$\phi_l(S) = 1 - \exp\left[-N^{\beta}\left(\frac{S}{S_0}\right)^m\right] \tag{14.7b}$$

$$\frac{\bar{S}_{nl}}{\bar{S}_l} = n^{-1/m} \tag{14.8a}$$

$$\frac{\bar{S}_{nl}}{\bar{S}_l} = n^{-\beta/m} \tag{14.8b}$$

$$\log \bar{S}_{nl} - \log \bar{S}_l = -(1/m) \log n \tag{14.9a}$$

$$\log \bar{S}_{nl} - \log \bar{S}_l = -(\beta/m) \log n \tag{14.9b}$$

where N is the number of independent segments with strength S_0, m is the Weibull shape parameter and β was proposed by Watson and Smith [8] to account for diameter variations, though its physical meaning is not clear.

Pickering and Murray [9] measured the variation of strength of a high-strength carbon fibre and found a linear plot corresponding to equation (14.9a) with $(1/m)$ =

0.126. The Weibull distribution itself should give a linear plot when log{log[1/(1–ϕ)]} is plotted against log(*S*). Their results showed up a basic problem in weak-link modelling. There was good linearity in the Weibull plots for the major part of the distribution, but points at the extremes diverged from the line. Unfortunately the extreme low values have most effect on failure at weak links. This is probably why Pickering and Murray found errors of 8–25% in predicting strengths at 2 to 500 mm from values at 1 mm test length. Amaniampong and Burgoyne [10] found that the two-parameter Weibull distribution fitted polyester strengths but the three-parameter was better for breaking strain. For aramid fibres the Gumbel distriburion gave a better fit. They also found the problem of extreme values lying off the straight line. Zhang *et al*. [11] discuss the application of Weibull and modified Weibull distributions to gauge length effects on wool strength. Yu *et al*. [12] combined SIFAN (see Sections 3.7.1 and 13.4.2) and optical microscope studies of wool to differentiate between breaks at thin places and breaks due to weaknesses in internal structure. They conclude that about 40–50% of breaks occur at the position of minimum diameter, with the remainder being associated with defects.

14.2.4 Difficulties in weak-link theory

Theories of the weak-link effect continue to be developed, though Peirce's theory is a useful approximation, and Spencer-Smith's a better one. Spencer-Smith's relation is open to criticism on the grounds that it must be based on experimental results for the fracture-zone length. Apart from the fact that this length is not known and may be very ill defined, it is very likely that when jaws are clamped on the specimens at a distance apart equal to the estimated fracture-zone length, the nature of the break will be different from that at much shorter or much longer lengths. When the jaws are close together, they will restrain deformation of the fibre, and the distribution of strain, giving rise eventually to rupture, will be different. The effect of changes in the mechanism of breakage cannot be included in any statistical theory, and it seems likely that different relations would apply for lengths much greater than, and much less than, the fracture-zone length. The variations for lengths near the fracture-zone length would depend on the particular properties of the fibre.

These difficulties also apply to yarns, and the redistribution of twist is another source of error there. Together these must account for the deviation of experiment and theory shown in Fig. 14.7.

14.3 Variability and other quantities

14.3.1 Variation of stress and strain

The weak-link effect is concerned with the effect of variability on strength, and we must also consider the influence of variability on other quantities. For a fibre under a given tension, the stress will vary from place to place and will follow the variations of cross-section. At each point, the specific stress will be given by the tension divided by the linear density at that point.

As a consequence of the variation of stress, the strain will also vary from place to

Table 14.5 Variation along successive sections (5 mm lengths) of a wool fibre [13]

Fibre No. 1					Fibre No. 2	
Diameter of section (μm)	Extension (%) of section with overall extension (%) of: 5.2	15.5	24.2	32.9	Diameter (μm)	Extension (%) (overall = 13.9%)
30.0	2.0	6.0	20.0	28.0	29.8	4.0
29.9	0.0	5.9	19.6	29.4	30.2	10.2
28.0	3.9	21.6	27.4	35.3	28.2	17.6
28.0	9.6	21.2	25.0	34.6	26.4	22.0
26.6	10.4	22.9	29.2	37.5 (break)	24.8	15.5 (break)

place. The thin places will extend more than the thick ones. Table 14.5 shows the variation in diameter and extension along 5 mm lengths of a wool fibre. Provided that all the lengths in a particular set of tests are equal, the average of the strain values for each length will be the same whether the lengths are long or short.

The effect of variability on the shape of the stress–strain curve of wool fibres has been extensively examined by Collins and Chaikin [14–17]. He *et al*. [18, 19] have reported simulations of the stress–strain behaviour of fibres with variable thickness for linear elastic and non-linear tensile properties.

14.3.2 Tensile modulus

Owing to variation in composition, the modulus may vary from place to place in a fibre or between the fibres in a given sample. With an irregular specimen, there will also be an effect due to specimen length. This arises because of a difference in the averaging. Suppose the specimen consists of n sections, each of length x, and the extensions of the sections are represented by δx, varying from section to section. Then, if the modulus is measured on a specimen of length nx, we have:

$$\text{modulus} = \frac{S}{\Sigma(\delta x)/nx} = Sx(1/\overline{\delta x}) \tag{14.10}$$

where S = stress, and $\overline{\delta x}$ = mean value of δx. But, if the modulus were measured on the lengths x and then averaged, we should have:

$$\text{modulus} = \frac{1}{n}\Sigma\left(\frac{S}{(\delta x)/x}\right) = \frac{Sx}{n}\Sigma\left(\frac{1}{\delta x}\right) = Sx\left(\frac{\overline{1}}{\delta x}\right) \tag{14.11}$$

where $\left(\frac{\overline{1}}{\delta x}\right)$ is the mean value of $\frac{1}{\delta x}$.

There is a difference between $(1/\overline{\delta x})$ and $\left(\frac{\overline{1}}{\delta x}\right)$ and thus the mean value of the modulus may vary with the length tested.

It is obvious that an apparently lower value of modulus results from softness of the

tester load cell and deformation within the gripped region of the fibre. There will be a more serious error if there is slippage of the fibre in the grips. These effects mean that the apparent modulus will increase as the test length increases. Pan *et al*. [20] report substantial increases in initial modulus of fibres as gauge length increases from 10 to 100 mm and regard this as a change in fibre properties and not just a testing artefact. However, it is difficult to see how, except for the immediate vicinity of clamps, the stiffness of a length of fibre could be influenced by distance from the gripped points.

14.3.3 Breaking extension

The weak-link effect also affects breaking extension. If a fibre breaks under a low load owing to the presence of a weak place, the rest of the specimen will have a comparatively small extension and the breaking extension will be low. The mean breaking extension will decrease as the specimen length increases.

14.4 Composite-specimen effects

14.4.1 Theoretical

If, instead of testing a single fibre, one tests a number of fibres together, the form of the specimen has a considerable influence on the result of the test. Practical cases are usually complicated and difficult to formulate mathematically, but the simple examples given by Peirce [3] may be used as approximations. It is assumed that the fibres are free to act independently.

- *Fibres gripped at the ends, of equal original length, and of uniform breaking extension.* All the fibres will break together and therefore, however variable the breaking loads may be, each fibre will have developed the maximum possible load, and the breaking load of the composite specimen will be equal to the sum of the breaking loads of the fibres.
- *Variable fibres gripped at the ends, of equal original length, in a constant rate of extension test* (CRE). The fibres with the lowest breaking extension will break first. Let the fraction of fibres having a breaking extension between e and $(e + \mathrm{d}e)$ be $\phi(e) \cdot \mathrm{d}e$. Then, when the extension is e, the fraction f of the total number of fibres remaining unbroken will be:

$$f = \int_e^\infty \phi(e) \cdot \mathrm{d}e \tag{14.12}$$

The force on the specimen will be influenced by any correlation between modulus and breaking extension but, if we assume a constant modulus, E, the stress will be given by:

$$\text{stress} = S = f \cdot Ee = Ee = \int_e^\infty \phi(e) \cdot \mathrm{d}e \tag{14.13}$$

The stress will be a maximum when $dS/de = 0$, that is, when:

$$E\int_{e}^{\infty}\phi(e)\,de - Ee\phi(e) = 0 \tag{14.14}$$

$$\int_{e}^{\infty}\phi(e)\,de = e\phi(e) \tag{14.15}$$

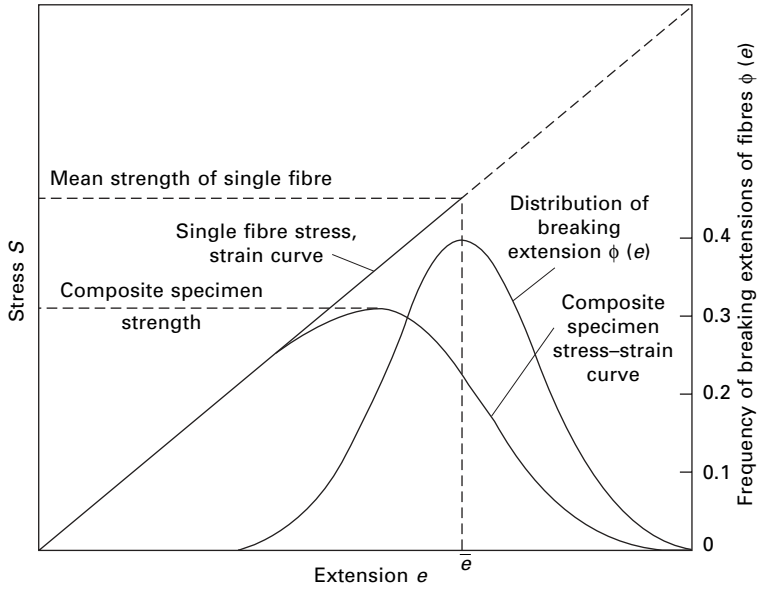
Writing $\hat{e}$ for this value of e, and substituting in equation (14.9), we get:

$$\text{maximum stress} = E\hat{e}^2 \cdot \phi(\hat{e}) \tag{14.16}$$

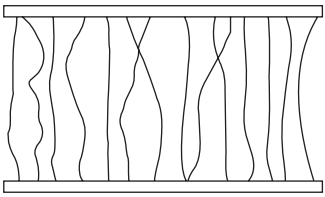
The mean breaking stress of the single fibres would be $E\bar{e}$, so that the ratio of the breaking stress of the composite specimen to the mean breaking stress of the fibres is $(\hat{e}^2/\bar{e}) \cdot \phi(\hat{e})$.

Figure 14.8 gives an example of this behaviour for a linear stress–strain curve and a normal frequency distribution. This clearly shows the reduction in strength resulting from the early breakdown of some of the fibres.

- *Variable fibres gripped at the ends, of equal original length in a constant rate of loading test* (CRL). Below the maximum load, the relation will be the same as in the previous case, Fig. 14.8, but then the specimen will fail completely because a decreasing load is not allowable.
- *Fibres gripped at the ends, of variable original length.* When a specimen is arranged between jaws, some of the fibres may not lie straight. This is illustrated in Fig. 14.9. The effect of this is to cause a much greater unevenness in the



14.8 Composite-specimen stress–strain curve, calculated for constant rate of extension of fibres with identical linear stress–strain curves but normal distribution of breaking extensions.



14.9 Fibres of varying length between jaws.

sharing of the load. When the fibres that are initially straight start to break, the fibres in which there was some 'slack' to take up will be less extended or may even not be contributing to the load at all. Consequently, the maximum load that can be developed will be much less.

- *Filaments under uniform tension, all slipping when one breaks.* This would be the case if the filaments were taken over a number of light pulleys. It is exactly the same as a single long specimen.
- *Filaments uniformly extended, all slipping when one breaks.* The lea test for yarns approximates to this condition. It is similar to the last case except that there will not be the same tension in each end of the specimen, owing to variations in the extensibility of the fibres.

There is a tacit assumption that a smooth stress–strain curve is found as in Fig. 14.8. This would be valid for an infinite number of fibres in the bundle. In practice there will be discontinuities. As the load increases and the jaws separate, a point is reached at which the first fibre breaks. The load is then taken by fewer fibres. In CRE, there would be a drop in tension; in CRL, there would be an increase of extension.

The mechanism of rupture is different when the fibres interact with one another. This is shown by the behaviour of twisted continuous filament yarns, as described by Hearle *et al.* [21]. A zero-twist yarn has a lower strength than one with a small amount of twist. Transverse compressive forces in the twisted yarn cause weak places in one fibre to be supported by neighbours. This will continue, with more fibres breaking, until the situation is reached in which the increase of load due to the breaking of a fibre is sufficient to cause another fibre to break and so on. The process is thus cumulative and the whole specimen ruptures. This happens at a load that is less than the sum of the breaking loads of the individual fibres. In twisted yarns, strength increases up to a twist angle of about 7°, when the effect of obliquity leads to a reduction in strength.

There is an extensive literature on the statistics of strength of interactive bundles of fibres, which is particularly important for composites, but also relevant to yarns and cables. An account of the chain of bundles model with load sharing is given by Phoenix [22], who also contributes a more recent review [23]. However, apart from bundle tests, the subject is of marginal relevance to the properties of fibres and will not be pursued here.

14.4.2 Practical bundle tests

Bundle tests are used extensively for rapid testing of cotton fibres. The earlier Chandler test was replaced by the Pressley test [24], a version of which is included in HVI test lines for cotton.

In the Chandler test, the combed bundle of fibres is wrapped with two spirals of sewing thread. At the centre, where the two spirals meet, the specimen is free to break. From the length of thread for ten revolutions, the circumference of the bundle is obtained, and consequently the breaking load per unit area can be calculated.

In the Pressley test, a bundle of fibres is combed straight and then clamped between jaws and broken. The fibre bundles are cut to a standard length and weighed, so that the breaking stress can be calculated. The results may vary considerably according to the width of the bundle, the tightness of clamping, the skill and technique of the operative, and the particular jaws used. However, provided that frequent checks are made with standard samples, reproducible results can be obtained. The original Pressley test had nominally a zero gauge length[1], but since then gauge lengths of a few millimetres have been proposed.

An advantage of a bundle test is that it automatically takes account of variability, which is a factor with a practical influence on yarn strength. The disadvantage is the more limited information and the lack of reproducibility.

14.5 Variability in practice

Table 14.6 shows values of the coefficient of variation of various quantities among 1 cm specimens tested by Meredith. It will be seen that the natural vegetable fibres show a large coefficient of variation; the natural protein fibres and rayon are rather more regular, and synthetic fibres such as nylon show only a small variability.

14.6 Changes in specimen during test

When fibres are extended, they usually contract in diameter. Consequently, the true stress increases more rapidly than does the stress based on the original dimensions of the fibre. This is important in fundamental studies of the subject, since what appears

Table 14.6 Variation within a sample of fibres [25]

	Coefficient of variation (%)			
	Fineness	Breaking load	Tenacity	Breaking extension
Cotton	24	46	43	40
Bast fibres	24	45	40	31
Rayon	12	20	17	23
Silk	17	19	20	15
Nylon	9	8	7	18
Wool	21	34	28	32

[1]The gauge length is the length of specimen between the jaws of the tester.

to be a basic property of the material may be a function of the conditions of test.

If σ is the true stress, and σ' is the nominal stress based on the original dimensions, we have:

$$\text{load} = F = \sigma A = \sigma' A' \tag{14.17}$$

$$\sigma = \sigma' \cdot \left(\frac{A'}{A}\right) \tag{14.18}$$

where A is the true area of cross-section and A' is the original area of cross-section.

If the specimen extends uniformly and the volume remains constant, we have:

$$Al = A' l' \tag{14.19}$$

$$\frac{A'}{A} = \frac{l}{l'} = 1 + \varepsilon \tag{14.20}$$

$$\sigma = (1 + \varepsilon)\sigma' \tag{14.21}$$

where l = length of specimen, l' = original length of specimen and ε = strain.

The maximum load will occur when

$$\frac{\mathrm{d}F}{\mathrm{d}\varepsilon} = \sigma \frac{\mathrm{d}A}{\mathrm{d}\varepsilon} + A \frac{\mathrm{d}\sigma}{\mathrm{d}\varepsilon} = 0 \tag{14.22}$$

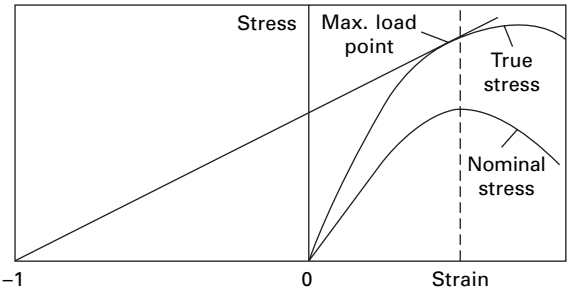
But, from equation (14.20):

$$\frac{\mathrm{d}A}{\mathrm{d}\varepsilon} = -A' \frac{1}{(1 + \varepsilon)^2} \tag{14.23}$$

$$-A' \frac{\sigma}{(1 + \varepsilon)^2} + \frac{A'}{(1 + \varepsilon)} \frac{\mathrm{d}\sigma}{\mathrm{d}\varepsilon} = 0 \tag{14.24}$$

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\varepsilon} = \frac{\sigma}{(1 + \varepsilon)} \tag{14.25}$$

This condition is satisfied at the point where a line from (–1) on the strain axis is a tangent to the curve, as in Fig. 14.10. This shows that the breaking load corresponds to a rather arbitrary condition in terms of true stress and thus has little fundamental significance.



14.10 True and nominal stress–strain curves.

However, the specimen will probably not extend uniformly and the weaker places will extend more than the stronger ones. This results in a further increase of stress on the weak places, so that the process is cumulative and breaking may occur. This means that the true stress near the point of break will increase even more rapidly than appears from Fig. 14.10.

It will be clear from this, and other parts of this chapter, that, in an investigation of the behaviour of a material (with a view to understanding it, rather than to using it), the mean stress–strain curve for the whole specimen gives only a rough idea of what is actually taking place. Exact stress–strain relations at particular points in the specimen would be much more valuable.

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