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An Analysis of the System Effects in Woven Fabrics Under Ballistic Impact

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ABSTRACT

Following a brief review of prior work on fabric-based armor systems, the system effects that occur during the ballistic impact of woven fabric body armor materials are discussed from a conceptual framework developed to relate single yarn impact mechanics to fabric impact mechanics. The consequence of assembling yarns into single-ply fabric structures is discussed from this perspective. A steep strain gradient along yarns in the region of the transverse deflection of the fabric is related to the constraint imposed on them by neighboring yarns. Striking and residual velocity data, collected for single-ply fabric systems of Spectra®, Kevlar® 29, and nylon with various different yarn deniers and weave types, are used to establish the response of spaced armor systems. The system effects of assembling fabric plies into body armor systems are determined by comparing the response of spaced armor systems to actual multiple-ply systems. There is a pronounced decrease in energy absorption capacity for the Spectra and nylon systems; this deleterious effect is ascribed to increased transverse stresses and possible interference of the deflection characteristics of fabric plies by subsequent plies.

The objective of body armor research is directed toward managing the conflicting goals of producing low cost, lightweight, comfortable systems with superior ballistic protective performance. Research into the mechanics of ballistic impact of body armor materials has been the subject of active research since World War II. Over the years, the approach to body armor research has included projects of immediate expediency, such as comparisons of the ballistic performance of various armor systems [8, 12, 13, 21] to projects designed to elucidate the fundamental mechanics of ballistic impact.

The energy absorption characteristics of body armor systems under ballistic impact depend on material parameters such as material failure criteria and constitutive properties; construction parameters such as fabric type, number of fabric plies, and system areal density; and impact conditions such as projectile mass, striking velocity, striking obliquity, and geometry. Figure 1 illustrates typical energy absorption data for a body armor system against various right circular fragment simulators as a function of projectile striking velocity. The energy absorption curves of Figure 1 are for the current U.S. Army personnel armor system for ground troops (PASGT) vest, which is primarily composed of Kevlar® 29 with a lightweight nylon shell fabric.

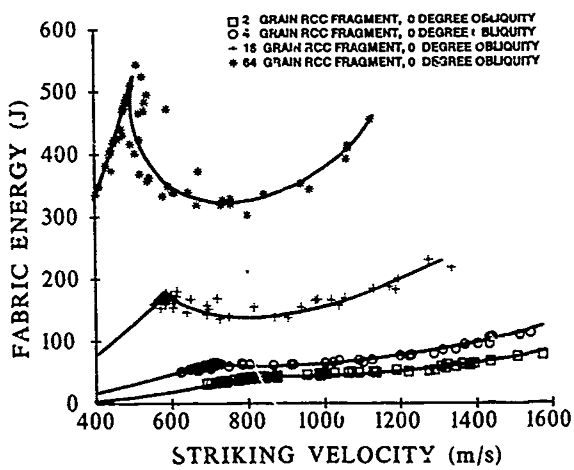

FIGURE 1. Energy absorption characteristics of the PASGT system. The energy absorbed by a fabric armor system increases with increasing projectile velocity up to the ballistic limit of the system; the energy absorbed by the system decreases rapidly as the projectile velocity exceeds the ballistic limit.

Fabric armor systems, such as the one whose energy absorption capacity data are illustrated in Figure 1, absorb all of the projectile energy up to the velocity where penetration begins to occur (ballistic limit). As projectile velocity is increased above the ballistic limit, energy absorption capacity decreases abruptly. Finally, within the limits of these experiments, system energy absorption capacity increases approximately in proportion to the projectile striking energy. This is illustrated in Figure 2, where the ordinate of Figure 1 was scaled by projectile striking energy and the abscissa was adjusted by the ballistic limit (Vc) for each projectile type. The ratio of fabric energy to impact energy tends to a constant value for each projectile type as striking velocity becomes much larger than the ballistic limit. Figures 1 and 2 illustrate some of the complexities of the response of body armor systems to ballistic impact.

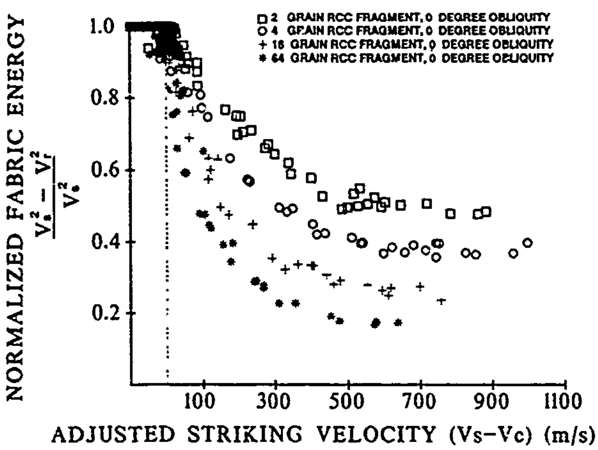

FIGURE 2. Normalized energy absorption characteristics of the PASGT system. At striking velocities well above the ballistic limit of the system, the energy absorbed by the system levels off and finally begins to increase approximately in proportion to the initial projectile energy. In the graph above, fabric energy was scaled by the striking energy, and striking velocity was shifted by the ballistic limit.

The complexity of the response of fabric armor to ballistic impact has precluded exhaustive experimental programs to permute single independent variables and observe changes in ballistic performance. Typical phenomenological studies have instead been forced to draw preliminary conclusions based on (necessarily) incomplete experimentation. Nevertheless, these studies [2, 9, 15, 19, 22 [1]] have significantly advanced the level of understanding of the impact event, particularly when viewed as a whole.

Experimental studies designed to elucidate the fundamental mechanics of ballistic impact [11, 17, 29] have been forced, with equal necessity, into similar circumstances. These studies have contributed such important information as the detailed deflection histories of several kinds of fabric under ballistic impact, approximate predictions of the distribution of energy in fabrics under impact, and approximations of the wave velocities in several fabric types. This information, however scarce, has been quite important as a source used to validate and benchmark more analytically correct models. Further research is required to determine the effect of projectile geometry on fabric failure, the relationship between material properties and construction parameters on transverse and longitudinal wave propagation characteristics, and the deflection histories of modern body armor materials.

The distinct possibility of a rate-dependent response of the polymers in a body armor system under the loading conditions typical of ballistic impact has further complicated the problem of fully understanding the response of these systems. A great deal of research has focused on this problem area [4, 14, 18, 20, 25]. These studies have typically concentrated on the response of single yarns to ballistic impact and have assumed tensile loading only. Further characterization of the constitutive properties of modern body armor materials is still required; some of that work is currently underway at our Center.

Numerical models to predict the performance of body armor systems have been the subject of considerable research, both here at the U.S. Army Natick Research, Development and Engineering Center (Natick) and elsewhere. These models provide the most acceptable promise of determining the trade-offs in performance characteristics due to variations in material properties. They may be viewed as tools of the materials engineer. Of course, they're not a panacea. We have estimated that the cost of computer run-time alone for a numerical simulation of the first 300 microseconds of the ballistic impact event for a system composed of, say, 50 layers of fabric, modeled at the level of detail of the individual yarn crossovers, would be far in excess of the cost of building and testing the system. The complexity of the problem has forced researchers to accept certain simplifying assumptions to make the problem more tractable. The approach to developing predictive models for the ballistic impact of body armor materials has been impeded by the lack of available detailed experimental data to validate the model assumptions. A brief review of past numerical modeling projects indicates some simplifying assumptions are typically used.

[1] The literature relating to ballistic impact of body armor materials is extensive. References cited in this introduction are intended to be demonstrative of a particular approach to ballistics research; a more complete bibliography is available elsewhere [3].

Vinson and Zukas [28] modeled multilayered body armor as a single constrained conical shell under quasi-static loading. The technique they used required complex experimental work to augment the numerical calculations. Results of the method outlined in their work incorrectly indicate ultimate strain approaches 185% for nylon fabric and the dynamic modulus of elasticity is only a small fraction of the static value.

Dent and Donovan [6] assumed that only the yarns directly contacted by the projectile absorb energy, and they were forced to incorrectly conclude that friction was the primary mechanism of energy transfer between the projectile and the fabric. Dent [7], in an attempt to refine that model, included the effect of crimp interchange, which he concluded was the primary mechanism of energy transfer.

Roylance [26] developed a model that attempted to capture the essential physics of the problem, provide insight into the impact mechanics, and keep the solution reasonably tractable. The model developed in that work still has much appeal. It included the assumptions that a multilayer fabric panel could be modeled as a single-ply pin jointed network, and that the impact could be approximated by point impact. The model indicated that the majority of energy absorbed by fabric under ballistic impact was due to strain and kinetic energy in the yarns directly in contact with the projectile. Roylance has recently extended the model to remove the point impact approximation [27].

Leech [10] developed finite element models for ballistic impact. While these models were more analytically rigorous than previous models, the lack of constitutive properties and failure criteria for body armor materials forced the conclusion, contrary to experience, that nylon body armor systems should outperform Kevlar systems at equal areal densities.

Researchers at Allied-Signal, Inc. have recently used the finite element analysis method to model the ballistic impact of composite materials for body armor applications [22]. In that work, the time step of the method and element spacing were modified so that the predictions of the model matched complementary experiment work. The model was used to determine failure criteria for the composite materials.

Quantitative experimental research relating to the response of body armor materials under ballistic impact is still required. In particular, histories of the transverse deflection of fabrics with differing construction characteristics and material properties would be highly desirable. Problematic areas, such as whether the transverse deflection characteristics of the first plies of a multiple-ply system of armor are repeated in subsequent plies or whether the time to failure of the first plies of a multiple-ply system is closely followed by the failure of subsequent plies, will ultimately be resolved through experimentation. These and other research projects are planned at this Center and at other research centers. Expediency dictates immediate answers, however, and some are in fact possible without extraordinary effort.

A qualitative understanding of impact dynamics may be developed from an understanding of less complex fabric systems and applied to more complex systems. This qualitative understanding of the impact event can be used to direct experimental work and guide model developers in selecting simplifying assumptions in their work.

In this paper, we have developed a qualitative description of the impact event using results from archival photographs of single layers of fabric under ballistic impact, available numerical models, and single yarn impact theory. This conceptual framework is extended, using results from striking and residual velocity experiments performed on single layers of fabrics, to help explain system effects that occur in multiple-ply armor systems.

Fabric Impact Mechanics— A Few Photographs

Some intuition about the mechanics of ballistic impact can be gained by inspecting a few photographs of single layers of fabric under ballistic impact. Figure 3 is a photograph of a single layer of 1000 denier (0.129 g/cm^2) Kevlar 29 fabric impacted at 254 m/s. It is apparent that some material outside the area of fabric

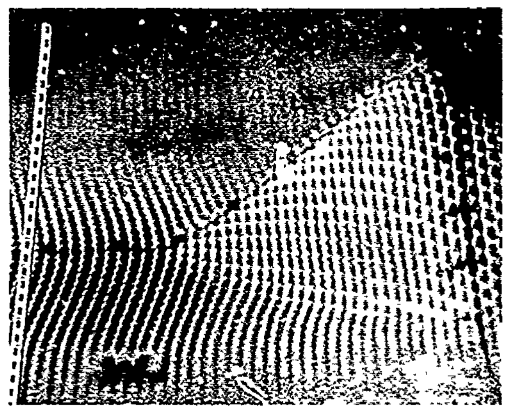

FIGURE 3. Effect of longitudinal wave propagation. In fabric armor systems under ballistic impact, material outside of transverse deflection streams inward toward the impact point, and is clearly under strain.

involved in the transverse deflection streams inward toward the impact point. The photograph shows that the extent of fabric deformation is greatest near the yarns that cross over the impact point. Apparently, yarns that cross the impact point have either undergone a greater extension than yarns, say, a few projectile diameters from the impact point, or have been under strain for a longer period of time, or both.

Figure 4, a photograph of a similar impact event, is a multiple exposure of a 200 denier (0.011 g/cm^2) Kevlar 29 fabric under impact at 250 m/s. Successive images of the fabric under impact were taken at 26, 63, 101, and 137 μs after impact. This photograph better reveals the significant curvature in the transverse deflection. The curvature in the material involved in the transverse deflection is thought to indicate a strain gradient in the material in that area.

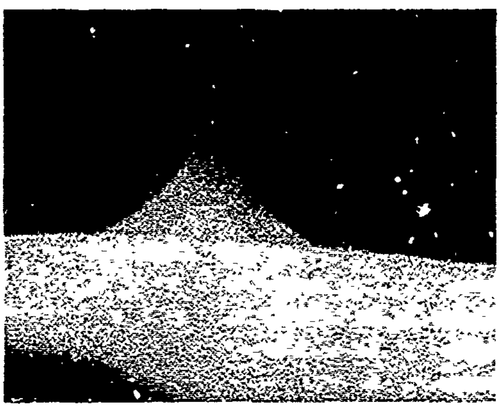

FIGURE 4. Transverse wave profile. The transverse deflection of these fabrics shows significant curvature, which implies that strain in the fabric decreases with distance from the impact point.

Further intuition about the mechanics of body armor materials under ballistic impact may be gained by applying the principles of single yarn impact mechanics to the information gained from inspecting the photographs. Many excellent references are available that detail the mechanics of yarn impact [4, 14, 18, 20, 25]. Briefly, when a single yarn is impacted by a projectile, a tent-shaped transverse deflection develops in the yarn with the projectile at the apex of the tent. At the instant of impact, a strain develops in the yarn and propagates away from the impact point at the speed of sound in the material. In the wake of this strain wave (or longitudinal wave), material is set in motion inward toward the impact point. The inwardly flowing material feeds the developing transverse deflection. In single yarns of most materials, the transverse deflection angle and the magnitude of strain in the wake of the longitudinal wave are constant.

In a single layer of fabric armor, analogous transverse and longitudinal waves develop and propagate away from the impact point in the impacted (or principal) yarns. The dashed line in Figure 3 illustrates the extent of deformation of the fabric at points far from the impact point. Vertical yarns in the photograph at points far from the transverse deflection appear to bow inward toward the impact point. The extent of deformation of these yarns appears to correspond to the extent of the transverse deformation of the fabric.

Apparently, a longitudinal wave in yarns not directly contacted by the projectile is driven by the transverse deflection of the principal yarns. The effect can be visualized by considering the impact of the principal yarns and neighboring crossing yarns as separate but coupled events. One can visualize the transverse deflection of the principal yarns pulling crossing yarns not in contact with the projectile out of the original plane of the fabric as the transverse wave develops. Since the transverse deflection of the principal yarns drives orthogonal yarns not in contact with the projectile out of the plane of the fabric, these latter yarns may be considered to experience an effective transverse impact. In turn, these yarns will develop transverse and longitudinal waves and assist the principal yarns in driving transverse and longitudinal waves in their neighboring yarns. This description of the impact event for fabric systems leads to the conclusion that the location of the strain front in adjacent yarns is a function of the transverse wave velocity and the end and pick spacing in the fabric.

This explanation of the impact event helps explain the bow in yarns far from the impact point. In a single yarn, the longitudinal wave speed is a material property; it's equal to the square root of the specific modulus of elasticity for most materials. Although the apparent longitudinal wave speed may be affected by construction parameters in woven fabrics, as suggested by Roylance [26], it's usually assumed to be a material property [7, 10]. Assuming a constant strain wave velocity, the location of the longitudinal wave front in adjacent yarns should be similar to the shape of the transverse wave front.

Clearly, one would expect some feedback in such a system. As the principal yarns drive the transverse deflections in neighboring crossing yarns, the crossing yarns inhibit the motion of the principal yarns. Since the principal yarns in the fabric are constrained from below by crossing yarns, and driven from above by the projectile, one would expect the consequence of this

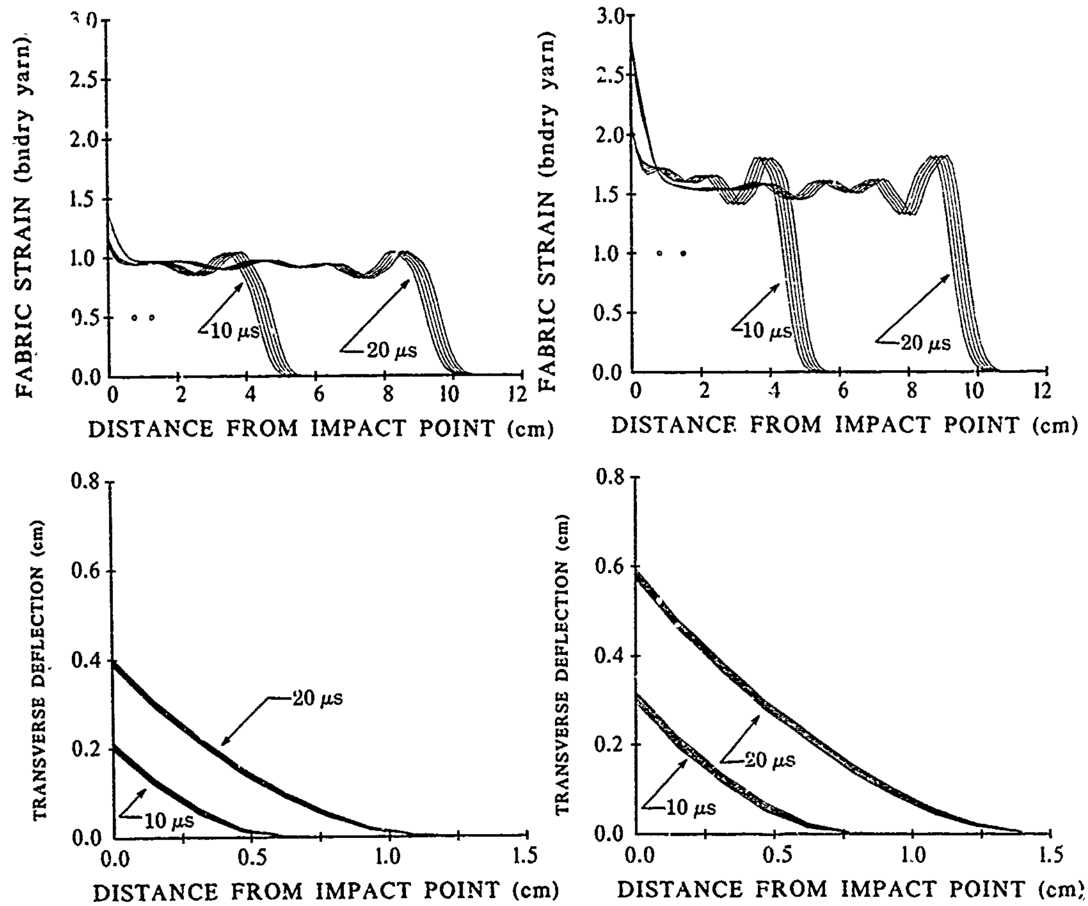

FIGURE 7. Predicted strain and deflection profiles of fabrics. Predictions of a direct analysis computer program for ballistic impact similar to the one developed by Roylance [26] indicate that strain in the wake of the longitudinal wave is approximately constant, that there is a sharp strain gradient in the neighborhood of the transverse deflection, and that the angle between the undeformed fabric and the transverse deflection becomes steeper with increasing projectile velocity. Figures on the left correspond to an impact velocity about equal to the ballistic limit of the system (200 m/s), figures on the right are for an impact velocity of 300 m/s. System modeled was a single layer of Kevlar.

terms of the performance of a system of yarns. This understanding of single layer fabric mechanics permits investigation of the system effect of combining single layers of fabric into a body armor panel. The consequence of constraining the transverse deflection of the principal yarns in a single ply of fabric is the development of a tensile strain gradient in the region of the transverse deflection. It's perhaps natural to assume that in a multilayer body armor panel, the transverse deflection of the first fabric layers is constrained by the subsequent plies. Our intuition is that this constraint should amplify the tensile strain gradient in the transverse deflection. Consequently, multiple-ply fabric body armor systems should fail at lower impact velocities than a collection of single-ply fabrics.

On the other hand, examination of the transverse deflection of single-ply systems indicates that the transverse deflection angle is related to impact velocity. Considering that individual layers of a multiple-ply body armor system are usually separated only by a fraction of a millimeter, it is possible that in a multiple-ply system the contact between layers could be concentrated at the impact point. Presuming the transverse deflection angle of the first ply is reproduced in each subsequent ply of the fabric panel, the subsequent plies translate together, and hence would provide little resistance to the transverse deflection of the first plies.

The transverse shear and compressive forces acting on the first plies of a multiple-ply system increase with additional plies and with additional projectile velocity. The possibility of shear or compressive failure of the yarns at the impact point cannot be overlooked [23].

The extent that the additional resistance to the transverse deflection of the individual plies degrades the performance of a multiple-ply system over the performance of a system of spaced armor is difficult to separate from the extent that the increase in shear and compressive forces at the impact point reduces performance. However, the combined system effects may be quantified and examined for different armor systems.

Experimental

We determined the striking and residual velocity characteristics of the fabrics listed in Table I for an XX[2]-grain chisel-nosed fragment simulator. The samples were clamped between thick aluminum plates with 1-, 2-, 4-, and 8-inch apertures and impacted in the center of the aperture. The various apertures were used partly for economy, partly to determine the response of the constrained fabric, and partly to establish a data base of the performance of single plies of fabrics under impact. While extensive data bases exist for the ballistic response of multilayered body armor systems, relatively little information is available for the ballistic response of single plies of these materials. For obvious reasons, the single-ply ballistic response of fabrics is the most desirable starting point for verifying numerical models to predict ballistic performance.

The effect of the different apertures on the ballistic performance of the 215 denier Spectra® fabric is illustrated in Figure 8. The effect of sample holder aperture size for this Spectra fabric was typical of all the fabric systems tested. Examination of Figure 8 indicates that the ballistic performance of the fabric was strongly affected by the sample holder aperture size at impact velocities near the ballistic limit of the fabric, but the effect of sample holder aperture size decreased rapidly as the impact velocity exceeded the ballistic limit. The smaller aperture size provided several constraints to the fabrics. First, the smaller holes constrained the transverse deflection of the fabric; second, the sample holders constrained the longitudinal deflection of the fabric. The constraint to longitudinal deflection extended closer to the impact point for the smaller aperture sample holders. We noted, however, that the sample holders were not very effective at fully constraining the longitudinal deflection of the fabrics. Some slippage of the fabric between the plates of the sample holders occurred for each fabric in each sample holder and over the entire range of test velocities. There was no clear correlation between clamping pressure and ballistic performance.

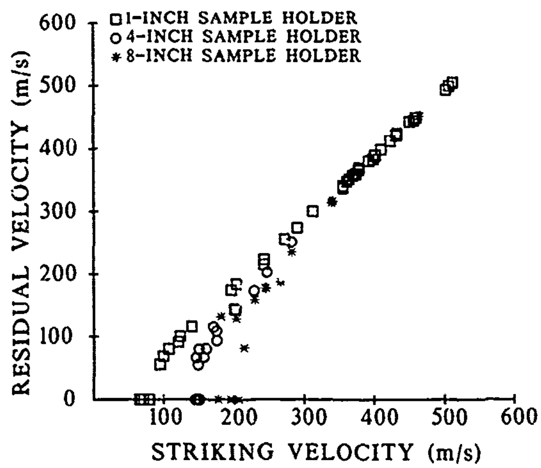

FIGURE 8. Typical striking and residual velocity data for single-ply fabric. The striking (V_s) and residual (V_r) velocity characteristics of single plies of the fabrics of Table I were determined using the sample.

The energy absorption characteristics of the fabrics were determined from the striking and residual velocity

[2] Some of the data of the ballistic tests would require a Confidential security classification if the characteristics of the projectile were fully identified. Omitting the projectile mass permits free disclosure of the test data and does not significantly affect discussion of the results. In addition to omitting the projectile mass, the energy absorption curves have been scaled by an undisclosed number to preserve the security classification of this report. Note that the response of fabric systems is strongly affected by projectile characteristics. The results and conclusions of this report are based on the performance of fabric armor systems under impact by one projectile type only and therefore must be considered preliminary.

TABLE I. Fabric characteristics.

Material	Denier	Fabric weight, oz/yd²	Fabric weight, g/cm²	Ends/picks, per cm	Weave
Kevlar 29	1500	14.0	0.048	13.4 × 13.4	2 × 2 basket
Kevlar 29	1000	8.7	0.029	14.7 × 14.7	plain
Kevlar 29	200	3.2	0.011	25.2 × 24.8	plain
Spectra 1000	650	6.5	0.022	13.0 × 14.2	plain
Spectra 1000	375	5.2	0.018	19.7 × 20.1	plain
Spectra 1000	200	3.3	0.011	21.7 × 22.0	plain
Nylon	1500	14.0	0.048	13.4 × 13.4	2 × 2 basket

data; a typical plot of system energy absorption is provided in Figure 9. Examination of this figure indicates that the energy absorbed by the fabrics reaches a maximum at the ballistic limit and sharply decreases as projectile velocity increases. Several of the energy absorption curves indicate a leveling of the energy absorbed by the fabric at high impact velocities, and some of the energy curves suggest a slight increase in fabric energy absorption at velocities much higher than the ballistic limit. The eventual increase is typical of multiple-ply fabric armor systems at velocities well above the ballistic limit, as illustrated in Figure 1.

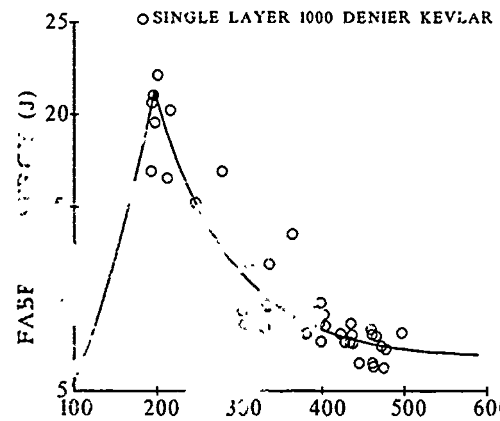

FIGURE 9. Typical energy absorption characteristics for single-ply fabric. The energy absorption characteristics of the fabrics in Table I were determined from the $V_s - V_r$ data. A typical plot is illustrated above. Fabric energy absorption is seen to decrease rapidly as the projectile velocity exceeds the system ballistic limit.

Discussion

The decreased energy absorption capacity of single plies of the fabrics under ballistic impact is consistent with the previous description of fabric mechanics. As discussed earlier, the impact-induced steady-state strain in the wake of the longitudinal wave increases with increasing velocity, and the strain gradient in the neighborhood of the transverse deflection becomes amplified as projectile velocity increases. Strain at the impact point exceeds the failure strain of the material more rapidly under these conditions: less material is placed under strain, and consequently less strain energy is absorbed by the material.

The energy absorption curve for each fabric of Table I was normalized by fabric areal density and plotted against a common pair of axes in Figure 10. The specific energy absorption curves indicate the potential ballistic performance of the various fabrics. Figure 10 indicates the superior performance of the Spectra material over the other fabrics, but the extraordinary performance potential of woven fabric Spectra suggested by both its single-layer ballistic performance and its tensile properties has not been fully realized, at least not for military body armor applications.

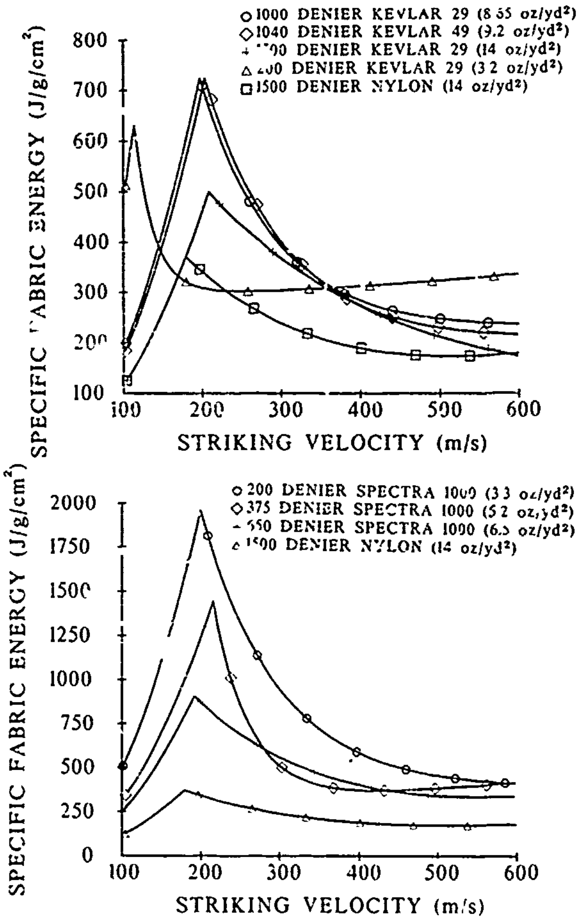

FIGURE 10. Specific energy absorption curves for single-ply fabric systems were determined for each fabric system by normalizing the fabric energy absorption curve by fabric areal density. The specific energy absorption curves give an indication of multiple-ply armor system potential. However, due to system effects of combining single plies of the material into body armor panels, the potential may not be fully realized. The legends used in the graphs above refer to various line styles used to draw respective curves.

In a multiple-ply fabric system, the force acting on the projectile is due to the component of tension in the direction of projectile velocity in the principal yarns of each layer of fabric. Each layer transfers the force from the principal yarns through previous layers to the projectile. In such a system, the transverse stress components at the impact point in the first layers are obviously affected by the subsequent layers. Where these stresses are large in comparison to the ultimate compressive or shear strength of the material, adding subsequent plies will adversely affect the performance of the system.

Additionally, we speculated that adding subsequent plies may constrain the transverse deflection of the first plies. This sort of constraint is expected to amplify the concentration of tensile stresses in the neighborhood of the transverse deflection and consequently adversely affect system performance. Several empirical observations reinforce this assumption.

EFFECT OF CONSTRAINING THE TRANSVERSE DEFLECTION

Hearle [10] photographed the transverse deflection of two-ply systems of Kevlar with alternating plies set on the bias. He noted the transverse deflection of these systems was octagonal, but he did not determine the ballistic limit of the system. In this system, the first ply clearly drives the transverse deflection of the second, and clearly the first ply is constrained by the second. However, transverse stresses at the impact point are similar for bias-ply systems and orthogonal systems. We used the 1000 denier Kevlar 29 fabric of Table I in our laboratory to reproduce this experiment. The peak energy absorption capacity of the two-layer bias ply system was over 30% less than the two-ply system with warp yarns in the same direction.

To illustrate the effect of constraining the transverse deflection of fabrics, we tested several heterogeneous systems of woven fabric. The first system, composed of one ply of 1000 denier Kevlar 29 fabric backed by one ply of 375 denier Spectra 1000 fabric, had a ballistic limit of 269 m/s. The second system reversed the order of the fabrics. The ballistic limit of the second system was only 114 m/s; the system with Kevlar material on the back face of the fabric panel reduced energy absorption by over 80%.

In a similar experiment, one ply of 1000 denier Kevlar 29 fabric backed by one ply of 1040 denier Kevlar 49 fabric provided ballistic performance equivalent to the same system with Kevlar 49 on the impact face.

In the Kevlar 29/Spectra 1000 experiment and Kevlar 29/Kevlar 49 experiment, the mismatch in material properties should have produced a mismatch in transverse deflection signature: the higher modulus material should have had a wider transverse deflection. Presumably, when the high modulus material was on the impact face of the panel, the transverse deflection of the first ply should have been constrained by the more narrow transverse deflection of the second ply, and the transverse deflection of the second ply should have been driven by the first. Reversing the order of the plies should have eliminated the contact between layers, except at the impact point. However, only the Kevlar 29/Spectra system showed a significant difference in ballistic performance.

Hence the results of these simple experiments are somewhat inconclusive. The results of the Kevlar 29/Kevlar 49 experiments seem to refute the speculation that interference of the transverse deflections will degrade ballistic performance. Nevertheless, significant evidence does exist to warrant further investigation of these effects.

RESPONSE OF SPACED ARMOR

The extent that system effects are significant in body armor materials is reflected in the difference in performance between a system of spaced armor and a more traditional edge-sewn and clamped fabric armor panel. If a system of armor were constructed with sufficient spacing between the layers so that no two layers were in contact during the impact event, the ballistic performance of the system would be exactly equivalent to the sum of the single-ply performances. Such a spaced armor system removes all multilayer system effects. Since the performance of a spaced armor system is exactly equivalent to the sum of the single-ply responses, the system effects of multiple-ply armor systems can be determined by determining the performance of a spaced system using the single-layer response and comparing the difference in performance to multiple-ply systems.

As discussed earlier, certain deleterious effects may be ascribed to local yarn slippage about the impact point. However, these effects are presumed to be evident in the single-layer response of the fabric and are not expected to become more pronounced in multiple-ply systems. We assume that system effects are due to additional local transverse shear and compression near the impact point due to the additional plies and to additional constraint of the transverse deflection due to the additional plies.

We determined the performance of spaced armor systems from the single-ply striking and residual velocity data using an iterative procedure. Experimental data for each system were curve-fit to a semiempirical expression derived to express projectile residual velocity as a function of impact conditions and system characteristics [2]. This equation was then used to determine the maximum velocity that would yield a residual velocity exactly equal to the ballistic limit of a single ply for the fabric under consideration. That velocity was then taken to be the ballistic limit of a two-ply system of spaced armor. The iterative procedure was continued for subsequent plies until the striking velocity approached the upper limit of the experimental data.

We determined the performance of spaced armor systems for each of the fabrics of Table I from the striking and residual velocity data for single plies of these fabrics. The energy absorption capacity of spaced armor systems (smooth curves) is plotted as a function of areal density, along with the performance of edge-sewn and clamped systems (figures) in Figure 11.

The consequence of reducing the denier of the Kevlar material from 1500 to 1000 (and consequently reducing the fabric weight) increased the specific energy absorption capacity of the single-layer systems at low impact velocities (as illustrated in Figure 10) and reduced the deleterious systems effects observed in the 1500 denier system (as illustrated in Figures 11b and c). The consequence of further reducing the denier of the Kevlar material from 1000 to 200 (with additional reduction in fabric weight) reduced the specific energy absorption capacity of single plies of the fabric at low impact velocities (see Figure 10). However, single plies of the lightweight Kevlar fabric provide superior specific energy absorption capacity at striking velocities over 400 m/s. Additionally, we saw a synergistic effect when we tested multiple-ply panels of this fabric at low-impact velocities, as illustrated in Figure 11a. The exact nature of the synergistic effect is not fully understood at this time, but it appears that shear and compressive failure of the Kevlar material are no more pronounced in multiple-ply systems than in single-ply systems.

Figures 11d-g illustrate that the energy absorption capacity of the Spectra and nylon fabric panels is significantly reduced from the equivalent spaced systems. In the Spectra systems, reducing yarn denier (and also fabric weight) consistently increase the specific energy absorption of single plies of the fabric (see Figure 10) but also increased deleterious system effects (Figures 11e-f). It is well known that the transverse properties of the Spectra material are inferior to the axial properties; such orthotropic material properties exist in most highly crystalline fibers including Kevlar. Howeve , the torsional shear modulus of the Kevlar material is over four times as great as the nylon material [16]. Perhaps the more pronounced system effects in the Spectra and nylon systems may be attributed to their relatively poor transverse properties. A more thorough determination of the transverse properties of these materials is somewhat difficult.

An accurate determination of the axial properties of body armor materials is possible [4]; such a determination of the transverse shear and compressive properties is more tenuous, but may be approximated using a method similar to the one described by Prevorsek [22]. This method requires an accurate determination of the axial properties of the body armor material, detailed experimental results from ballistic impact of fabrics, and an accurate predictive numerical model for the ballistic response of fabrics.

Conclusions

In this report we have developed a conceptual framework to relate the response of single yarns under ballistic impact to single layers of fabric under ballistic impact. This description of the ballistic event for fabrics is used to explain the deflection characteristics of actual fabrics under ballistic impact. We conclude that a steep strain gradient exists in the neighborhood of the transverse deflection of fabrics under impact. This strain gradient is understood to be a consequence of the constraint to transverse motion of the principal yarns (or yarns in direct contact by the projectile) by neighboring orthogonal yarns. Interaction between the principal yarns and orthogonal yarns is described as a separate ballistic event with feedback. This description is also used to describe far-field effects observed in actual fabrics under impact. In such fabrics, yarns appear to bow inward toward the impact point at distances far from the transverse deflection. This effect is understood to be a consequence of friction between yarns passing through the transverse deflection (which are described as being under high strain) and orthogonal yarns (which are understood to be under lower strain).

We have compared the ballistic performance of multiple-ply armor systems to the performance of equivalent spaced armor systems to evaluate system effects that occur in actual body armor systems. These effects are described as a combination of several effects, including possible interference of the transverse deflection of the first plies of a multiple-ply system by subsequent plies, and the effect of increased transverse stresses on the first plies of a multiple-ply system due to forces in the subsequent plies. These system effects are more significant for some systems than for others.

Several small-scale experiments used to elucidate the effect of constraint of the transverse deflection in fabrics show pronounced effects in some of the materials but

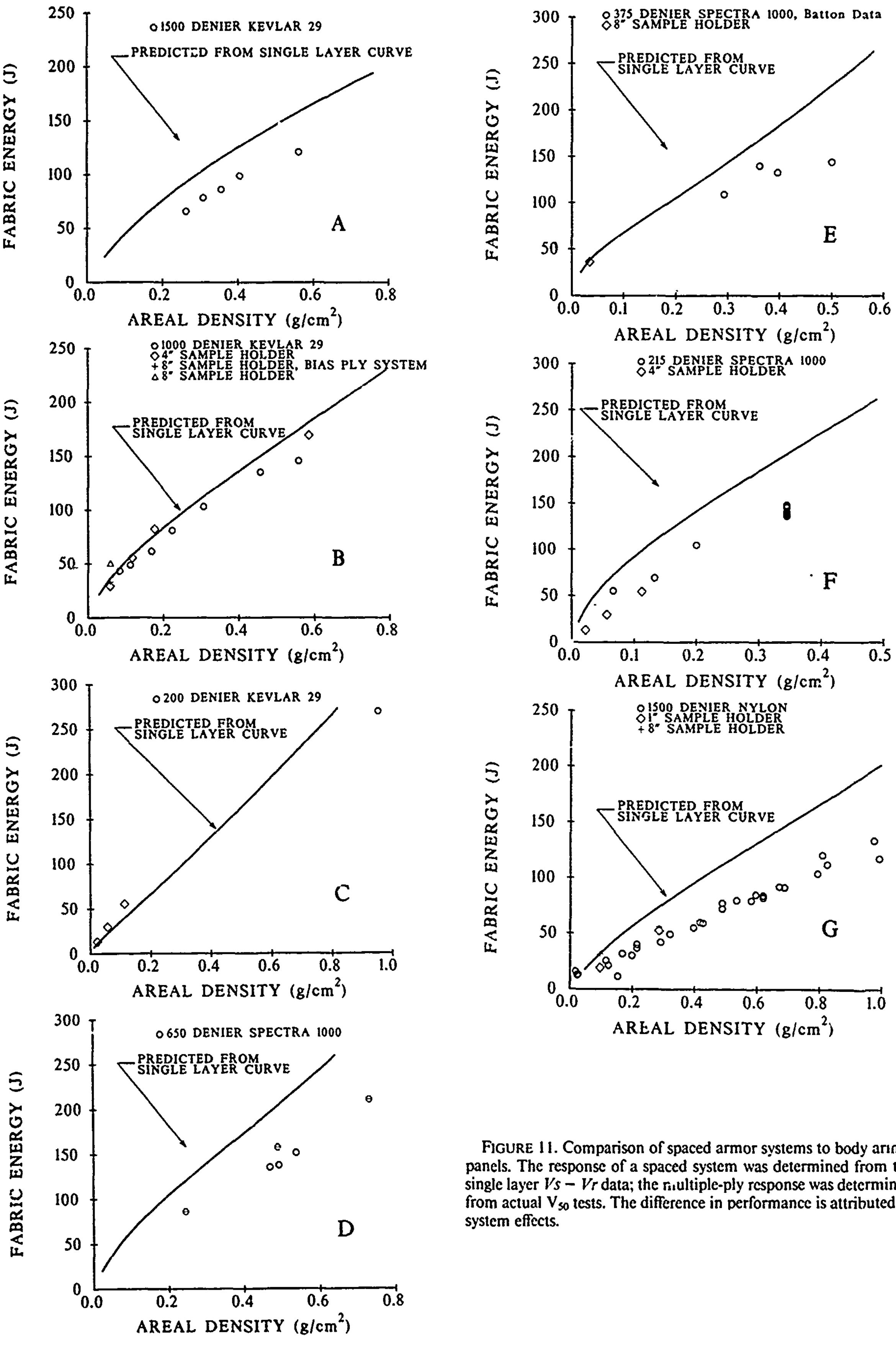

FIGURE 11. Comparison of spaced armor systems to body armor panels. The response of a spaced system was determined from the single layer $Vs - Vr$ data; the multiple-ply response was determined from actual V_{50} tests. The difference in performance is attributed to system effects.

negligible effects in others. This problem will be the subject of further research.

The ballistics data and analysis presented in this report indicate plain-woven, 1000 denier Kevlar 29 should outperform equivalent areal density 1500 denier basket-woven fabric systems. Additionally, the ballistics data and analysis of this report indicate the 375 denier Spectra 1000 material provides superior performance to the 650 denier Spectra 1000, and both Spectra materials are superior to 1500 denier Kevlar 29 systems. The difference in ballistic performance of these systems against the fragment simulator discussed in this report is illustrated in Figure 12. Here the curves were approximated from actual ballistics data; the differences in performance against the fragment simulator discussed in this report are quite apparent.

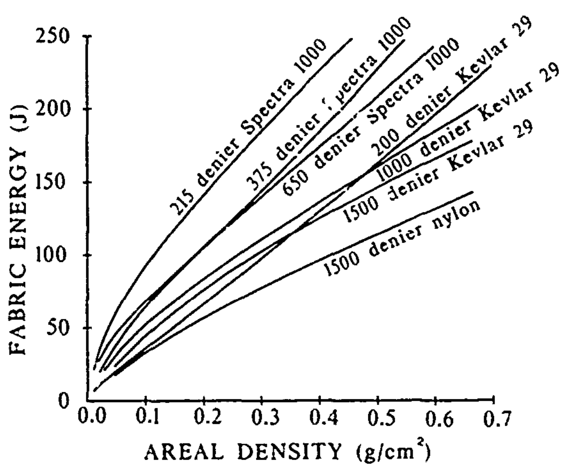

FIGURE 13. Response of spaced armor systems. Each of the spaced armor system responses, as predicted from single layer $V_s - V_r$ data, is shown in the plot.

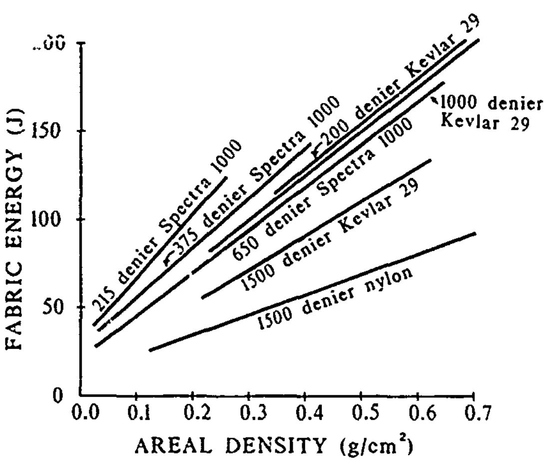

FIGURE 12. Response of multiple-ply armor systems Approximate curves derived from actual ballistics data for multiple-ply systems are shown together in the plot.

The curves of Figure 13 are a collection of the predicted energy absorption capacity curves for spaced armor systems from Figure 11. The Figure 13 curves again illustrate the extraordinary performance of the Spectra material. Comparison of the spaced armor response curves of Figure 13 with the actual ballistic performance curves of Figure 12 illustrates the difficulty of predicting the response characteristics of a multiple-ply system from single-ply response data. The difference in performance between these two kinds of systems is a consequence of system effects (namely additional transverse stresses and additional constraint due to the addition of subsequent plies). Although the effects have been quantified in this report, it has not been possible to relate the deviation of the respective responses to fabric geometry or material properties in an exact sense. As discussed earlier, numerical models to predict the performance of fabric body armor systems under ballistic impact are the subject of active research at this Center. Since an exhaustive treatment of the geometry of multiple-ply body armor systems is not feasible with these models, some simplifying assumptions must be used in formulating the models. The extent that these models can predict the complexity of system responses in various fabric systems will be the subject of further research here.

Spectra materials show evidence of shear or compressive failure at the impact point in multiple-ply fabric armor systems. The ballistic performance of these systems may be improved by improving the shear properties of the fibers, perhaps even at the expense of reducing the materials' axial tensile properties.

Appendix

A Note About Fragment Geometry

Figure 12 illustrates the superior performance characteristics of the 1000 denier Kevlar system over equivalent weight 1500 denier Kevlar systems against chisel-nosed fragment simulators. However, these two systems are known to provide equivalent performance against 2-, 4-, 16-, and 64-grain right circular fragment simulators at the areal density of the current PASGT vest. Additionally, Figure 12 illustrates the superior performance characteristics of each of the Spectra materials over the 1500 denier Kevlar material. These systems are known to provide equivalent performance at equal weights against 2-, 4-, 16-, and 64-grain right circular fragment simulators at the areal density of the current PASGT vest.

The ballistic performance of modern body armor materials against right circular fragment simulators is significantly different than the performance of the same systems against chisel-nosed fragment simulators, primarily because of the difference in fragment geometry. The consequence of this change in geometry is thought to be an increase in shear stress in the immediate region of the impact point. Since right circular fragment simulators have been shown to provide a better approximation of actual fragments than chisel-nosed fragments [30], right circular fragment simulators should be used exclusively for screening tests of body armor materials, acceptance testing of body armor systems, and quality assurance testing. Ballistic limit data for the 17-grain chisel-nosed fragment simulator may be of some value, simply because it is used as a standard in many other countries.

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