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MECHANISMS OF IMPROVED BALLISTIC FABRIC PERFORMANCE (U)

F. FIGUCIA *
C. WILLIAMS
B. KIRKWOOD
W. KOZA

U.S. ARMY NATICK RESEARCH AND DEVELOPMENT LABORATORIES
NATICK, MASSACHUSETTS

Protection of U.S. infantry personnel in ground warfare environments requires constant technical vigilance on the part of Government scientists to assure that the most advanced state-of-the art is being implemented for the benefit of the soldier. This paper addresses that requirement as related to protection of personnel against fragmenting munitions.

Though the level of ballistic protection already achieved and currently being fielded exceeds anything ever developed in the past, the potential exists for even greater improvement in protection against fragmenting threats, and the need exists for protection against new threats. New developments in weapons technology utilizing surface coatings, novel shape factors and higher density materials continually challenge the level of protection achievable with existing armor systems.

A more intensified scientific approach must be devoted to the ballistic problem to provide adequate protection against the rapidly changing threat patterns in the field. The problem is a difficult one for a number of reasons. Fibrous materials have proven their worth both ballistically and functionally, but relatively little scientific information has been developed in this area as compared to other material disciplines. Penetration mechanics of such materials are physically unique and somewhat confounding, and are not clearly defined. Finally, scientific contributions from the private sector have been essentially non-existent due to the marginal commercial attraction of armor items.

It is expected that through this paper a firmer scientific base will be established and that the future use of this technology will eventually lead to a better understanding of the physical interaction between flexible fabric and penetrating projectile.

GENERAL APPROACH

The approach taken in this study is to analyze the projectile impact of a fabric in logical steps, and perform laboratory experiments to quantify the various physical responses which are active. The event involves a number of fiber characteristics and penetration mechanisms interacting in microseconds of time.

The process begins with the initial contact of a projectile upon an orthogonally woven fabric. This sets up a potential exchange of projectile kinetic energy into yarn tensile stress-strain energy. As long as the tensile mode of response remains in effect, the energy of the projectile is translated longitudinally along the yarns in continuous pulses which can be thought of as wavelets of stress-strain energy. These travel at velocities which vary with the crystalline character of the target material. The amount of yarn which becomes involved through this mechanism increases from the time of initial contact until the projectile penetrates the fabric and the strain is released.

At the same time as the in-plane exchange of energy takes place, projectile energy is also dissipated through fabric transverse motion. The forward thrust of the projectile carries target fabric out of its original plane. The displaced material takes the shape of a pyramid (1,2) whose base and height dimensions continually increase until penetration occurs.

The problem is approached through an analysis of the energy dissipation in these two modes (planar and transverse). Theoretical energy absorption is derived after quantification of appropriate parameters. The computation for planar energy encompasses penetration time, wave velocity, number of contacted yarns, and yarn energy absorption potential. Computation of the transverse component of energy involves the shape and dimensions of the fabric distortion, the average missile/fabric velocity, and the mass of the fabric displaced.

These computed energy absorptions are then compared with that measured in actual tests. The agreement obtained will establish the importance of the studied parameters and their application to future efforts in the field.

MATERIALS

The main thrust of this analysis was toward the behavior of woven fabrics as opposed to other constructional forms.

Fabrics representative of two polymer types were studied; nylon 66 (polyamide) and Kevlar 29 (polyaramid). Fabrics were selected with constructional features as nearly identical as possible. Characteristics of the two materials are tabulated below.

Table 1
Characteristics of Kevlar 29 and Nylon 66 Fabrics Used for Analysis

	Kevlar 29	Nylon 66
Polymer Type	Polyaramid	Polyamide
Yarn Fineness, Tex (Denier)	111 (1000)	117 (1050)
Weave	2 x 2 Basket	2 x 2 Basket
Weight, g/m^2 (oz/yd^2)	431 (12.7)	505 (14.9)
Yarns/cm, w x f	19.7 x 17.3	20.5 x 17.3
Yarn Crimp (%), w x f	10.1 x 1.0	12.5 x 4.5

Experiments were performed to obtain a) actual measurement of fabric energy absorption under ballistic impact and b) data with which to compute this energy based on hypothetical energy transfer modes. Measurement of actual energy absorption is described under Fabric Energy Absorption. The remaining experiments for yarn stress-strain properties, strain wave velocity, penetration time and transverse displacement were for computed data.

Fabric Energy Absorption

Tests to measure the energy absorption of single fabric layers were performed in two series using the two different fabric clamping arrangements depicted in Figure 1. The first uses a pair of aluminum plates between which the fabric is clamped. The target area is a 22.9 cm

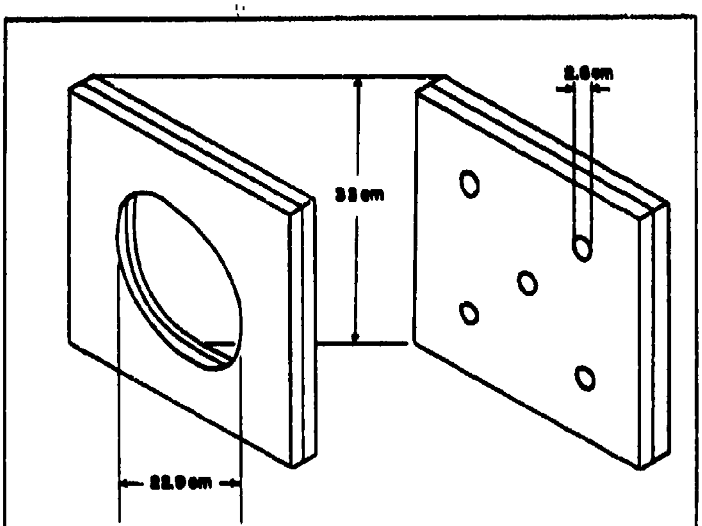

Figure 1. Fabric Clamps Used For Energy Absorption Tests.

diameter circle which has been cut out of the plates. The second clamp system has the same outside dimensions but uses thicker, heavier aluminum plates. Rather than using a single target circle, it has five 2.5 cm circles cut from the plates. This clamp was discussed in more detail in a previous report (3).

Energy absorption for Kevlar and nylon fabrics was measured using both clamping arrangements at projectile velocities ranging from stopping velocity to about 500 m/s. The test apparatus and methodology were described in a previous study (4). Briefly, the energy absorbed using either fabric clamp is computed from accurate measurement of projectile velocity before and after penetration using electronic sensing devices and digital counters. These velocities are converted to kinetic energy, the difference ($E_{in} - E_{out}$) being the projectile energy absorbed or transmitted to the fabric.

<u>Yarn Stress-Strain</u>

Tensile stress-strain curves were generated for individual yarns using an Instron Tensile Tester. A gage length of 12.7 cm was used with a crosshead speed of 5 cm/min resulting in a straining rate close to 40%/min.

Data at higher rates of strain will be referenced in the Discussion portion of this paper. These data were developed prior to this study using pneumatically driven tensile test equipment to achieve rates in the order of 3×10^4%/min. The best estimates of externally applied straining rates under ballistic impact are in the range of 10^6 to 10^7%/min.

<u>Strain Wave Velocity</u>

Measurement of strain wave velocity in the fabrics was made using an extension of a method developed by Koza (5) for similar measurements in single yarns. Fabric target samples were arranged as shown in Figure 2.

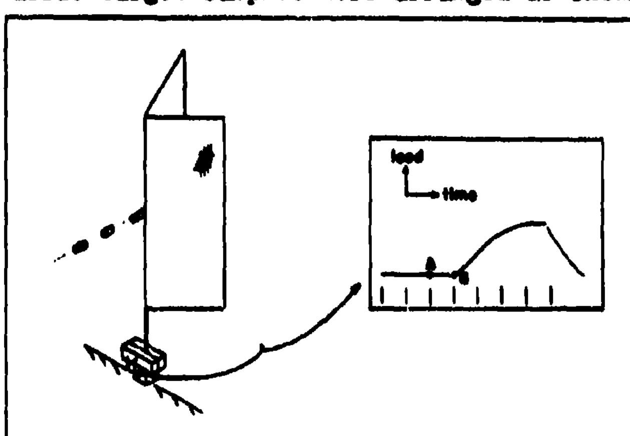

Figure 2. Test Setup For Fabric Strain Wave Velocity.

The fabric was clamped at the top but only 10 yarns extending from the bottom edge were clamped below. These were the ends of the same yarns to be contacted by the projectile at the center of the fabric. A piezoelectric crystal load cell was fastened to the bottom clamp as shown and its output directed to an oscilloscope. Knowing the distance between the load cell and the point of contact of the projectile with the fabric, it was only necessary to measure the time of travel of the wave over this distance to obtain wave velocity. To accomplish this the test was performed with the room in darkness and with a multiflash generator and camera set up to photograph the flight of the projectile. The first flash was synchronized with the sweep of the dual oscilloscope beams. The upper beam recorded load cell response vertically vs time horizontally. The lower beam gave a spike signal for each flash. The example in Figure 2 shows that the projectile contacted the fabric on the 3rd flash which on the load-time recording is a point of no apparent load (point A). The response of the load cell occurs at point B a measurable time later. The distance AB represents the travel time of the wave.

Wave velocities were measured in this way for both nylon and Kevlar fabrics in both warp and filling directions. Projectile velocities of approximately 305 m/s were used for these tests.

Penetration Time

The time elapsed during penetration was measured over the same range of projectile velocities as used for the fabric energy absorption tests. The fabric clamp with the 22.9 cm diameter hole in the center was modified to facilitate this experiment. A 0.6 cm slot was bored upward from the bottom edge of the clamp on the inside face of each plate. This relieved about 10 yarns from the clamping pressure during testing. These were the same yarns contacted by the projectile at the center of the target. They were extended downward to the clamp and load cell which were coupled together below the target as shown in Figure 3. Penetration time (t) was

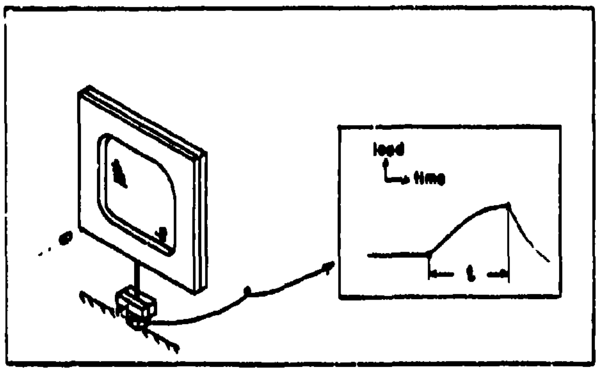

Figure 3. Setup For Penetration Time Tests.

measured from the oscilloscope force-time trace as that time from the initial response of the load cell to maximum load (penetration). Test specimens were oriented with the filling yarns vertical. Since these had less crimp than the warp yarns, sharper loading curves were produced.

Tranverse Displacement

The component of projectile energy transmitted transversely in the fabric is a function of the size of the fabric pyramid formed during penetration. The pyramid dimensions were measured from photographs of the exit side of the fabrics taken at projectile penetration (Figure 4).

Nylon Kevlar

Figure 4. Transverse Distortion of Nylon and Kevlar Fabrics at Penetration

Measurement of the base dimensions of the pyramid were made directly from the photographs which were actual size. The pyramid heights were measured from the peak of the extended pyramid back to the location of the point of initial contact of the projectile. This point was established as the intersection of the diagonals drawn from the corners of the pyramid base.

Projectile velocities for these tests were at the point at which penetration just takes place and the largest pyramids occur.

DISCUSSION

The energy absorbed by single layer fabrics under transverse impact is propagated by two mechanisms: a) tensile stress-strain work performed by the individual yarns acting within the fabric plane, and b) transverse kinetic motion of the displaced fabric mass. The in-plane energy absorption, E_p can be computed as the product:

$$E_p = 2(t)(c)(n)(E_y) \qquad \text{(Equation 1)}$$

where: E_p = Fabric in-plane energy absorption (J)
t = Penetration time (s)
c = Strain wave velocity in fabric (m/s)
n = Number of yarns under strain
E_y = Yarn energy potential (J/m)

The constant "2" accounts for the propagation of energy in both directions from the point of impact along the contacted yarns.

The transverse energy component, E_T, can be estimated from pyramid dimensions and projectile/fabric velocities as:

$$E_T = \frac{A W \bar{V}^2}{2} \qquad \text{(Equation 2)}$$

where: E_T = Transverse energy (J)
A = Area of pyramid base (m^2)
W = Fabric weight (kg/m^2)
$\bar{v}$ = Average velocity of projectile during penetration (m/s)

The input parameters to the above equations can vary substantially depending upon fabric construction and ballistic test conditions. These variables along with other relevent factors will be discussed in the following sections.

Failure Modes

The prediction of in-plane energy absorption by equation 1 is applicable as long as the resistance to penetration is through tensile work done by the yarns. It is probably fair to assume that tensile straining of yarns takes place, to some extent at least, in ballistic impacts of all fibrous materials. However the impinging energy will ultimately cause failure through the path of weakest resistance of a given material. Two such modes have been observed in previous ballistic experiments. They are failure due to low heat resistance (melting failure) and failure due to excess stiffness (brittle failure). These are illustrated in the scanning electron micrographs of Figure 5.

The polyamide fibers are representative of the nylon 66 used in this study. Melting is obvious at the broken fiber ends. Melting has also been noted on the surface of unbroken fibers outside the perimeter of missile contact.

Brittle failure is illustrated by an experimental polyaramid which exhibited poor ballistic resistance despite its high strength. The sharp transverse failure shown is typical of other high strength brittle fibers such as glass and steel.

Polyamide Experimental Polyaramid

Figure 5. Fracture Morphology of Fibers with Poor Heat and Shear Resistance.

Kevlar, which is also a polyaramid with brittle characteristics, apparently maintains sufficient shear resistance to withstand the transverse pressure of the missile. Figure 6 shows Kevlar fibers after ballistic impact. Neither of the failure modes of Figure 5 are evident. The fibrillated broken ends are typical of those from laboratory tensile tests.

Figure 6. Fibrillation of Kevlar Fibers After Ballistic Impact.

Yarn Stress-Strain Energy

The nylon and Kevlar yarns used in this study exhibit the characteristic stress-strain behavior shown in Figure 7 when tested at a quasi-static straining rate of 40%/min. Previous studies (6, 7) have shown that for tensile straining rates of 3 x 10^5%/min differences exist in the ultimate strength, ultimate extension and initial modulus properties.

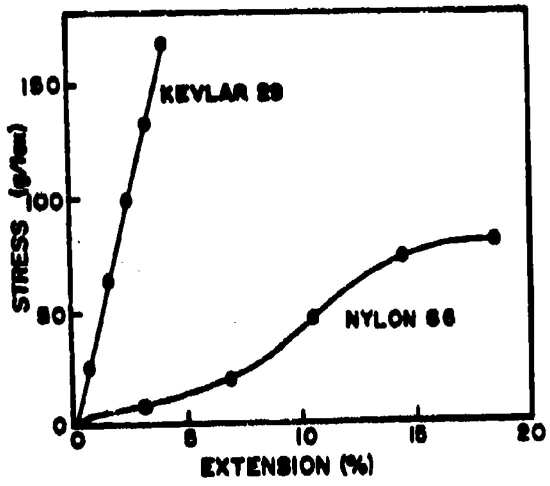

Figure 7. Stress-strain Behavior of Nylon and Kevlar Yarns.

However the energy absorbed by the yarns, as measured by the areas under the stress-strain curves, remains essentially the same as at the slow strain rate. Similar trends in tensile behavior have also been noted for a wide variety of other polymeric materials tested at high and low rates of tensile strain (8). Mechanical properties of nylon and Kevlar yarns at the two strain rates are shown in Table 2.

It is assumed for purposes of this study that yarn energy absorption at ballistic strain rates (estimated at 10^6-10^7 %/min) remains at the levels of Table 2. The conversion of Table 2 energy data to the units of equation 1 give E_y values of 3.9 J/m for Kevlar and 7.9 J/m for nylon.

Table 2

Tensile Properties of Nylon 66 and Kevlar 29 Yarns at Low and High Rates of Strain

	Nylon 66		Kevlar 29	
	L*	H*	L	H
Break Stress (g/Tex)	79	90	169	198
Break Extension (%)	19	16	4.3	3.7
Initial Modulus (g/Tex)	387	540	3700	5400
Break Energy (g/Tex)	7.4	7.3	3.5	3.7

*L = 40%/min strain rate
*H = 3 x 10^5%/min strain rate

Strain Wave Velocity

The longitudinal propagation of stress along single yarns has been treated theoretically by many researchers (9, 10, 11). In general, strain waves travel in continuous pulses from the point of stress (contact of projectile) outward along the yarn with a velocity (c) which is related to yarn modulus (E) by $c = (E/k)^{\frac{1}{2}}$ when E is expressed in textile linear density units. They continue until they lose their intensity or they reach a boundary such as a test clamp from which they are reflected back toward the point of impact. Some feel that this causes a multiplication of stress at the point of reflection which, given sufficient time, will cause failure at these locations. This may be a contributing factor to the change in response from tensile to other possible modes of failure discussed earlier.

Application of yarn wave theory to the fabric case is complicated by such reflections from successive yarn crossovers and also by the crimp formed in the yarns during weaving. Therefore it was decided that direct measurement of the wave velocity in the constructed fabric was the only appropriate method of analysis for this study. Tests were performed in both warp and filling fabric directions. Results were compared to previously obtained data for single uncrimped yarns and are shown in Table 3.

Table 3. Strain Wave Velocity Measured in Fabric and Free Yarn

	Strain Wave Velocity (m/s)	
	Kevlar 29	Nylon 66
Warp	900	900
Filling	5000	1000
Free yarn	7600	2400

Velocities are greatest in the uncrimped free yarns for both materials. Once these same yarns are woven into fabric however, the velocities are reduced due to fabric structural effects. The extent of this structural interference on wave velocity varies with fabric direction. It can be related to crimp in the manner shown in Figure 8. The superior wave propagation characteristic of uncrimped Kevlar is gradually reduced until this advantage is totally lost at approximately 10% fabric crimp. This result emphasizes the importance of fabric structural effects on ballistic performance. It has been shown(3,4) that Kevlar fabrics woven with a minimum of interlacings and yarn crimp (satin weave) perform significantly better than tighter weaves. This constructional advantage which had previously been attributed to improved transverse mobility is now shown to be related to in-plane energy parameters.

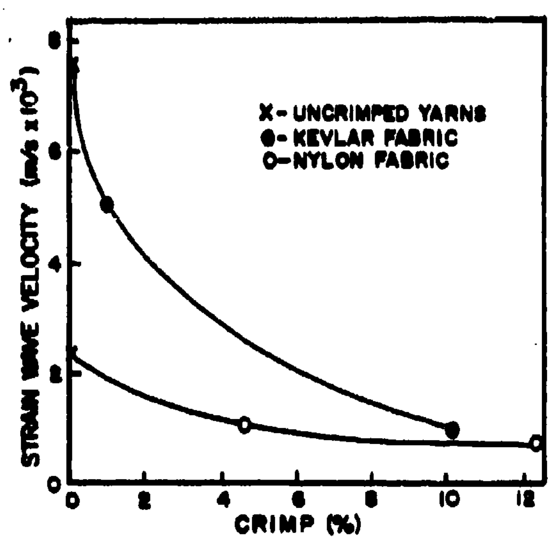

Figure 8. Effect of Fabric Crimp on Strain Wave Velocity

Penetration Time

Penetration time defines the period during which the yarns are under stress and therefore the distance travelled by the strain waves. Penetration times (t) were measured for input to equation 1 over the series of projectile velocities shown in Figure 9. Kevlar shows a distinct dependency on projectile velocity which reflects the reduction in extension with increased strain rate observed in Table 2.

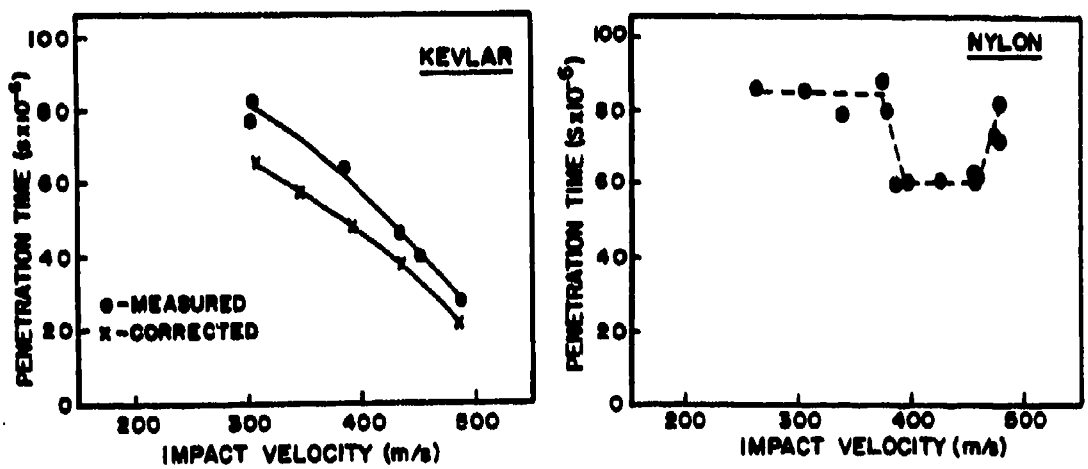

Figure 9. Effect of Projectile Velocity on Time of Penetration for Kevlar and Nylon Fabrics.

Nylon does not show the rate dependency of Kevlar but rather an erratic pattern which may have some explanation based on heat phenomena. No further attempt is made to explain these results at this time.

Alteration of the clamp faces to facilitate measurement of penetration time eliminated the barrier effect of the clamp on the waves traveling in one of the four directions away from the impact point. This undoubtedly increased the penetration time over that which would apply for a totally clamped fabric. A correction of 25% was used to reduce the values for Kevlar. A similar correction for nylon was not considered necessary since it does not appear that the tensile mode was active.

Transverse Energy

The amount of projectile energy lost through transverse fabric motion E_T is estimated from equation 2, which measures the kinetic energy of the displaced fabric mass at the average penetration velocity.

Measurements were made of the fabric pyramids formed during impact at velocities near that at which penetration just occurs and the largest pyramids are formed. E_T values obtained under these conditions were used to estimate those at higher velocities through the use of data of Roylance (2). This resulted in a reduction of transverse energy absorption with increasing impact velocity (Figure 10).

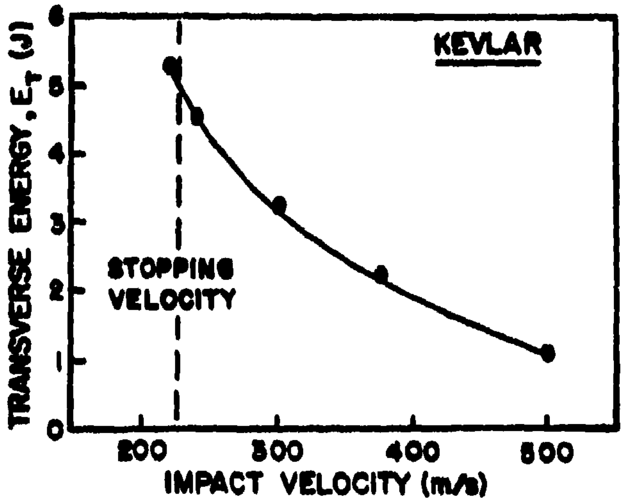

Figure 10. Effect of Projectile Velocity on Transverse Energy Absorption of Kevlar.

Theoretical vs. Experimental Energy Absorption

Single layer fabric samples were tested for energy absorption over a range of projectile velocities using 2.5 and 22.9 cm diameter clamps. Figure 11 shows the effects of the clamp boundaries on the results. The maximum energy absorbed by the two materials at the velocity of initial penetration (left most point) is reduced about 50% in going from the larger to the smaller target. This difference becomes smaller however as projectile velocity increases due to the accompanying reduction in penetration time and wave propagation distance. The reduction in energy absorption (50%) is not proportional to the ratio of target diameters (11%). Considerable yarn strain was evident in all directions beyond the 2.5 cm boundaries, indicating that the strain wave intensity was sufficient to force through the nearby boundaries resulting in more yarn involvement and energy absorption levels greater than predicted.

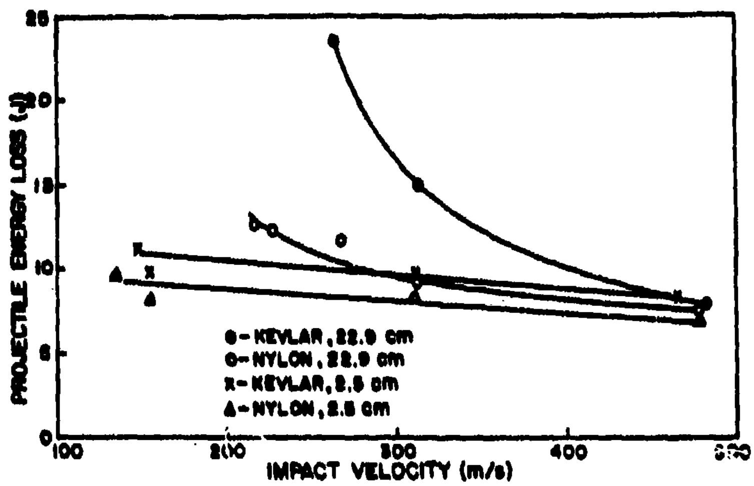

Figure 11. Effect of Clamp Boundaries on Experimental Energy Absorption.

The theoretical energy trend for the 22.9 cm Kevlar targets showed close agreement with that obtained experimentally (Figure 12). This

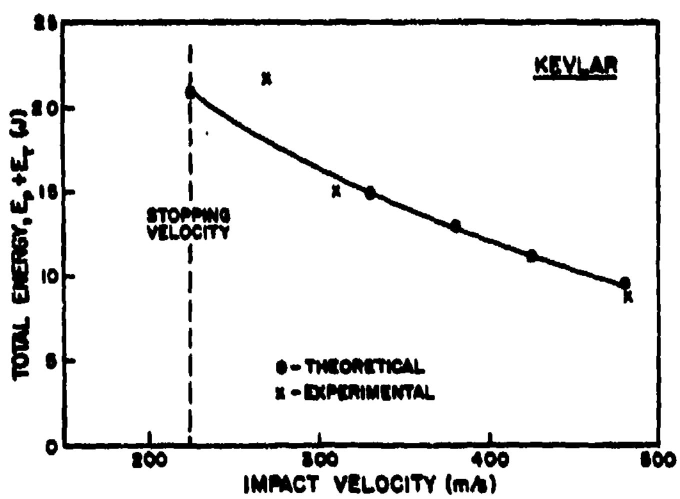

Figure 12. Comparison of Experimental and Theoretical Energy Absorption for Kevlar.

indicates that the tensile and transverse response modes predicted by equations 1 and 2 were active and the Kevlar achieved its maximum potential.

In the case of nylon (Figure 13), the theoretical energies were actually greater than those computed for Kevlar due to its superior yarn energy absorption potential. The experimental results however showed the actual performance of nylon to be in the range of 25-50% of potential. This inefficiency is attributed to the disruption of the idealized response pattern due to the influence of heat.

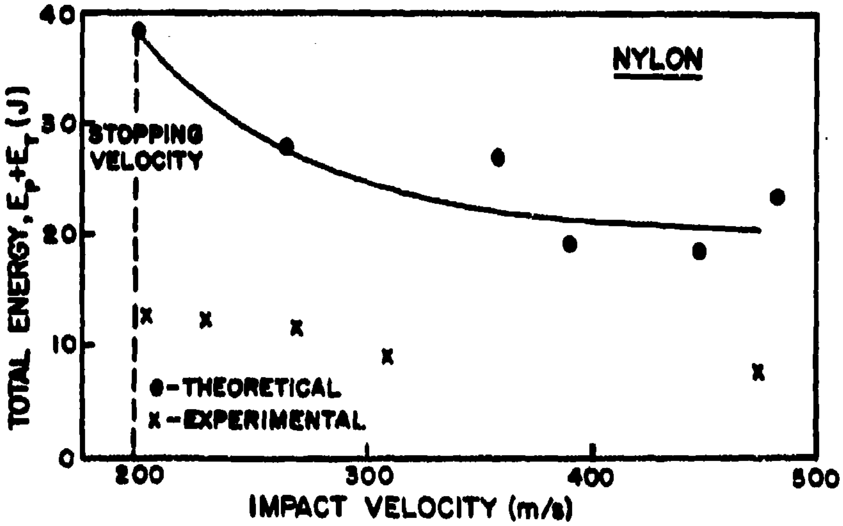

Figure 13. Comparison of Experimental and Theoretical Energy Absorption for Nylon

CONCLUSIONS

The energy from a ballistic projectile incident on a fabric target is dissipated through two distinct modes, namely energy absorbed within the fabric plane and energy exerted in displacing the fabric transversely.

Maximum ballistic resistance is achieved when the projectile energy dissipated within the fabric plane is absorbed through tensile resistance of the yarns. When this response mechanism is active, the time for projectile penetration is maximized, resulting in increased material involvement and increased energy absorption through both modes.

Performance models based on idealized tensile response and practical fabric parameters can be used to predict maximum expected energy absorption. Deviation from predicted performance is indicative of non-tensile failure responses such as melting and shear which severely reduce ballistic efficiency. The scanning electron microscope is a valuable device for verification of such failure patterns.

Strain wave velocity is the most important parameter influencing ballistic performance. Rapid propagation of stress away from the point of impact incorporates more material into the resistive process. It also distributes the energy such that the energy/mass ratio is kept below levels at which shear or heat failures may otherwise occur. Strain wave velocity is significantly affected by fabric construction. Potential for improved ballistic performance exists through loose fabric weave design and reduced yarn crimp.

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