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Test for measuring cut resistance of yarns

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A test procedure for evaluating the cut resistance of yarns under tension-shear loading conditions is described and demonstrated. A knife blade is pressed transversely at a constant rate against a yarn gripped at its ends, the load-deflection relation is measured, and the energy required to cut through the yarn is computed. Results for Zylon (polybenzobisoxazole or PBO) are presented. The cut energy and strain to initiate cutting depend on the sharpness of the blade, the slicing angle, and the pre-tension in the yarn. The dependencies are explained by changes in failure mode of the fibers within the yarn. The test provides information needed to extend a computational model of ballistic response of fabrics to sharp fragments and to design a cutting tool. © *2003 Kluwer Academic Publishers*

1. Introduction

Several catastrophic commercial aviation accidents have occurred when fragments from a burst turbine engine penetrated the fuselage and severed flight-critical components ([1], for example). To reduce the likelihood of future accidents, the FAA is evaluating the performance of lightweight ballistic blankets that can be inserted in fuselage walls to arrest engine debris. Recent ballistic tests with fan blade fragments showed that a few layers of fabric made from advanced high-strength polymers can stop fragments of the sizes and velocities expected from propulsion engines on commercial aircraft [2].

However, the tests also showed that sharp-edged fragments penetrated the fabric more easily than blunter fragments. Post-test examination of the fabrics indicated that tensile failure of the yarns was assisted by a cutting mechanism when the fragments had sharp edges. The sharpness effect was confirmed in quasistatic penetration tests [3]. Thus, since fabrics exhibit a lower ballistic limit and absorb less energy when attacked by a sharp-edged fragment than they do when attacked by a blunt fragment, an understanding of fabric cut resistance is important for designing protective barriers.

A computational model of fabric failure under ballistic impact conditions has been developed to assist fragment barrier design [4]. This model's predictions of energy absorption and residual velocity can be satisfactory when the penetrator is a blunt-nosed fragment and the fabric yarns fail in tension, and the model is often useful in specifying the number of layers required to arrest a given projectile mass and velocity. In the case of sharp-edged fragments, however, the model overpredicts the protective capacity. Thus, the model must be modified to include yarn failure under tension-shear. The work reported in this paper was performed to aid further development of the model by generating data and a better understanding of cutting failure in yarns.

2. Background

Although cut resistance of fabrics is an important property of protective apparel, cut resistance is difficult to measure, and a test method that provides quantitative parameters useful in design does not exist. Thus, the design and specifications for protective clothing cannot be accomplished with any rigor. The resistance of fabric to cutting may depend on the way the cutter is applied. For example, if a scissors is the cutter, the fabric yarns are stressed in shear and tension. If the fabric is placed on a surface such as a table and a knife is drawn across it, the fabric is stressed in shear and compression. A fabric gripped at its edges and slashed with a knife may be cut in tension and shear.

Interest in protective gloves has motivated several tests to evaluate cut resistance under shear and compression [5–9]. Two standard tests exist. In the American standard [5] issued in 1997, a cutting edge is placed under specified loads and moved across a fabric specimen mounted on a mandrel. The distance from the site of initial contact of the cutting edge to where the fabric is cut through is taken as the cut resistance of the fabric. The European standard [6] defines cut resistance as the number of times a dead weight must be applied to a cutting edge before the fabric is cut through. While data from these standards are useful in ranking materials in terms of cut resistance, they don't provide quantitative properties useful for designing protective apparel. Moreover, the ranking from such a compression-shear test may be opposite that of, say, a scissors test.

In the fragment barrier scenario of interest to us, the fabric has no solid backing, and therefore experiences no compressive load. Rather, the yarns in the fabric are stressed in tension and shear. To measure cut resistance pertinent to this loading situation, we sought a test in which a yarn is gripped at its ends and loaded transversely by a cutter.

3. Test arrangement and protocol

The objective of this study was to develop a test procedure that reliably and reproducibly measures the cutting resistance of yarns under tension-shear conditions. Since cut resistance is sensitively dependent on the sharpness of the cutter, the sharpness must be specified and the test must account for cutter dulling during cutting. Other variables such as cutter angle with respect to fabric, rate of load application, and yarn pre-tension may influence cut resistance and should be variable and measurable in the test.

Fig. 1 shows the fixture constructed for gripping a fabric sample on opposing sides. A moveable grip and a screw mechanism permit adjustable tension to be applied to the fabric; a load cell measures the tension level. A special clamping structure was designed to prevent the yarns from slipping in the grips when the load is applied [2]. This proved to be a difficult but important task. In the transverse loading geometry, even slight slippage influences the derivation of the true yarn strain [10]. We firmly clamped the yarns by wrapping the fabric ends around a flattened steel rod, which was tightly clamped between two steel plates.

We isolated individual yarns from neighboring yarns by cutting and removing adjacent yarns on either side. The fabric length between grips (i.e., the yarn gauge length) was about 165 mm (6.5 in.) Each fabric sample had approximately six isolated yarns with a spacing of 12.5 mm (0.5 in.) between them. At both edges of the sample, 15 yarns were retained intact to keep the sample aligned during testing.

Fig. 2 shows the experimental setup for the yarn transverse cut tests. The fixture with the fabric is placed on the crosshead of a commercial laboratory mechanical testing machine so that the yarns of the fabric can be moved against a cutter mounted on the fixed beam of the machine. The rate of loading and the angle of the cutter with respect to the direction of motion, defined here as the slice angle, are adjustable. The upward movement of the ram, at a constant ram rate of 0.25 mm/s (0.01 in./s), pushed the yarn against the cutter blade. The ram stroke and the transverse load on the yarn midpoint were recorded continuously throughout the test. The axial load on the yarn, as well as the stress and strain in the yarn, were calculated from the transverse load, as shown below.

The cutter was a commercially available hardened steel utility blade (11-921 heavy duty utility blade, manufactured by Stanley Tools, New Britain, CT 06050) with a 30 degree included angle and an edge radius of 2 μm. To avoid effects of dulling from test to test, a new cutter was used for each test.

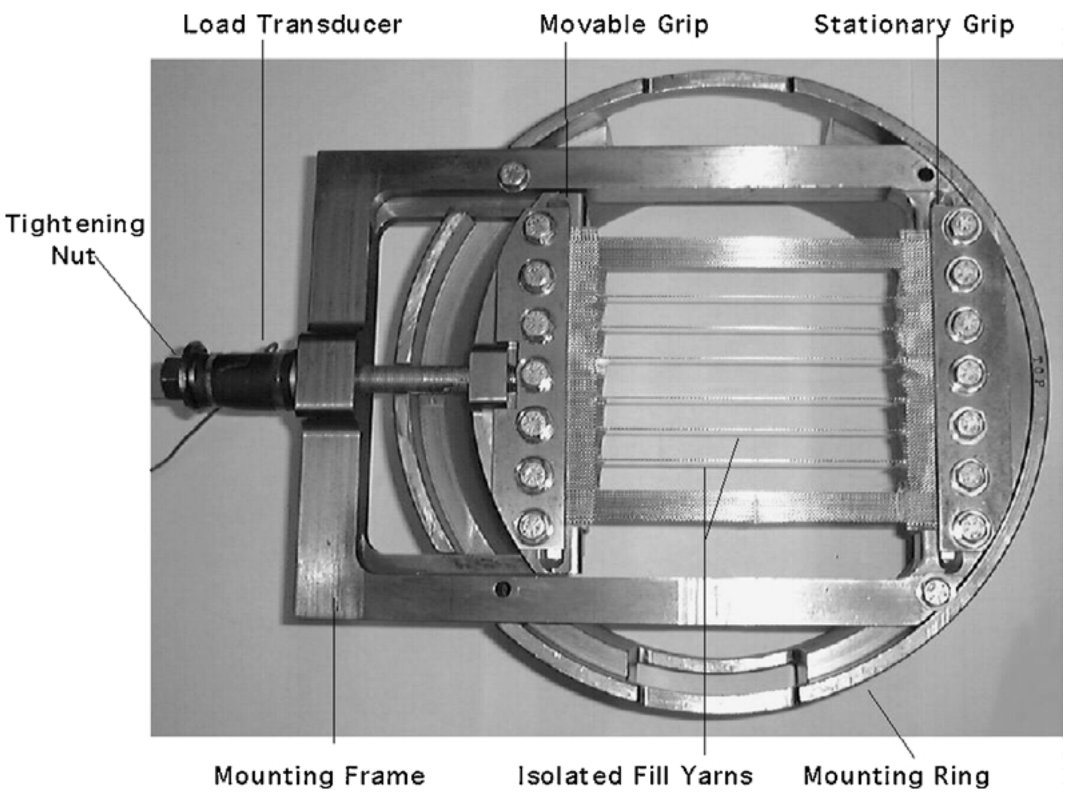


Figure 1 Holding fixture for cut test and fabric specimen with isolated yarns.

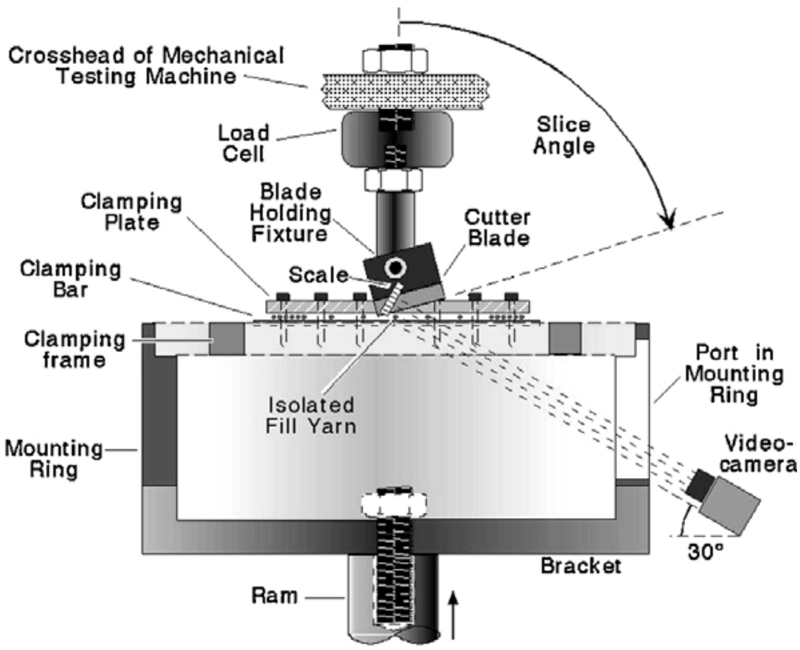


Figure 2 Arrangement for cut test.

A CCD camera trained on the stationary cutter recorded mechanistic details of yarn failure. For tests using inclined cutters, the CCD camera recorded the yarn travel along the edge of the blade and permitted evaluation of yarn strain and stress. The camera was oriented at an angle of 30° with respect to the fabric plane, and a scale bar was attached to the cutter at right angles to the direction of the camera to assist in determining the yarn travel. A microphone recorded acoustic signals from failing fibers within the yarns. However, in the case of inclined blade angles, sounds associated with fiber failure were difficult to distinguish from background noise.

The stress-strain behavior and the energy absorbed during cutting were determined from the load-stroke records. The geometry for the stress-strain analysis is shown in Fig. 3. The strain in the yarn was calculated from the transverse deflection of the yarn. The stress was calculated from the axial load on the yarn, which is derived from the measured transverse load and the angle of yarn deflection.

For the case of a 90° slice angle (Fig. 3a), for which no yarn travel along the blade can occur, the yarn elongation, L, the induced strain, ε, and the angle of yarn deflection, θ, are given by

$$L = 2[(L_o/2)^2 + d^2]^{1/2}, \quad (1)$$

$$\varepsilon = (L - L_o)/L_o, \quad (2)$$

$$\theta = \arctan(d/L_o), \quad (3)$$

where L_o is the initial gauge length between grips and d is the ram deflection (which equals the actual deflection of the yarn's midpoint). The axial force along the yarn (F_y) is determined from the measured transverse load (F) by

$$F_y = F/(2\sin\theta) \quad (4)$$

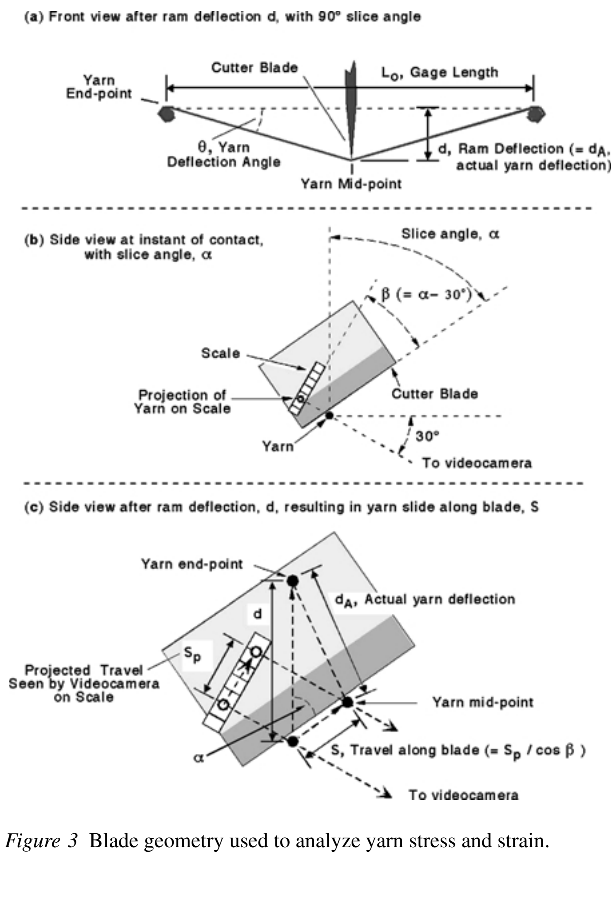


Figure 3 Blade geometry used to analyze yarn stress and strain.

and the stress, σ is given by

$$\sigma = F_y/A, \quad (5)$$

where A is the yarn's cross-sectional area.

For the more general case of an arbitrary slice angle, α, the travel of the yarn along the blade must be taken into consideration (see Fig. 3b and c). The videocamera record shows the distance of travel, S_P, as projected onto the scale. The actual travel along the blade, S, can be determined from

$$S = S_P/(\cos\beta), \tag{6}$$

where $\beta = 60 - \alpha$. The actual yarn deflection, d_A, can then be derived, using the cosine theorem, from

$$d_A = [d^2 + S^2 - 2dS\cos(90^\circ - \alpha)]^{1/2} \tag{7}$$

The yarn strains and stresses can then be derived by substituting d_A for d in Equations 1 and 3, and then solving Equations 2, 4, and 5.

We defined cut resistance as the area under the stress-strain curve, and we investigated how slice angle, yarn pre-tension, and cutter sharpness changed the cut resistance. Finally, we examined the cut ends of individual fibers to seek changes in the type or extent of fiber failure that might correlate with cut resistance.

4. Test results on Zylon yarns

The test procedure was applied to rectangles of fabric 125 mm by 300 mm (5 in. by 12 in.) having a 30 × 30 yarn count. The 500 denier Zylon yarns consisted of about 330 12-μm-diameter polybenzobisoxazole (PBO) fibers. Relevant properties of Zylon yarn are shown in Table I; details of transverse failure behavior are given in [10].

Fig. 4 shows results from a typical test with the utility blade oriented at 30° to the direction of motion and no axial pre-load. The four images from the CCD record depict (a) the instant of blade contact with the yarn, (b) the initial fiber breakage, (c) the peak transverse load, and (d) a late stage of the test. By comparing the locations of the yarn midpoint in the four images (indicated by the scale) with the location of the arrow representing the initial contact location, one can determine the amount the yarn traveled along the blade edge during the test. In this case the yarn traveled roughly 0.25 mm, which is significant when compared with the total stroke of ~1.3 mm.

The onset of fiber failure corresponded with a slope change in the load-stroke curve, Fig. 4e. The sharp discontinuities perhaps resulted from the sudden failure of a group of fibers or from a sudden change in configuration of the fibers in contact with the blade. The area under the axial load-stroke curve is the energy absorbed in deforming and then breaking the yarn. Hence, this area is the cut energy. The shape of the load-stroke curve shows that a large fraction of the cut energy is absorbed after initial fiber breakage.

TABLE I Relevant properties of Zylon fabric material

Fabric name[a]	Material	Volume density (g/cm^3)	Mesh (yarns/inch)	Tensile modulus (GPa)	Failure strain (%)	Area of cross section (mm^2)
Zylon-AS	PBO	1.54	30 × 30	171	3.4	0.0365

[a]Zylon is a Toyobo registered trademark.

The load-stroke curves were converted to stress-strain curves as described above. The elastic modulus corresponding to the slope of the linear part of the curves was 140–150 GPa. The values are lower than results from tensile tests on unwoven yarns, shown in Table I, probably due to damage produced during weaving. The cut energy for Zylon when the blade edge is perpendicular to the direction of movement (a 90° slice angle) was 0.105 J (0.93 in.-lb). The threshold strain for initial fiber breakage was 0.46%.

4.1. Effect of slice angle

The cut behavior of yarns is expected to vary with the angle the blade edge makes with the direction of motion, i.e., with the slice angle.

Fig. 5a shows the load-stroke curves for various slice angles. The stress-strain curves derived as described above are shown in Fig. 5b. The curves initially coincide, but deviate from one another after the initiation of fiber breaking. Deviation from the 90° slice angle curve occurred at lower strains and at lower stresses at smaller slice angles. The CCD images showed that in the 90° tests, fiber failure occurred predominantly at the blade edge, although in the later stages a few fibers failed at remote locations due to blade dulling. At inclined angles, however, all fibers failed at the blade edge. The arrows in Fig. 5a and 5b indicate where the videocamera records show fiber failure started.

Fig. 5c shows the average cut energy obtained from tests at different slice angles. The cut energy for Zylon decreases drastically with decreasing slice angle. Even a slight decrease in slice angle from 90° to 82.5° produced a 75% drop in the cut energy. The reason will be discussed in the following section.

4.2. Effect of blade sharpness

A series of transverse cut tests with a 20-μm-radius cutting edge showed that yarns were substantially more cut resistant than when tested with the 2-μm-radius utility blade, as shown in Fig. 6. Cut energy decreased with slice angle, as it did with the utility blade. However, with the blunter blade, the initiation of fiber breakage was delayed and higher peak stresses were sustained, leading to increased cut energy. Similar results were obtained in tests in which sharp and blunt fragment simulators were pushed through fabrics gripped at the edges [2].

A ceramic blade with a root radius of 4 to 5 μm produced cut resistance values intermediate to the utility blade (2 μm) and the 20-μm steel blade for non-90° slice angles. These results are consistent with sharper blades cutting more easily. However, at a 90° slice angle, the 5-μm edge of the ceramic blade cut more easily than the 2-μm edge of the steel utility blade. This is explained by the plastic deformation and blunting of the steel blade, which resulted in the steel blade having a larger root radius than the ceramic blade. The ceramic blade did not dull significantly during the 90° cut.

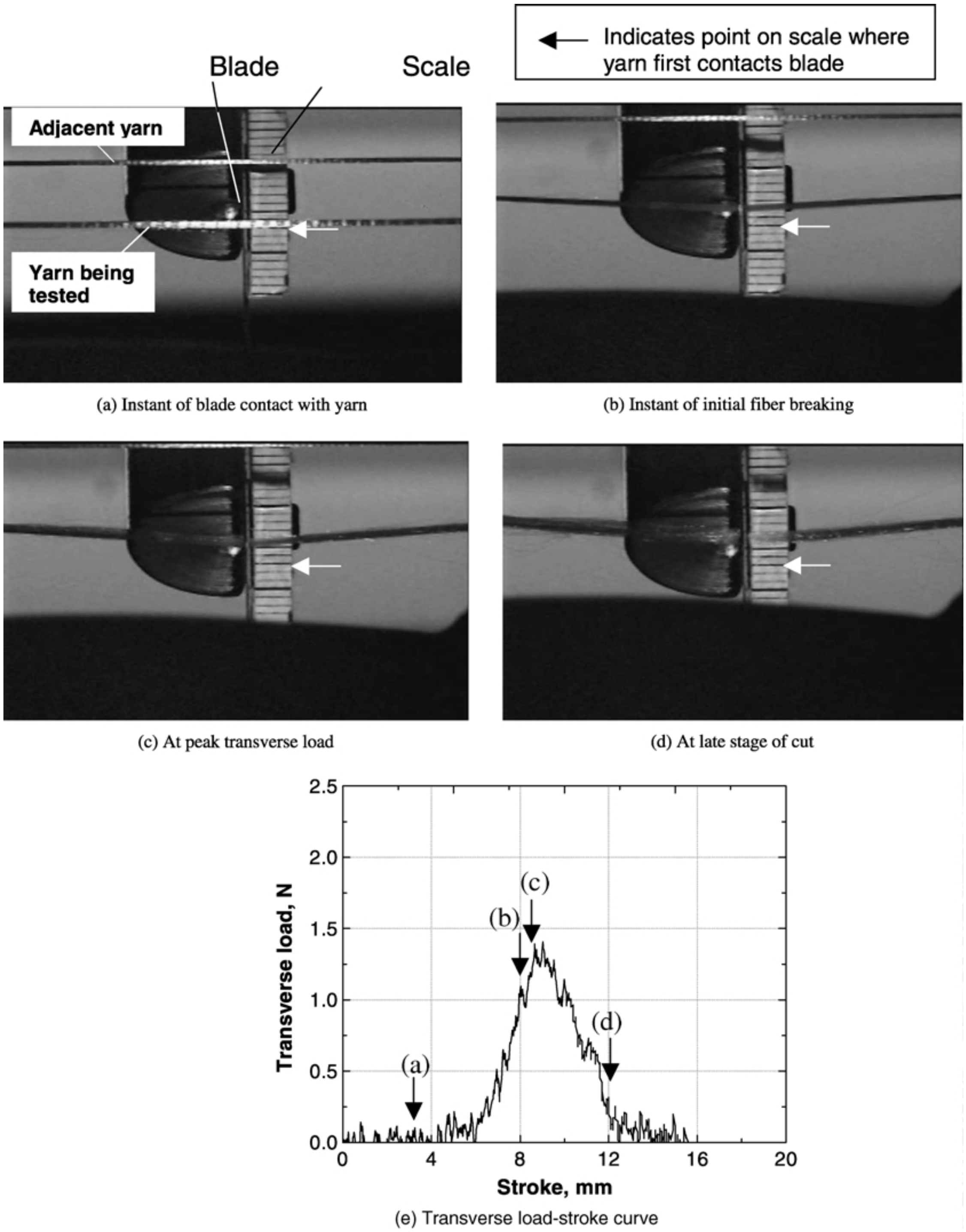


Figure 4 Videocamera images of blade-yarn interaction at 4 stages of a cut test and relation to load-stroke curve. (30° slice angle; no pre-tension, 6.46 in. gauge length. Arrow shows point on scale where blade first contacts yarn.)

4.3. Effect of pre-tension

Since fabric layers toward the back of a multi-ply fragment impact barrier will be stretched and loaded in tension before being contacted by the edge of a sharp fragment, it was important to measure the effect of pre-tension on cut resistance. The fixture in Fig. 1 was used to apply tensile loads of 1 lb and 3 lb per yarn, and cut tests were performed at a 90° slice angle. Fig. 7 shows the resulting stress-strain relations as well as those from a test at zero pre-load. Pre-tension shifts the curves to lower stresses and strains, results in earlier fiber failure, and reduces the cut energy.

5. Discussion

The test described and demonstrated here provides load-stroke curves, stress-strain curves, and cut energies for yarns under tension-shear cutting conditions. Such information, not provided by existing standard tests for cut resistance, is needed for finite element simulations and engineering design of fabric structures that protect against sharp fragments and other sharp objects. The test allows evaluation of the effects of slice angle, sharpness, and pre-tension, and despite the high sensitivity of cut resistance to contact parameters, provides good consistency and reproducibility. CCD camera

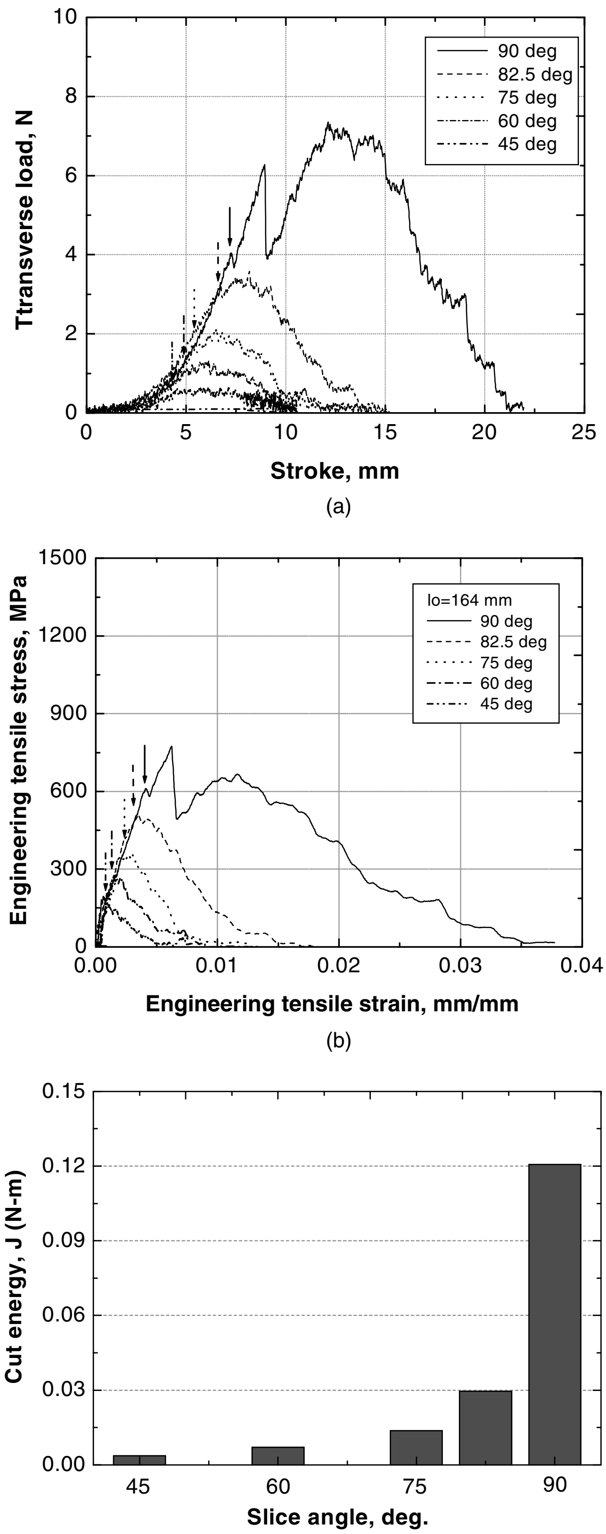


Figure 5 Effect of slice angle on (a) load-stroke curve, (b) stress strain curve, and (c) cut energy. (Arrows indicate where fiber failure first occurs.)

observations provided insight into the yarn failure physics underlying the measured cut resistance behavior. The cut energy per unit linear density is a useful material parameter for comparing the robustness of yarns of different materials and deniers.

The stress-strain curves suggest that yarns behave in a tensile manner in the early stages of deformation, but behave nonlinearly after fibers begin to fail (Fig. 5b). At all slice angles (except 90°), strength degraded monotonically as fibers progressively failed. The strain at which fibers begin to fail and the rate of fiber failure with strain are important parameters for modeling fabric cutting behavior.

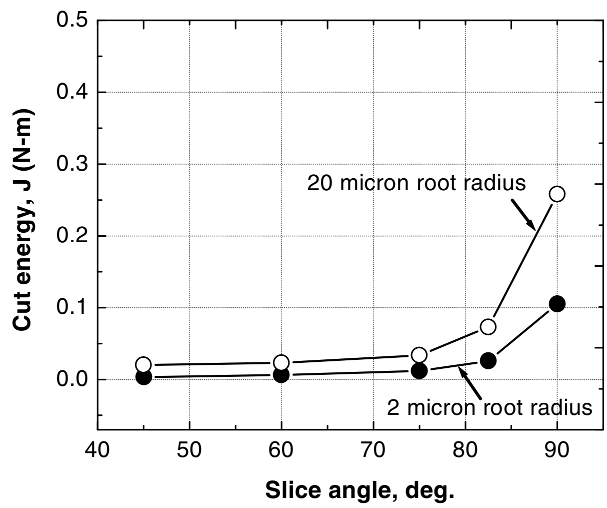


Figure 6 Effect of blade sharpness on cut energy.

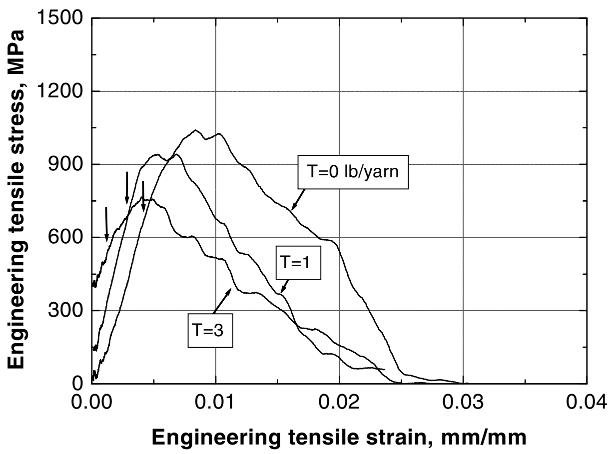
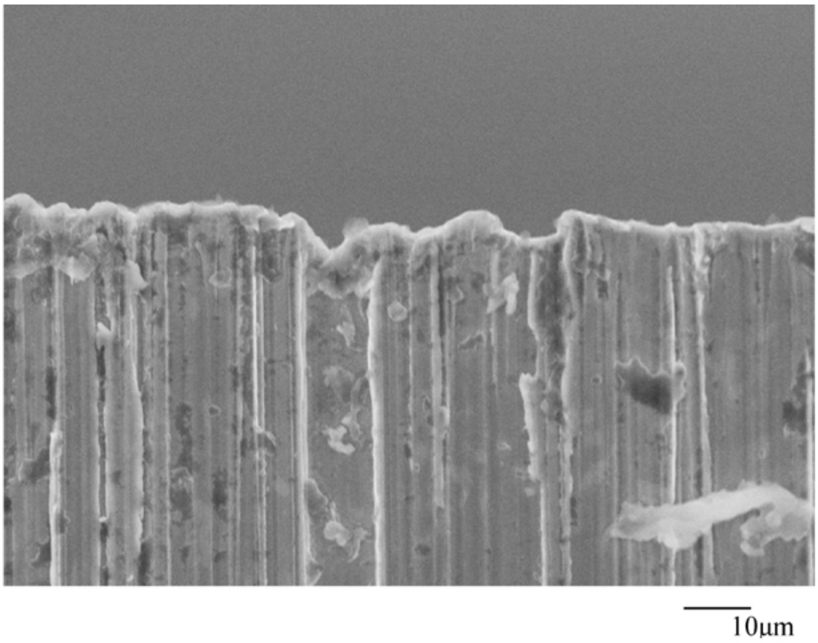


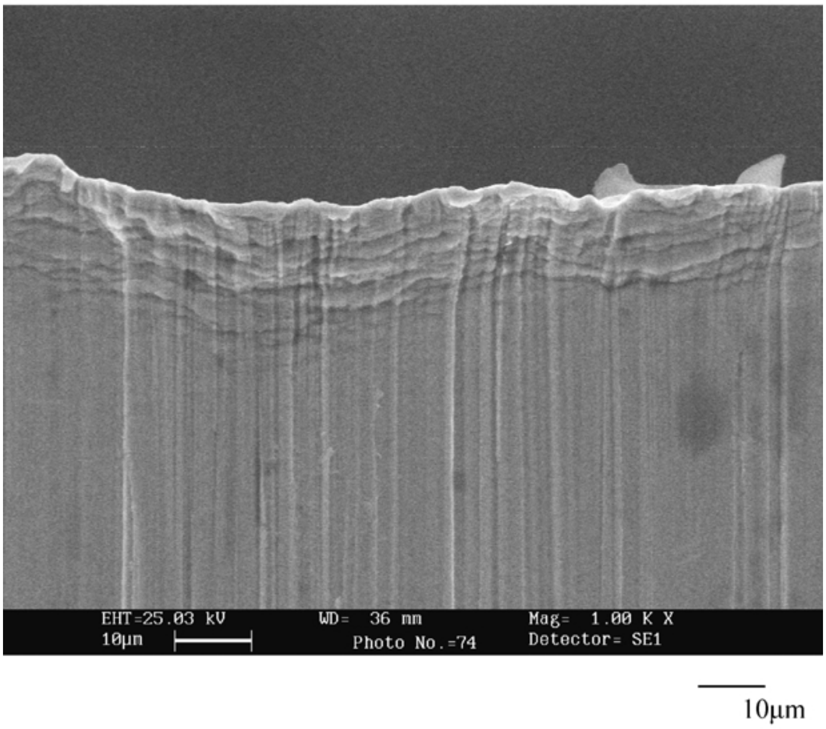
Figure 7 Effect of pre-tension on cut resistance at 90°.

The effect of slice angle is dramatic. Fig. 5c shows that the cut energy of a 500-denier Zylon yarn is 0.12 J when the blade edge is 90° to the direction of motion, but falls to 0.03 J (25%) at 82.5°, and less than 5% at a slice angle of 45°. Thus, the advantage of cutting fabric with an inclined blade is immense. The effect is due in part to the enhanced shear component imposed on the tensile state in the yarn and the exposure of fresh, sharp edge to the yarn as the blade advances.

The cut resistance of Zylon depends greatly on blade sharpness. Thus, the edge root radius must be specified during tests. Moreover, since blades deform and chip during testing, a new blade should be used for each test. Fig. 8 shows the significant deformation of a blade edge after a cut test at a 90° slice angle on Zylon. Tests performed at inclined angles expose new portions of the blade edge to the yarn because the yarn travels along the edge as the stroke increases. Thus, the cut energy is much lower than for 90° tests (Fig. 5c). Generally, a yarn will exhibit greater cut resistance to a blunter blade. A ceramic blade, by virtue of its high hardness, is



(a) Morphology of virgin blade edge



(b) Deformed blade edge after one cut test of Zylon yarn at 90°

Figure 8 Blade deformation resulting from cutting Zylon.

not expected to blunt as readily as a metallic blade, and hence may deliver reproducible results in multiple tests.

Insight into the cut resistance results and the dulling behavior of the blades was provided by scanning electron microscope (SEM) images of the failure surfaces of the fibers. The failed ends of fibers severed at a 90° slice angle were severely deformed, whereas the fiber ends from the 82.5° tests were much less deformed, and those produced with 60° and 45° slice angles showed little plastic deformation. These observations are consistent with the variation of the cut energies with slice angle shown in Fig. 5c.

The results and observations presented here are being used to refine a computational model of fabric response to impacting projectiles, extending penetration prediction capabilities from blunt fragments to include fragments with sharp edges. However, the cut resistance test is also expected to be useful in ranking textile materials for specific applications, developing computational models of the cutting process, devising techniques for fabricating holes and shapes in fabrics, and designing cutting instruments and protective clothing.

An early practical application of the results was the design of a tool to make holes in Zylon fabric. To evaluate the effectiveness of Zylon fabric in arresting fan blade fragments from a bursting turbine engine, full-scale ballistic tests needed to be performed on an aircraft fuselage with multilayer Zylon barriers installed in the fuselage wall. Since the barriers were required to be attached to the airframe by the fasteners that held the insulation blankets to the longerons and ribs, holes had to be made in the fabric. The high cut resistance of Zylon made this a formidable task. Several techniques were considered, including laser cutting, water jet cutting, mechanical coring, and punching with an awl. A simple and effective solution was devised from the results of the present study—a conical shaft with four equispaced steel/ceramic blades around the periphery and inclined at 45° to the shaft axis. When this four-bladed "arrowhead" was pushed downward and through a multilayer fabric barrier, yarns running in both directions in the fabric were sliced through, producing the 1.5 cm (5/8-in.) hole needed to accommodate the fabric on the posts on the airframe.

6. Conclusions

(1) The resistance of yarn to cutting in tension-shear can be measured reliably and reproducibly in a simple transverse load test. Special care is required to clamp the yarn securely to minimize slipping at the grips.

(2) Cut energy, determined from stress-strain curves, and the strain required to initiate yarn fiber failure are quantitative measures of cut resistance that should be useful in designing protective fabric structures.

(3) Cut resistance depends on test variables. Both cut energy and failure initiation strain decrease with decreasing slice angle, blade sharpness, and yarn pre-tension.

(4) The failure mechanisms of yarn fibers as observed in CCD images during testing and post-test SEM examination depend on test parameters and provide explanations for the dependencies in Conclusion 3.

(5) Cut resistance is highly sensitive to the condition of the blade edge. Proper evaluation of the cut resistance of high-strength yarn requires a well-defined blade edge and frequent discarding of used blades. Ceramic blades may be more efficient than metallic blades.

(6) Cut resistance of Zylon drops dramatically when the blade edge is even a few degrees from normal to the load direction, most likely because of the sawing action and the continual exposure of new sharp blade edge to the yarn.

Acknowledgments

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