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Textile Materials: Recovery from Imposed Deformation

Subtle interactions between the elements of fibrous assemblies complicate investigations of recovery behavior.

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Textile materials consist essentially of assemblies of fine, flexible fibers arranged in more or less orderly geometrical arrays. Individual fibers within the assembly are usually in a bent and twisted configuration, and are in various states of contact with neighboring fibers. When the assembly is deformed the fibers move relative to each other, and this relative motion accounts to a large extent for the characteristic flexibility of textile materials. Fibers are available with an enormous range of mechanical properties, and they can be assembled in a number of different geometries, each with distinctive structural features. A natural outcome of this diversity of form and properties is the evolution of the concept of textile engineering, which is concerned with the design of textile materials to fulfill specific sets of requirements.

To determine the suitability of an engineering material for a particular use it is customary to ask two questions: To what extent will the material resist the deforming force that will be applied? Will the material sustain the maximum contemplated load? In engineering with textile materials it is often necessary to add a third question, namely: To what extent will the material recover when the deforming force is removed? The reasons for the additional question are implicit in the nature of textile materials. The fibers are viscoelastic and hence will exhibit delayed recovery from strain; in addition, the large number of contact points provide frictional restraints which further hinder the recovery process. In textile applications where esthetic requirements predominate, such as in most apparel or furnishing uses, the recovery behavior is of particular importance. In some industrial applications also, the recovery behavior is of direct and explicit significance—the flat-spotting of tires being a good example. However, since the nonrecovered work of deformation has a strong influence on the useful life span of a structure having multiple uses, the recovery behavior of industrial fabrics is almost always of great implicit (and sometimes unrecognized) importance. In this article I discuss the theoretical and experimental aspects of the recovery of textile materials from various modes of deformation and examine some implications and applications of results of studies in this field.

Generalized Recovery Behavior

As an aid to understanding the relative importance of viscoelasticity and frictional restraint in the recovery of textile materials, it is of value to consider the recovery of a single element of a fibrous assembly from a generalized loading condition. It is not necessary at this stage to consider particular types of stress, since the discussion presented below is of general validity. The application to specific stress conditions will be presented later.

The recovery behavior of an element in isolation is shown in Fig. 1. Line OAB represents the characteristic relationship between stress and strain for the fiber subjected to stresses and strains increasing with time; for most textile materials this relationship is nonlinear. The fiber is then considered to be held at a fixed strain I for a period of time during which the stress decays; this is represented by the line BC. In practical situations the fiber may be held under conditions of varying stress and strain, but the simple restraint described here, which corresponds to the maintenance of some geometrically limiting configuration of the assembly, is very common in textile applications. Following the period at fixed strain, the applied stress is removed and the fiber recovers according to the relationship represented by the line CD. The residual strain when the fiber is again under zero stress is denoted by R.

One of the most informative representations of the recovery behavior of the materials is shown in Fig. 2, which shows the variation of residual strain R as a function of the initial strain I. In a graph of this type perfect recovery from deformation is represented by a horizontal line through the origin, and completely plastic deformation is characterized by a line through the origin with a slope of 45°. All real materials have characteristics which lie within the shaded area bounded by these two lines, (*1*) and since recovery from small deformations is generally more perfect than recovery from large deformations, the experimentally determined characteristics are usually convex downward, as shown in the figure. Since no increment of residual strain can be greater than the corresponding increment of initial strain, the limiting slope of the line for a real material is also 45°. The curve for a particular material is, of course, specific to the condition of test

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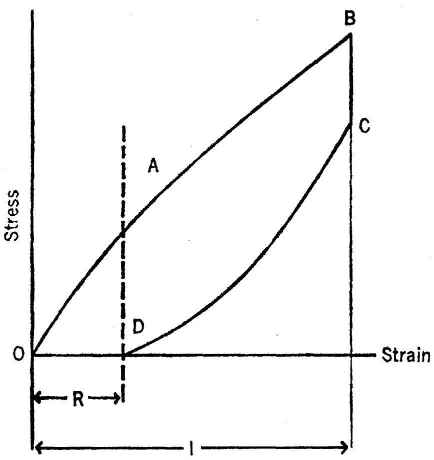

Fig. 1. Stress-strain relationship and recovery behavior of a single unit of a fibrous assembly.

and is affected by changes in the rate of straining, in the times allowed for stressing and relaxation, and in the temperature and relative humidity at which the straining and recovery take place.

When the fiber is incorporated into an assembly in which the interfiber contacts impose a level of frictional restraint, the recovery behavior becomes more complex. Figure 3 shows the stress-strain curve for a cycle of stress and strain identical with that shown in Fig. 1. However, in this case a level of frictional restraint S is assumed to be present. At small levels of deformation the recovery behavior from an imposed strain is profoundly modified, for unless the stress at the beginning of the recovery phase exceeds S the deformation will be completely nonrecoverable. An example of this type of deformation is the attenuation of assemblies of fibers during the processing of staple fibers into yarns. The recovery of fibers against frictional restraints is illustrated in Fig. 4. The minimum strain level at which the fiber can exhibit recoverable deformation is given by S/E where E is the initial slope of the stress-strain curve—that is, the modulus appropriate to the particular type of deformation under consideration. For initial deformations I which are greater than S/E the behavior of a fiber exhibiting perfect recovery will again be represented by a horizontal line but will have a constant value of S/E rather than zero (line a, Fig. 4). For real materials the effective modulus in the direction of decreasing strain E' is smaller than the initial modulus E, and the residual strain attributable to the frictional restraint is S/E' (line b, Fig. 4). It is interesting to note that a fiber exhibiting a low level of recovery in isolation will often show a disproportionately lower level when it is part of an assembly. This is a consequence of the fact that the recovery modulus E' normally falls with worsening elastic recovery, and for given values of initial strain I and stress level S, both R_m, the intrinsic residual strain associated with the resiliency of the fiber itself and R_f, the frictional residual strain, are likely to be high.

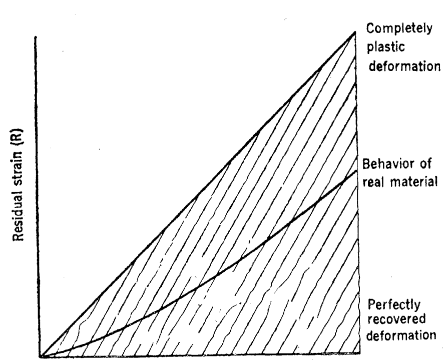

Fig. 2. Relationship between the residual strain R and the initial strain I for a fiber recovering in isolation. Also shown are the limiting relationships for completely plastic and for perfectly recovered deformations.

Characteristics of Fibrous Assemblies

The discussion presented above is perfectly general and is applicable to all types of deformation and all levels of frictional restraint. It is a worthwhile exercise to examine in more detail the nature of fibrous assemblies in order to evaluate the more important practical applications. Insofar as anything so complex can be typified, Fig. 5 represents a typical fiber in an assembly. Most commercially available textile fibers have diameters which fall within the range 10 to 30 micrometers, and a value of 15 μm represents reasonably well a large proportion of the fibers making up this range (*2*).

Estimates of the mean density of contact points and the mean force per contact are more difficult to obtain. In low density assemblies of random (*3*) and almost parallel (*4*) fibers the number of contacts per unit length can be shown to be proportitonal to $(1-\varepsilon)/d$, where ε is the fractional air space of the assembly and d is the fiber diameter. More detailed analytical work (*5*) has shown that the proportionality constant is approximately unity, and this conclusion is supported by experimental work in which radioactive tracer techniques were used (*6*). Taylor's work indicated that the number of contacts per centimeter on a fiber in an almost parallel array could range from 22 to 332 as the value of the packing density $(1-\varepsilon)$ of the assembly varied between 0.027 and 0.179 (*6*). The maximum theoretical packing density for a parallel assembly of straight incompressible circular fibers is 0.91, and the maximum packing density observed experimentally in these assemblies is approximately 0.80 (*7*). In highly twisted yarns where the fibers are arranged approximately in families of coaxial helices, values of 0.60 are more common (*8*). There is also evidence (*7*) that the relationship between the number of contact points and density remains approximately linear up to these densities. On the basis of the foregoing work the typical fiber shown in Fig. 5 has been assumed to make 50 contacts per centimeter in an assembly of packing density 0.1 and 400 contacts

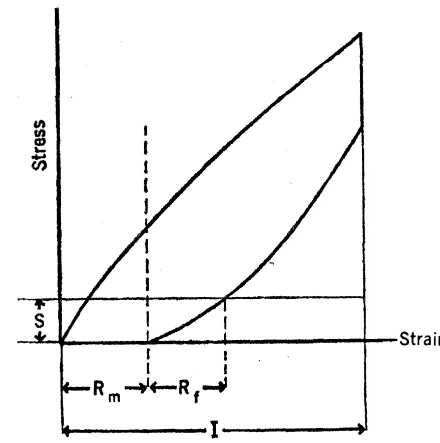

Fig. 3. Stress-strain relationships and recovery behavior of each unit within a fibrous assembly. A level of frictional restraint denoted by the stress level S is assumed to be operative.

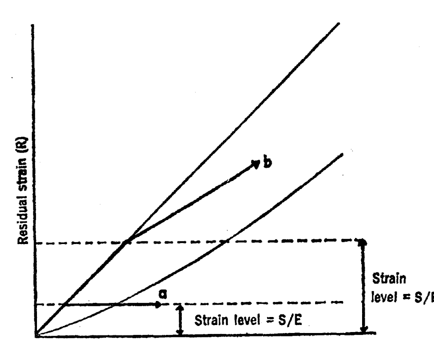

Fig. 4. Relationships between the residual strain R and the initial strain I for a fiber recovering within an assembly against a frictional restraint.

per centimeter at a packing density of 0.8. Thus, in an assembly of average packing density of 0.4, the average distance between contact points is 50 μm.

The force per contact point has been variously estimated by several workers (*5, 7, 9*) to be within the range of 1 to 10 dynes. Most of these estimates are based on measurement of the force required to withdraw a single fiber from an assembly, or on measurements of the strength of arrays of discontinuous fibers containing only a small number of turns of twist per unit length. In more random, more densely packed assemblies, where more fiber distortion is present, it is likely that the higher values are more nearly correct; a value of 5 dynes per contact has been chosen for this discussion. For convenience, a coefficient of friction of unity has been assumed in all the calculations. This implies that the transverse frictional forces opposing relative motion at each contact point are equal in magnitude to the normal forces—namely 5 dynes per contact.

Nature of Fiber Deformation

The fiber suffers five main types of deformation, either singly or in combination. These are transverse compression, longitudinal extension and compression, torsion, and bending. Consideration of the relationships between the imposition of, and recovery from, deformations and the contact force on the generalized fiber described above permits an assessment of the relative importance of these deformations, each of which is discussed in turn below.

Transverse compression is probably the least important of the fiber deformations, and it is only in very specialized applications that it exerts a controlling influence on the behavior of a fiber assembly. In most textile structures the area of interfiber contact is probably less than 1 percent of the total fiber area, and even in densely packed assemblies, such as commercial bales of fiber, the recovery behavior is controlled predominantly by the recovery from bending. The compressional behavior of filaments has been shown to have an influence on the tensile behavior of yarns, particularly in highly twisted yarns at high stress levels (*10*). With a very brittle fiber, such as glass, the ability to withstand transverse compressive forces at the fiber-to-fiber contact points can be the factor limiting the realization

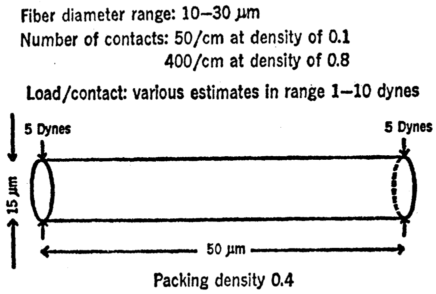

Fig. 5. Values of fiber diameter, distance between contact points, and force per contact for a fiber in a typical assembly.

of the potentially high strength of the material. The transverse compressional behavior of a fiber is also of considerable theoretical interest in its own right, since it provides a means of deducing some of the fundamental elastic constants of the highly anisotropic polymer material (*11*). It is also of immediate practical interest in composite structures, where the compatibility of the transverse compression and recovery behaviors of the fiber and matrix has a strong influence on the ultimate properties of the composite (*12*). This is a field in which a great deal remains to be learned; and with the growing interest in fiber-reinforced composites it is certain to attract attention.

The measurement of the recovery of textile materials from longitudinal extension is a routine matter, and is by far the most thoroughly explored aspect of recovery behavior (*13, 14*). Because it is so easily measured, the tensile recovery behavior is often used as a general measure of resilience of textile materials even in applications involving other types of deformation (*15*). This generalization is of some validity since the bending recovery is to a large extent

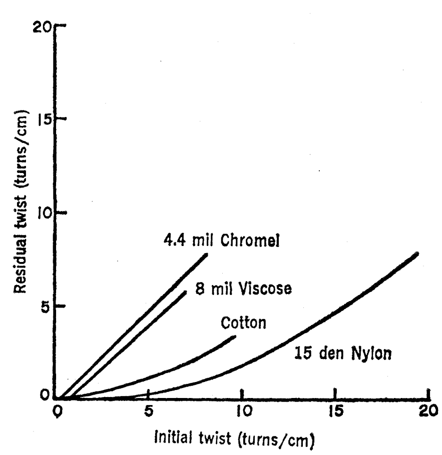

Fig. 6. Torsional recovery behavior of various materials.

predictable from the tensile recovery, but the relationship between the recoveries from the various modes of deformation is a subject which has not been adequately explored.

Frictional restraints do not usually have any significant effects on the recovery behavior of fibrous assemblies from extensional deformations. A representative value of initial modulus of a textile fiber is 6×10^{10} dynes per square centimeter (*13*). For a fiber with a diameter of 15 μm this implies that a tensile load of 10^3 dynes is required to produce an elongation of 1 percent. Thus the previously discussed frictional restraint level of 5 dynes will give rise to a residual elongation of only 0.005 percent, an insignificant amount.

The recovery from longitudinal compression is a much more difficult subject to deal with experimentally. The application of Euler's criterion to a fiber with flexural rigidity of 20×10^{-3} dyne cm^2 (*16*) under a compressive load of 5 dynes indicates that buckling will take place for any length greater than 2 millimeters. Considerations of this type explain the lack of experimental data on fiber compressional recovery, and such measurements as have been reported were carried out on specimens of large diameter monofilament (*17, 18*). As a corollary, of course, it is demonstrable that unless a supporting matrix material is present, as in a tire, then the occurrence of direct longitudinal compressional deformation will be rare in textile assemblies, and the compressional recovery behavior does not have much significance in its own right. Its real importance lies in the fact that, like the extensional recovery previously discussed, it has a controlling influence on the bending behavior.

When a fiber is bent the portion of the material on the outside of the bend is in tension, and the portion on the inside is in compression. The elements of the fiber are subject to limitations on compressive loading similar to those discussed above for complete fibers, and under certain circumstances the polymeric material on the inside of the bend shows evidence of compressive buckling. When the fiber is allowed to recover the equilibrium condition is determined by the vanishing of the total bending moment over a cross section. This condition involves the moduli and recovery behaviors of the material in both tension and compression, and has been the subject of much debate. It appears that for most fibers the moduli in tension and compression are essentially equal, and while the direct experimental evidence is conflicting, an experimental comparison of the tensile and bending recovery of viscose fibers provides indirect evidence that the recoveries from tension and compression are similar (*18, 19*). Thus, as with the extensional behavior, the direct influence of restraints on compressive recovery is probably small.

The frictional restraints play a larger part in torsional deformations than in longitudinal extension and compression. The torsional rigidity of a typical textile fiber is 5×10^{-3} dyne cm^2 while the maximum torque applied by two diametrically opposed restraints of 5 dynes on the 15-μm diameter fiber is 75×10^{-4} dyne cm. Thus the minimum residual twist after a torsional deformation is approximately 0.25 turn per centimeter. This is a small but not insignificant amount of twist, and on this basis the torsional recovery is worthy of more detailed study. It has practical applications in false-twist texturizing, a process used to give continuous filament yarns some of the loftiness (bulkiness) associated with spun staple yarns. In this process the extent of yarn loftiness developed is closely related to the amount of torsional stress in the yarn (*20*). Torsional stress-strain and recovery behavior is also of importance in the study of the formation of spun staple yarns, particularly the newer methods of open-end spinning (*21*). Various workers have measured the torsional recovery behavior of filament materials (*22, 23*) and some representative data gathered from these sources are shown in Fig. 6. The data for Chromel and the viscose rayon are particularly interesting since the torsional stress-strain curves for these materials exhibit a small Hookean region followed by a long region of plastic flow, and the recovery behavior can be deduced from the stress-strain curve with some precision. No such simple interpretation is possible with the other materials, which have much more complex stress-strain behaviors in torsion.

The recovery of textile assemblies from bending deformations is of great practical importance. The flexural rigidity of a typical fiber may be taken as 20×10^{-3} dyne cm^2 and the mean bending moment of a force of 5 dynes over a 50-μm length of fiber is 12.5×10^{-3} dyne cm. Thus, if the frictional restraints are assumed to act parallel to the axis of bending, the residual curvature following a bending deformation can be expected to be of the order of 0.6 cm^{-1}; a similar value is found if the forces are assumed to act in a direction perpendicular to the axis of bending. This is a reasonably large curvature, and on the basis of the approximate calculation presented above it is to be anticipated that the frictional restraints will always play a significant part in the bending recovery behavior of real systems. This supposition is borne out in practice, and considerable effort and ingenuity have been expended in the measurement and characterization of the bending behavior of fibers and fibrous assemblies, particularly woven fabrics.

The measurement of the bending recovery of fibers is difficult, particularly at high curvatures, since the length of the specimen involved in the deformation decreases as the curvature increases. In this respect bending deformation differs from tensile and torsional deformations, where at least one of the specimen dimensions, namely the length, can be of any convenient magnitude. Four types of experimental determinations have been reported in the literature (*24–27*); these are illustrated in Fig. 7. In my method (*24*) the fiber is constrained between two plates spaced apart a little more than the diameter of the fiber. The fiber is positioned so that a buckling deformation can be applied and the bent fiber eventually takes up an elastica configuration in which the distribution of curvature is known and the maximum curvature is predetermined. The recovery is measured by means of a projection microscope. The measured recovery is that appropriate to the mean value of the curvature distribution and the result is subject to some error if the bending recovery behavior is markedly nonlinear with curvature, but it can be shown that the error is generally small.

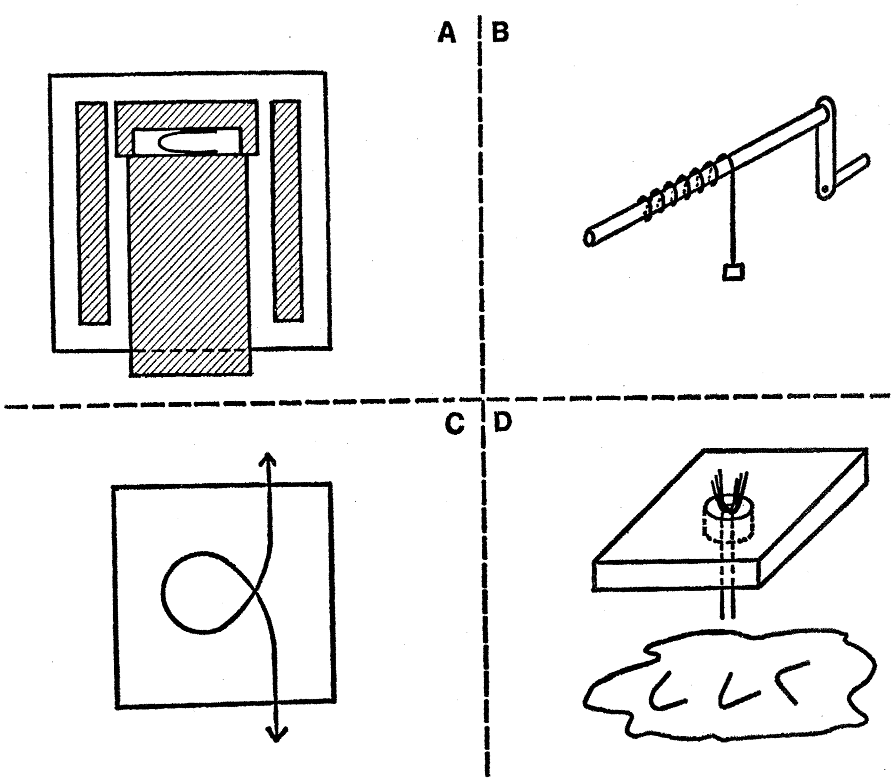

Fig. 7. Experimental methods for the determination of the bending recovery behavior of fibers. (A) Methods of Skelton (*24*); (B) Miles (*25*) and Freeston and Platt (*26*); (C) Miles (*25*); (D) Hassenboehler (*27*).

Miles (*25*) also makes use of the known geometrical properties of an elastica. In his method a complete loop of filament is restrained between two glass plates and the ends of the filament are attached to a moving jaw and a load cell, respectively. The initial and residual curvatures are deduced from measurement of the width of the loop. This method has the great advantage that, in addition to free recovery, the recovery against specific resistance forces can be measured.

A method in which a truly constant curvature is applied to the filament has also been described by Miles (*25*) and was developed and used by Freeston and Platt (*26*). In order to impose the curvature a length of tensioned filament is wrapped many times around a mandrel of a specific diameter, and when the tension is released the recovered curvature may be deduced from the smaller number of turns of larger radius of curvature remaining.

An interesting variation on my method has been developed by Hassenboehler (*27*). A bundle of fibers is pulled into a hole in a metal plate by means of a loop of wire, thus setting up a range of bending strains in the individual fibers. The recovery is found by pulling the bundle through the plate and letting the bent fibers fall onto a glass plate, where they are photographed. By suitable choice of hole and wire diameter, and bundle size, the range of fiber curvatures found in a creased fabric can be simulated, and the relationship between fiber and fabric recovery can be explored.

Results from filament recovery bending taken from the literature are shown in Fig. 8. The 8 mil (1 mil $= 2.54 \times 10^{-3}$ cm) diameter viscose rayon and the 0.5 mil diameter Chromel filaments show almost completely plastic behavior in excellent agreement with theoretical expectations based on the tensile load-elongation curve. The curve for the 4.5 denier viscose rayon fiber, which shows a mixture of plastic and elastic behavior, is in exact agreement with the theoretical recovery calculated from the tensile recovery curve. The excellent bending recovery of the cotton fiber treated with dimethylolethyleneurea is in accord with the measured crease recovery behavior of cotton fabric similarly treated.

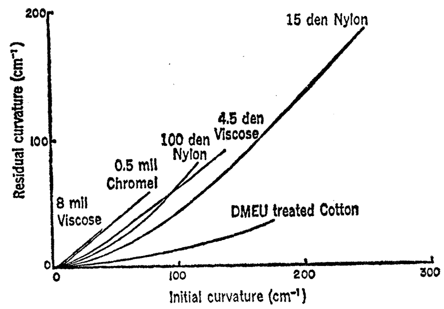

Fig. 8. Bending recovery behavior of various materials; *DMEU*, dimethylolethyleneurea.

Fabric Bending Recovery

As was described previously, the relationships between filament and fabric bending recoveries are complicated by the presence of frictional restraints, even at low levels of bending strain, where the filaments themselves show good recovery. The bending recovery behavior of a fabric can be explored by taking the fabric through cycles of curvature and measuring the couple and curvature at each point of the curve. A typical experimental record is shown in Fig. 9a. In the initial stages of bending the frictional restraints within the assembly must be overcome and a large couple is required to produce small changes in curvature; consequently the flexural rigidity—that is, the slope of the couple-curvature curve, is high. As the applied couple increases, all the interfiber contact points are in relative motion and the flexural rigidity falls to the level determined by the purely elastic bending resistance of the fibers (Fig. 9b). Each time the direction of bending is reversed the same phenomenon occurs, and it can be shown that this leads to the development of a closed couple-curvature curve for cycling between equal and opposite limits of curvature. The area enclosed by the curve is the nonrecoverable work of deformation of the assembly and much information concerning the nature of the restraints

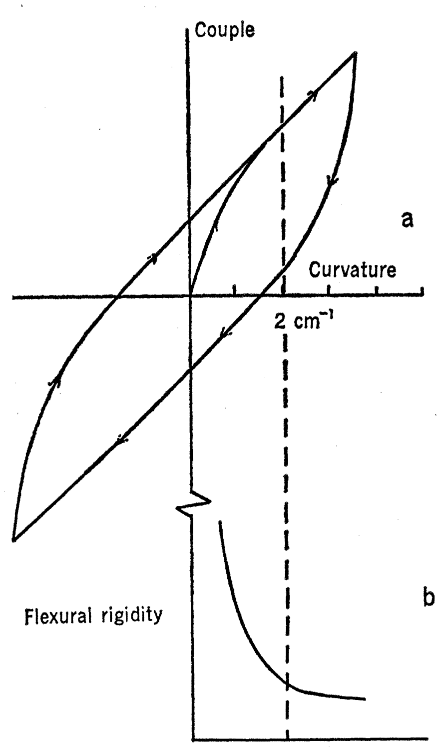

Fig. 9. Typical bending hysteresis curve for a fabric taken through a cycle of bending between equal and opposite limits of curvatures (a). Also shown is the variation of flexural rigidity with curvature for the fabric (b).

can be deduced from the measured variations of this hysteresis loss, and of the flexural rigidity, with curvature. Experimental methods for the measurement of these variations and their theoretical implications are described by Livesey and Owen (*28*), Popper and Backer (*29*), and Skelton (*30*). More complete bibliographies of continuing work in the field are provided by Grosberg (*31*), Owen (*32*), and Abbott *et al.* (*33*).

Typical measurements of bending recovery in some commercial fabrics are shown in Fig. 10. The cross-hatched areas show the general limits of the variation of both the intrinsic residual curvature and the frictional residual curvature from initial curvatures up to the maximum curvature that can be applied to the fabric; namely, that level involved in a full crease where the faces of the fabric on the inside of the bend are in contact (*34*). At low levels of initial curvature, up to approximately 10 cm^{-1}, the intrinsic residual curvature is small and the recovery behavior is dominated by the frictional restraints. However, the intrinsic residual increases much more rapidly with curvature than does the frictional residual and for high levels of initial strain the intrinsic residual curvature is more important. In most applications of textile materials efforts are made to reduce the total residual curvature, and Fig. 10 shows ways in which this can be achieved. The intrinsic recovery may be improved by chemical modification, as in the resin treatment of cotton and other cellulosic fibers. The level of the frictional restraints in the assembly may be reduced by either of two mechanisms: the relaxation of the interfiber pressures by heat-setting or by taking the fabric through some form of humidity cycling; or by the addition of lubricants which lower the coefficient of friction between the fibers. It should be noted that the former mechanism is usually much more effective in reducing the level of restraint, because the contact pressures can be changed by several orders of magnitude, while the coefficient of friction can only be changed by a factor of 2 or 3. The final method available for the reduction in residual curvature is to reduce the fall in recovery modulus of the fiber material. As was discussed previously, the fall in recovery modulus is probably the main reason for the observed increase in the frictional residual curvature with increasing strain.

The recovery modulus has received

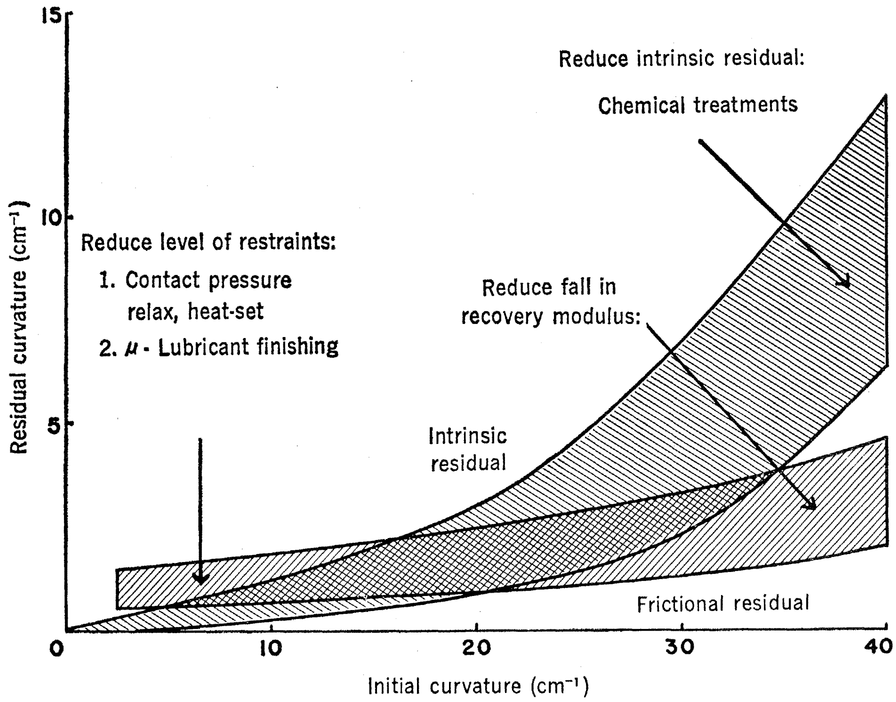

Fig. 10. Experimental results showing the variation of the intrinsic and frictional components of the residual curvature for a range of commercial fabrics. Various means of reducing the residual curvature are shown and are discussed in the text. [Data from Skelton (*34*)]

very little attention in the past, partly because of the experimental difficulties involved, and partly because of a lack of appreciation of its importance. Where levels of recovery are critical, however, it can become very important, and it is probable that it accounts in large part for the lack of success of nylon-cotton blends compared with polyester-cotton blends in wash-and-wear clothing applications. In this case the recovery modulus of the nylon is very much less than that of the polyester, particularly at low levels of strain.

To make an accurate measurement of the recovery modulus at zero stress it is necessary to be able to impose a strain on the specimen in the direction opposite to that of the initial strain. This can be done conveniently only for torsional strains, and though there is not an exact correspondence between torsional and tensile and bending behavior, the torsional measurement is probably valid enough for all practical purposes. A typical record for a specimen subjected to cycles of increasing torsional strain is shown in Fig. 11a; the corresponding ratio of recovery modulus : initial modulus derived from the slopes of the curves as they cross the strain axis can be found for all levels of initial strain, giving the characteristic curve shown in Fig. 11b. Only if this line were horizontal would the frictional residual curvature be constant at all levels of strain.

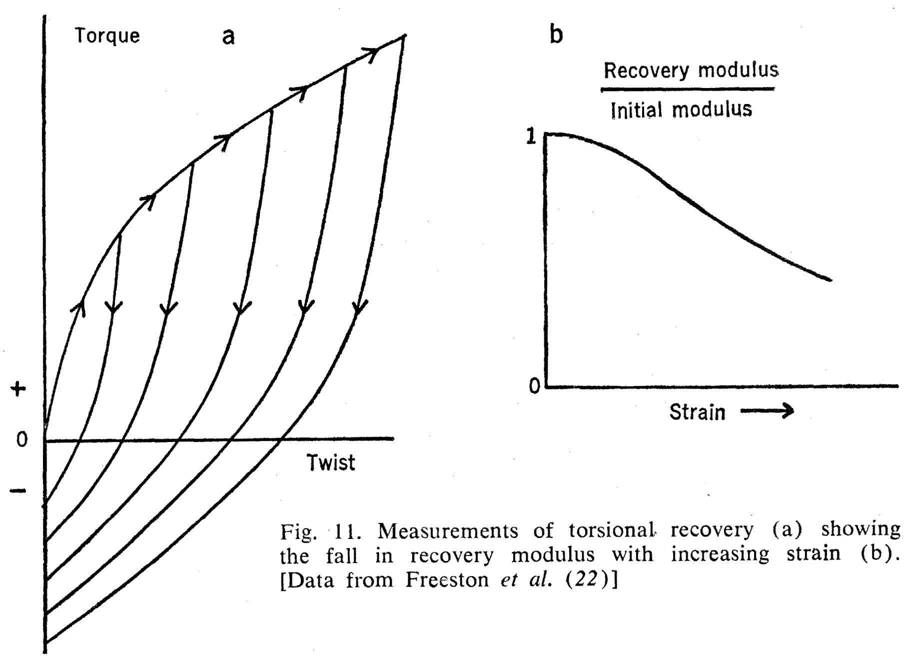

Fig. 11. Measurements of torsional recovery (a) showing the fall in recovery modulus with increasing strain (b). [Data from Freeston *et al.* (*22*)]

Other Recovery Problems

In the discussion of bending behavior presented above I have concentrated on the recovery of woven fabrics from bending strain. There are other areas of interest where the bending of textiles is of implicit importance and in which considerable work has been conducted. For example, in a study of the tensile strength of woven tapes (*35*), the strength loss in certain woven structures was shown to be related to the level of frictional restraints in the tape, and hence, to the loss caused by bending hysteresis. The restraint prevents the equalization of filament strains in the warp yarns as they are pulled from the original bent configuration in the tape to an essentially straight configuration at break.

Knit fabrics present a separate class of problems. Because of their loop structure, all types of deformation in knit fabrics, including tensile deformation, involve large torsional and bending strains within the fabric. The tensile behavior is particularly interesting, since the friction can operate at two distinct levels in influencing the behavior. At the interfilament level its effect is similar in type and magnitude to that discussed previously. However, the frictional forces between yarns at the loop intersection points oppose the redistribution of yarn lengths within the loops, and, in certain circumstances, can lead to discontinuous tensile and recovery characteristics as the deformation and recovery proceeds in discrete steps (*36*).

Another example of the indirect influence of bending is found in fabric shear: a woven fabric can shear only by the production of bending strains in the intersecting crimped yarns. Because

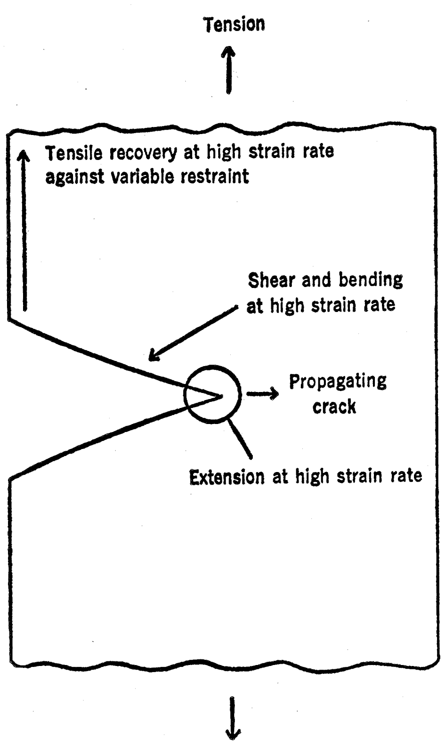

Fig. 12. A schematic representation of crack propagation in a woven fabric showing the mechanisms controlling the propagation.

a large shear deformation produces only a small curvature change in the yarn, and the frictional restraints at the interyarn level are comparatively high, it is to be expected that the shear recovery behavior is very sensitive to the amount of frictional restraint. This is indeed the case, and the behavior in shear can provide a very good indication of the state of relaxation of a fabric (*37*).

As a final example of the complexities involved in the recovery behavior of textile materials, I will discuss the phenomenon shown in Fig. 12. If a fabric is held under tension, and is damaged by the introduction of a hole or slit, then under certain circumstances the crack can propagate spontaneously through the fabric at speeds of several hundred feet per second (*38*). When this happens a very complex sequence of events takes place that includes several of the mechanisms discussed above. After a yarn is broken it undergoes tensile recovery at a high rate of strain against the variable restraint imposed by the next yarn as it is in turn extended. In the course of the transfer of the recovered energy from yarn to yarn the fabric suffers shear deformation at a high rate of strain and the yarns themselves become bent. If enough energy is transferred, the next yarn, which is suffering tensile deformation at a high rate of strain, will break and the process will be repeated. This phenomenon has been reported in decelerators of various kinds, as well as in air-supported structures, and a knowledge of the exact conditions controlling its occurrences would be very valuable for design purposes.

Conclusions

When textile materials are deformed the forces of elastic recovery and the forces of frictional restraint can be similar in magnitude, and the recovery behavior of the materials from imposed strain is complex. Some quantitative analysis of the recovery behavior of fibrous assemblies is possible, but complete understanding is not easy to obtain because in this, as in most other problems in textile mechanics, the possibilities for subtle interactions between the elements of the structure are endless. It is the hidden complexity of these familiar materials that makes textiles such a challenging and rewarding field of study.

References and Notes

1. Under certain circumstances textile materials can exhibit better than perfect recovery. The most spectacular instance of this is the phenomenon known as "supercontraction" in wool, in which a fiber stretched in an alkaline medium will shrink to much less than its original length when the tension is removed. Supercontraction is fully discussed in P. Alexander, R. F. Hudson, C. Earland, *Wool: Its Chemistry and Physics* (Chapman & Hall, London, 1963), p. 77. A similar effect has been reported in a range of synthetic fibers extended at high strain rates [S. K. Batra and S. Backer, *Text. Res. J.* **36**, 1029 (1966)] and has also been observed to a lesser degree at low strain rates by several workers. In synthetic fibers it is attributable generally to the release of lightly set strains imposed and "frozen in" during the manufacturing process; it plays an important part in the mechanism of fabric shrinkage for these materials.
2. The unit traditionally used to classify textile yarns and fibers according to size is the denier. This is defined as the mass in grams of 9000 meters of fiber or yarn. The denier of commercially available fiber ranges from 1 to 6, and fiber-forming polymers range in density from 0.90 for polypropylene to 1.54 for viscose rayon. These values lead to a range of fiber diameters of 10 to 30 μm [see, for example, W. H. Gloor, *Nomograms for Fiber Property Calculations* (Technical Memorandum MAN64-22, Research and Technology Division, USAF Wright-Patterson Air Force Base, Ohio, 1964)].
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20. Various aspects of the mechanism of false-twist texturizing are discussed by M. J. Denton and by H. W. Drause in a series of letters in *J. Text. Inst.* **57**, T372, T586, T589 (1966); *ibid.* **59**, T550 (1968); see also G. R. Wray, *ibid.* **60**, T102 (1969).
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