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Problems in Strain Measurement in Impact Tests on Textile Materials

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THE NEED FOR IMPACT TESTS ON TEXTILE MATERIALS

We are all consumers of textile products, and, as consumers, we are constantly experimenting with fibrous materials in apparel, in household goods, and in selected mechanical usages. We are aware of the "static" textile properties, such as crease resistance, moth resistance, ease of laundering, or "wash-wear" characteristics, warmth without weight, drape, hand, and wear resistance. But little is said in the popular advertising about the dynamic properties of fibrous assemblies—of their mechanical behavior under conditions of high-speed application of load. Yet tire cords, parachute risers, marine cordage, and aircraft arrester and towing systems are clearly textile applications which require efficient structural behavior under high-speed loading conditions. Likewise do ballistic fabric, safety nets, reinforced helmets and inflatable fabric structures undergo dynamic loading over a wide range of impacting speeds. To assure satisfactory performance of these applications, the textile engineer must study the stress–strain behavior of fibers, yarns, and fabrics at high strain rates ranging from a few feet per second to several thousand feet per second.

Satisfactory impact behavior of textile materials is also necessary to meet the demands of industry for higher unit productivity, achieved in most instances by increases in textile process speed. The many new fibers which appear yearly on the textile scene cannot survive competition with older fibers if they do not contribute new desirable properties to the consumer item. But first they must survive processing exposure to high-speed drawing and spinning, to the rapid accelerations of the winding process and of weaving, to the tensions and sharp bending of rapid knitting, and to the high velocity, repeated impacts of the modern sewing machine. The textile material must be *made* before it is sold, and to make it efficiently one must be knowledgable concerning the interaction of fibers and high speed textile processes.

TEXTILE MATERIALS—A DEFINITION

Strict definition of textiles suggests that weaving is a necessary feature of such materials, but the more accepted meaning of the word includes all sheetlike structures which are composed of relatively fine fiber components. The structure may be directly formed of fibers, the so-called nonwoven (whose fiber length is several times the length of conventional paper fibers). It may be composed of yarns which have been knit or woven, braided, or knotted and intertwined (in a lace structure). The yarns may have a simple twist structure or may be built up in a compound system with sub units and elementary twisted "singles." The important thing to be noted is the fact that a textile itself is rarely a uniform homogeneous material. The single fiber is itself a complicated system from the point of view of its molecular chain structure and its fibrillar formation; the manufactured textile material is *doubly* complicated by the geometry of its fiber assemblage which interacts with the basic fiber properties in determining mechanical behavior of the end product.

Textile materials are rarely used in flat sheet form. More often they are cut and pieced to approximate three-dimensionally curved shapes of the wearer, and, when this is done, the structural weak point of the system resides in the joint or seam. Thus, when impact usage of a fabricated textile system is expected, seam behavior under high strain rates, as well as under static test conditions, must be known.

PROBLEMS IN MEASURING TEXTILE STRAINS

The commonly accepted method of evaluating strain of textile materials under tensile loads is to measure the relative displacement of the two aws which are clamped on the specimen. In metal, plastic, and rubber specimens, the specimen is frequently thicker or wider at the jaws than at the center span between the jaws and can therefore withstand considerable clamping force. In textile testing, the yarn or fabric frequently has the same dimensions along the entire specimen length, in jaws and between jaws. In such cases it is important to avoid excessive jaw pressures which may combine with the tension of the free span to create a local stress concentration within the jaw, causing early rupture at a tensile load well below what the textile specimen is capable of handling. In clamping textile specimens, therefore, one generally lengthens the clamping area and decreases the lateral load per unit length of the sample. This step provides improved breaking load readings, but it creates many problems in the accurate measurement of strain. In what follows we shall attempt to describe these textile strain problems together with certain of their solutions. The solutions are in some instances, useful in both static and dynamic tests. In other cases they provide answers satisfactory only for static testing.

1. Complexity of the Textile System

Textile material rarely behaves like an isotropic elastic sheet. It is usually orthotropic, having two principal directions of stiffness, shear rigidity and Poisson (or contraction) ratio. Strain measurement in such a structure is difficult, for the strain of various parts of the textile specimen may differ in a given test. In a twisted yarn or cord the fibers in the center generally have a lower helix angle than the outside fibers and hence are under greater strain in a tensile test. In a woven fabric, test yarns lying parallel to the loading direction and located at the side of the specimen neck inward, while the centrally located yarns remain straight. Thus their strain histories vary during a tensile test. In a seam structure such as is pictured in Figure 1, the longitudinal stress-bearing yarns entering the stitch loop from different positions are under different strains, those at the loop extremities being subjected to higher strain levels and breaking first, those at the loop center undergoing less strain and breaking last.

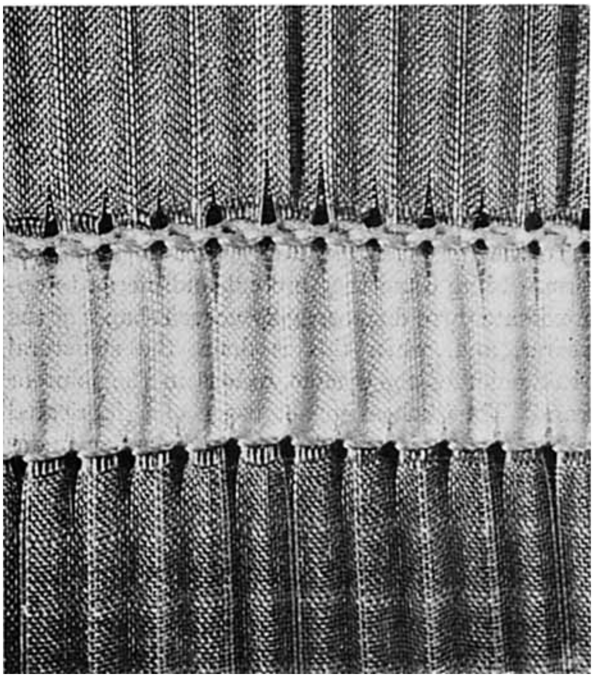

Fig. 1. Strain inhomogeneities at a fabric seam under stress.

2. Anisotropy of Textile Materials

The basic fiber in textile structures is not isotropic, but even if it were, the structural design of yarn and cloth of itself induces anisotropic behavior into every textile system. As pointed out above, textile cloths are usually orthotropic in their mechanical properties. The following classical stress strain equations for orthotropic materials have been shown pertinent to behavior of a nonwoven fabric and they suggest some of the difficulties we may have in the valid measurement of stress–strain behavior of such a system:

$$\epsilon_x = b_{11}\sigma_x + b_{12}\sigma_y + b_{13}\tau_{xy} \tag{1}$$

$$\epsilon_y = b_{21}\sigma_x + b_{22}\sigma_y + b_{23}\tau_{xy} \tag{2}$$

$$\gamma_{xy} = b_{31}\sigma_x + b_{32}\sigma_y + b_{33}\tau_{xy} \tag{3}$$

where ϵ_x, ϵ_y, and γ_{xy} are normal strains and shear strain in the directions x, y, respectively; σ_x, σ_y and τ_{xy} are the normal and shear stresses in the x, y directions, respectively. The coefficients b are functions of the principal directional elastic tensile and shear moduli and Poisson ratios of the material. Note that directions x, y are not (in general) the principal directions of the nonwoven material. In the case of a uniaxial tensile test wherein the axis of pull, y and the principal direction of the fiber orientation in the nonwoven do not coincide, an extension ϵ_y exerted on the web by jaws of the conventional textile test machine, will develop a tensile stress σ_y in the fabric. Because of the free edge σ_x will be zero. But the stress σ_y will be accompanied either by a shear stress

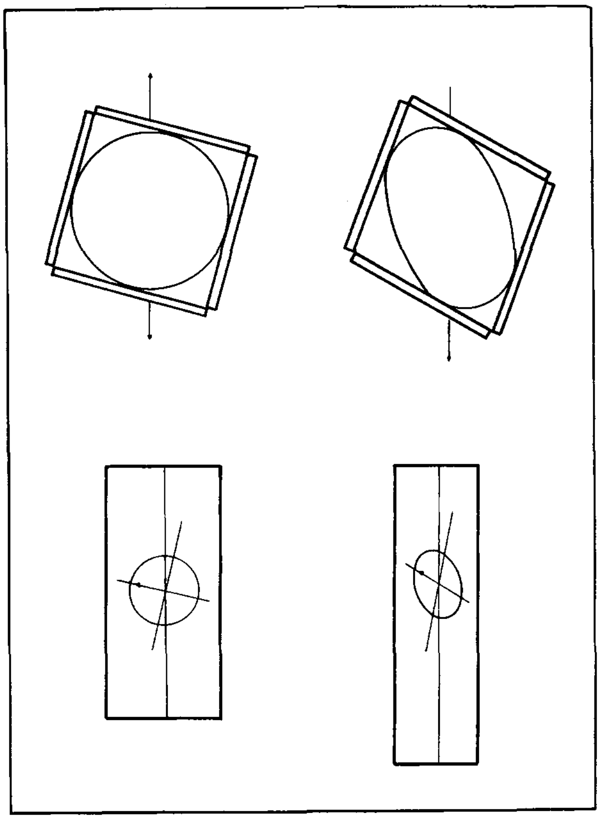

Fig. 2. Trellis behavior of a textile fabric.

τ_{xy} (if $\gamma_{xy} = 0$, meaning that the jaws are not allowed to rotate) or by a shear strain, γ_{xy}, if the jaws are allowed to rotate (with $\tau_{xy} = 0$). Many tensile testers provide a mixture of these conditions and the observation of their average jaw separation is simply not an adequate strain measurement. Textile fabrics in fact often act like a trellis model loaded off its axes of symmetry, as is shown in Figure 2 (after Weissenberg[1,2]).

3. Jaw Effects: Restraint

The function of the jaw in a textile tensile test is to clamp the specimen and provide a mechanical connection between it and the moving and fixed cross heads. Many textile specimens subjected to uniaxial pull in the y direction will show significant contraction in the x direction. In fact, Poisson ratios approaching and even exceeding 1.0 can occur in certain cloth constructions. Free contraction of the specimen is prevented at the jaws because of their clamping action and the frequent result of this restraint is a waisted specimen as illustrated[1,2] in Figure 3. Clearly, the specimen strain is not uniform along its length, and jaw displacements do not describe material strains.

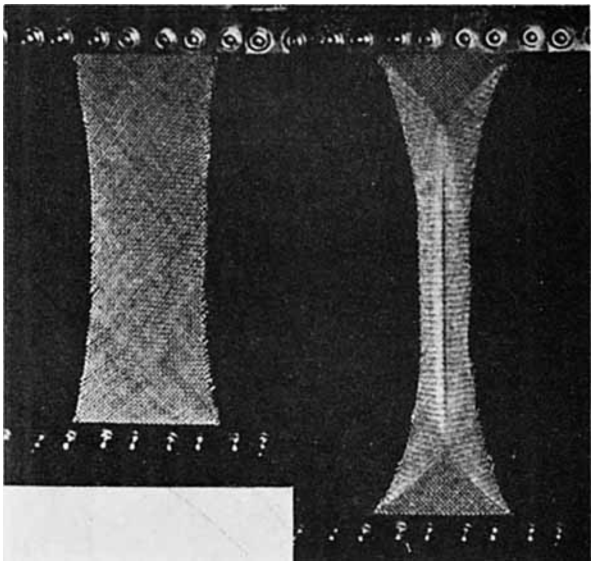

Fig. 3. Uniaxial test of bias fabrics.

4. Jaw Effects: Slippage

To avoid clamp ruptures, numerous special textile jaws have been designed to decrease the unit area pressures required to develop a total frictional force equal to the tension in the specimen. However, this reduction in stress concentration is generally accompanied, as has been stated above, by an increase in the working area of the jaw and a lengthening of that section of the specimen which is involved in nonhomogeneous extension and local slippage. As a result, the jaw-to-jaw separation becomes entirely inadequate as a direct measurement of specimen strain.

One move to eliminate such jaw effects on strain measurements was made by Kaswell and Hamburger,[3] who suggested the technique of measuring the separation of gage marks on the specimen at loads below rupture, comparing the values with data on jaw separation, and establishing an effective gage length. This effective length could then serve as the basis for calculating breaking strains from knowledge of jaw separation. Clearly, this method was intended to circumvent the need to measure gage mark separation at the moment of specimen rupture, this measurement being an uncertain, if not dangerous procedure for many textiles.

It has also been proposed that the tensile test be run at a fixed strain rate but with two different gage lengths. One could then take the difference in the extension readings for each load and, attributing this extension difference to the differences

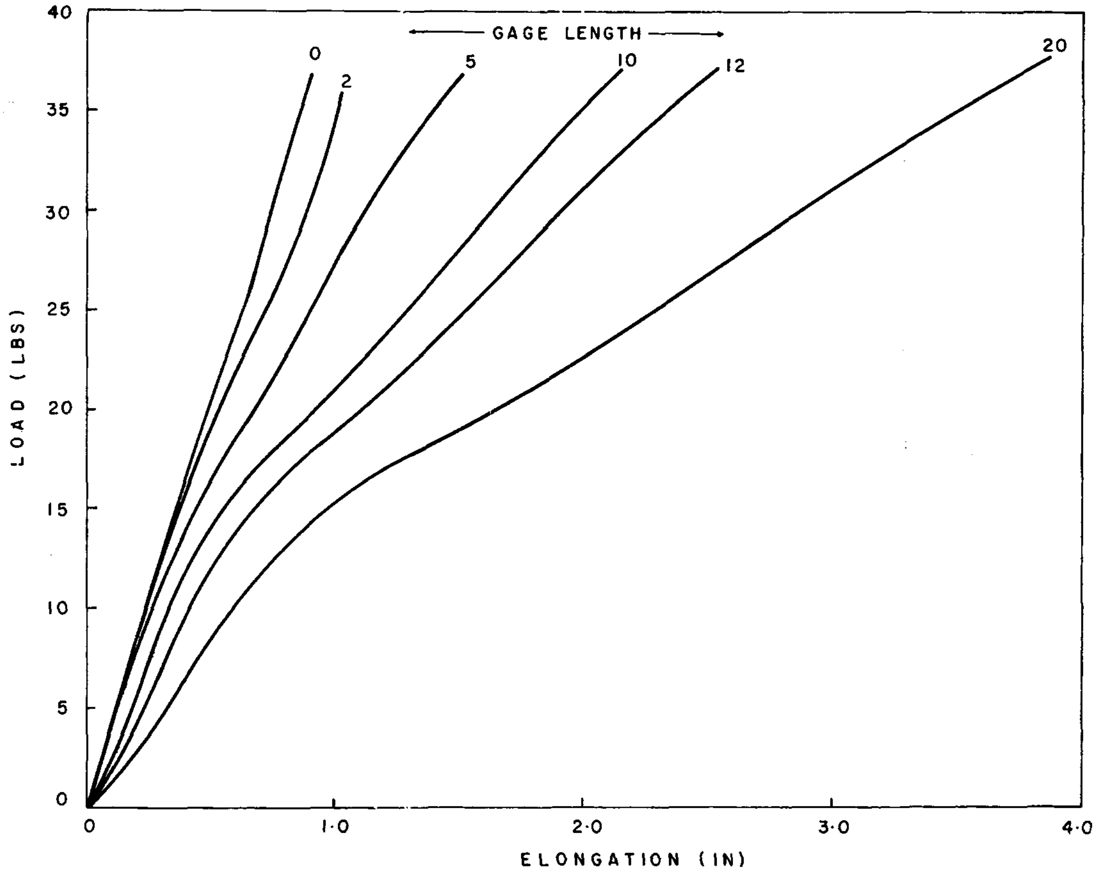

Fig. 4. Load–elongation behavior of various gage lengths (cotton–rayon tape).

in the two gage lengths, one could replot the valid load-strain curve of the material. Still another method involves the use of several different gage lengths in successive tests, then a replotting of the extension at a given load versus gage length. This curve is then extrapolated to zero gage length and the extension intercept is taken to represent both the slippage and extension of the specimen in the jaw. This extension must then be subtracted from the measured jaw separation to give the true strain reading for the chosen load. The procedure is then repeated for other loads to give a table of values of true strain versus specimen load. The extrapolation procedure is illustrated in Figures 4 and 5. Figure 4 shows the load versus jaw movement data plotted for capstan jaw tests of a rayon-cotton webbing or tape at gage lengths of 2, 5, 10, 12, and 20 in. The data of Figure 4 are cross-plotted in Figure 5, and the elongation curves are extrapolated to zero gage length. These elongation intercepts of Figure 5 are then plotted back in Figure 4 as the zero gage length (correction) curve—this curve to be subtracted along the strain axis from each of the other raw data curves of Figure 4 to give the valid load–elongation picture at each gage length tested. It is clear that the uncorrected curves were in error (elongationwise) from over 400% in the case of the 2-in. gage length to about 30% in the case of the 20-in. gage.

The extrapolation method illustrated in Figures 4 and 5 is cumbersome and on occasions, unreliable. The method assumes uniformity of specimens (since we are extrapolating and then subtracting from original data from many tests), and it assumes that the rate of load build-up, which can seriously affect slippage and extension of the specimen in the jaws, can be adequately standardized and held constant in the different gage length tests. We have found the technique sometimes inadequate for these reasons, sometimes at slow test rates, sometimes at impact-testing speeds. The data of Figures 4 and 5 were obtained at a strain rate of 100%/min. Corresponding tests at 50%/min. strain rate were entirely inconsistent with the 100%/min. data. The 100% rate data were in close agreement with load–extension data taken with flat

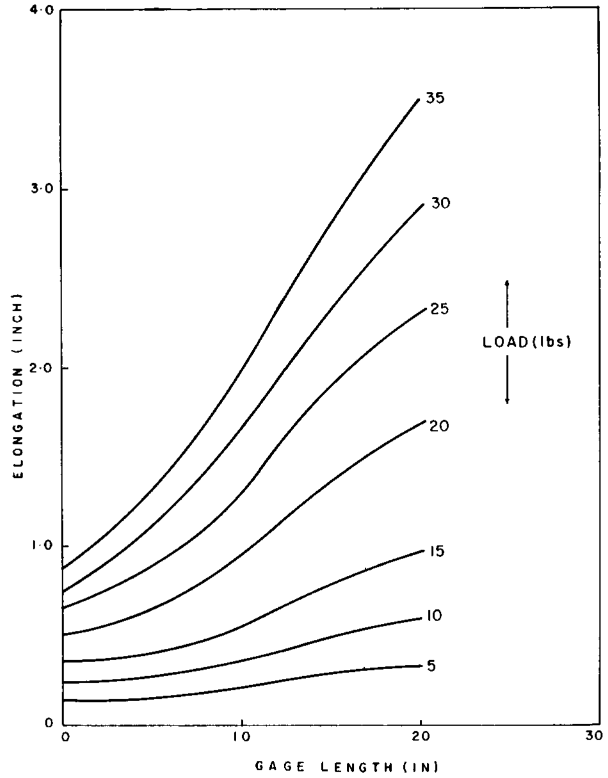

Fig. 5. Cross plotting of data from Fig. 4.

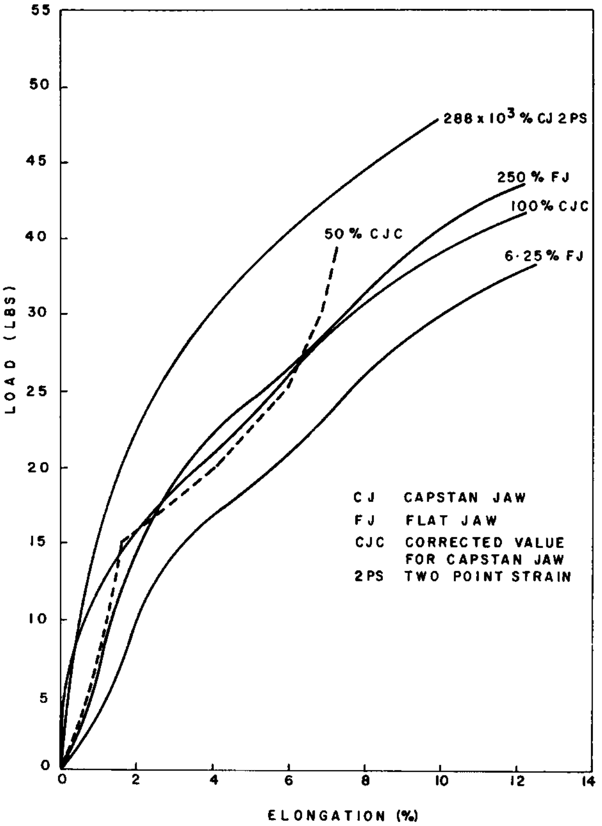

Fig. 6. Load–elongation behavior of cotton–rayon tape at various strain rates. Values on curve give strain rate (%/min.).

(minimum slippage) jaws and with gage-marked capstan jaw tests (see Fig. 6).

The effective gage length method assumes that the ratio of jaw extension to between-jaw-extension remains constant in the latter part of the tensile test (between the last gage measurement and the rupture point). Further, it is dependent on the ability of the operator to judge gage mark separation during the test. In impact tests the behavior in and out of the jaws is not as linear as might be desired, and there is not time for gage mark measurements except by photographic means.

The materials engineer dealing with bulk solids avoids the problems cited above by increasing the cross-sectional dimensions of the specimen at the jaws and by limiting his strain readings to the region of uniform cross section in the middle of the specimen. His strain-measuring instruments are hung onto the specimen and consist of mechanical or optical levers, mechanical-electrical devices, or all-electric (as, for example, the bonded wire strain gage) systems. Such devices cannot be used in measurements of textile structures because of the unusual flexibility of these materials, which leads to an inability to sustain the weight of the strain gage without bending, or because of the interference of the forces necessary to activate the strain gage, with the accurate reading of the textile load. Further, the high strains involved in textile systems (often up to 50%) preclude use of the common strain gage designed for metal systems. Finally, the presence of high level strain energy at rupture in the textile structure frequently induces severe lashback, which invites damage to expensive instruments and poses a safety problem for laboratory personnel. These objections to use of bulk material methods of strain measurement of textile structures apply in both static and dynamic tests. In fact, all the strain measurement problems cited above for slow-speed textile tests apply to an even greater extent in high-speed testing of textiles.

STRAIN MEASUREMENTS IN IMPACT TESTING

Clearly, the difficulties of fastening flexible, yet very strong textile structures to a jaw system are accentuated in higher speed tests. It is worth noting, however, that the reaction of textile ma-

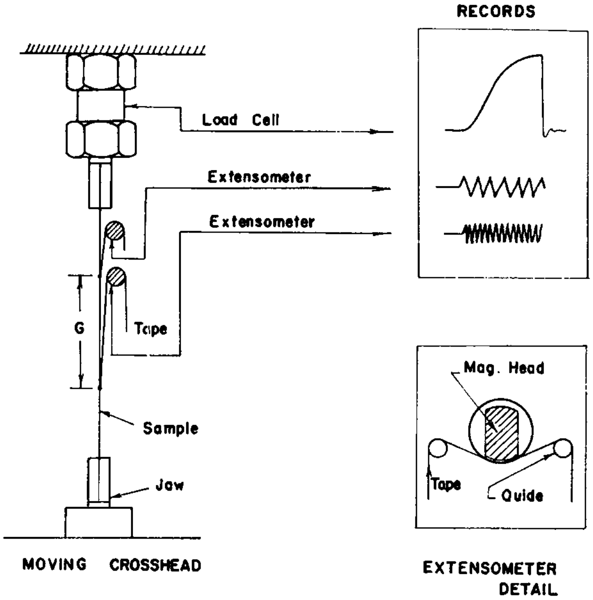

Fig. 7. Schematic of load-strain measuring system for high-speed testing of textile structures. *G* denotes gage length for strain.

terials to stress concentrations differs in high- and low-speed tests. A fabric or yarn which ruptures *within* a flat jaw at low testing speeds often ruptures *between* the jaws in an impact test, and capstan jaws can sometimes be done away with to provide a reliable strain reading based solely on jaw movement data. The opposite is sometimes true, but this must be checked for each individual case. The cotton-rayon tape represented by the data of Figure 4 was tested both at slow speeds and at high speeds. Flat jaw movement data at slow speeds were used, since it did not involve jaw breaks at strain rates of 6%/min. and of 250%/min. The 100%/min. corrected capstan data derived from Figure 4 were consistent with these two flat jaw rates (6% and 250% min.). However the 50%/min. corrected-capstan readings were anomalous (see Fig. 6).

Where direct strain readings on the sample are desired, there arises an additional problem in high-speed testing of textiles, namely the inertial effects of the strain measurement system. The element attached to the specimen must have a small mass, lest its resistance to acceleration during the test interfere with valid readings of specimen stress. A small, linear, differential transformer has been used successfully as a strain-measuring element in static textile-testing systems. The presence of large deformations, large strains, and high rupture energies precludes widespread use of the linear differential transformer as a strain gage in high-speed textile tests, however.

A reasonable solution to the direct strain-measurement problem for textile impact tests is the use of magnetic tapes as the strain record. A procedure developed in the Textile Laboratories at MIT by one of us (J.G.K.) involves the pre-recording on a standard high fidelity magnetic tape of a sine wave whose wavelength can be selected from tape to tape. The tape is mounted in the impact test with one end fastened (sewed or stapled) to a point on the specimen, then run over a specially designed record-reproduce magnetic head, with the other end of the tape hanging free. When the specimen point moves, it pulls the tape with it, and the tape motion is detected at the magnetic head.

The schematic appearance of the system is shown in Figure 7. The mass of the tape is negligible (0.1 g./ft.), and the resistance to its movement over the magnetic head is adjusted to less than 1 lb. at test speeds of 40 ft./sec. The resolution of tape reading can reach 10^{-3} in. without difficulty. The upper limit of strain reading (and displacement measurement) is infinite for practical purposes. The limits of speed for which the tape movement can be effectively read out in an oscilloscope are 0.5 in./sec. to 100 ft./sec.

Two or more tapes can be used at one time to describe the displacement history of any designated pair of gage marks, and the differences between these two displacements at any time furnish data on the local strain of that portion of the specimen. Two-point impact strain readings have been found entirely feasible on many textile structures of sheet form. Impact strain measurements on yarn specimens have been taken with a single tape attached to the moving flat jaw in cases where jaw breaks did not occur. This latter tape also provides a check on test velocities. The use of two-point strain reading for impact tests on twisted structures (such as ropes) has been found possible, but the torsional rotation of the rope during the test has interfered significantly with the reliability and reproducibility of the results. An example of successful two-point strain reading taken at impact speeds on the cotton-rayon tape referred to above is shown in Figure 6.

The strain readings obtained with the magnetic tape system eliminate the effects of the strain inhomogeneity in the region of the jaws. However, the stress concentrations of such regions may still seriously affect the maximum load readings obtainable for a given textile specimen. Also, to avoid penetration of the strain inhomogeneity into the center of the specimen it is often necessary to use a specimen of length six to ten times its width. This implies use of considerable quantities of material for testing and sometimes exceeds the dimensions (with jaw travel) of the testing machine. A far better method for eliminating the jaw restraint of sample contraction, has been proposed by Weissenberg,[1,2] who uses slanted jaws placed parallel to the predetermined lines of zero elongation in the material.

Finally, it should be noted that anything the magnetic tape can do in measuring impact strains can be done by photography, though usually with considerably more effort. In high-speed tests at rates above 100 ft./sec. the tape is no longer a suitable device, and as speeds of test approach ballistic velocities, it is doubtful that any system can compete with the photographic method. Within the range of 0.5 in./sec. to 100 ft./sec., the tape method holds promise of simplicity, low cost, and versatility in strain measurements on textile materials.

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Synopsis

The limitations of conventional methods of measuring strain are discussed in light of the structural composition of textile materials. The difficulties introduced in static and impact testing by stress concentration and strain inhomogeneity are considered. The need for two-point strain measurement in regions of homogeneous strain is emphasized. A low inertia strain-measuring system utilizing magnetic tape is described as applied to tensile tests at jaw speeds of 1 to 100 ft./sec.

Résumé

Les limitations des méthodes conventionnelles pour mesurer la tension, sont discutées en fonction de la composition structurale de matériaux textiles. Les difficultés introduites dans des épreuves statistiques et d'impact par la concentration des tensions et l'inhomogénéité des tensions, sont considérées ici. On insiste sur la nécessité de mesurer la tension près de deux points dans des régions de tensions homogènes. Un système mesurant la tension à faible inertie et qui utilise des bandes magnétiques, est décrit comme appliqué à des épreuves de traction à des vitesses de débit de 1 à 100 pieds/sec.

Zusammenfassung

Die Grenzen der konventionellen Methoden zur Verformungsmessung werden im Lichte des strukturellen Aufbaus der Textilmaterialien diskutiert. Die Schwierigkeiten, die sich bei statischen und Stossprüfungen aus der Spannungskonzentration und der Verformungsinhomogenität ergeben, werden erläutert. Die Notwendigkeit einer Zweipunkt-Verformungsmessung im Gebiet homogener Verformung wird betont. Ein Verformungsmessungsgerät geringer Trägheit mit Magnetband und seine Verwendung für Zugprüfungen bei einer Backengeschwindigkeit von 1 bis 100 Fuss pro Sekunde wird beschrieben.

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