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Examining the Relationship Between Ballistic and Structural Properties of Lightweight Thermoplastic Unidirectional Composite Laminates

by Lionel R. Vargas-Gonzalez, Shawn M. Walsh, and James C. Gurganus

ARL-RP-0329 **August 2011**

This is a reprint from the *SAMPE Proceedings Fall 2011 Conference*.

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EXAMINING THE RELATIONSHIP BETWEEN BALLISTIC AND STRUCTURAL PROPERTIES OF LIGHTWEIGHT THERMOPLASTIC UNIDIRECTIONAL COMPOSITE LAMINATES

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ABSTRACT

The pursuit for lightweight personal protection (helmets, body armor, etc.) has been a key issue for the Army in recent years. Previous efforts have shown that the variation of orientation and architecture in ultra-high molecular weight polyethylene (UHMWPE) composite panels can significantly affect ballistic performance characteristics. In our experiments, an architecture now referred to as "ARL X Hybrid" emerged as the clear leader in the compromise between ballistic performance and back face deformation (BFD). For this work, thermoplastic unidirectional materials (both aramid and polyethylene based) were evaluated using 17 grain FSP V_{50} and 9 mm BFD testing in both typical ([0°/90°]) and X Hybrid architectures, at an areal density target ~27% lighter (7.8 kg/m^2) than the currently fielded state of the art. Digital Image Correlation (DIC) was employed to characterize the materials during testing and to help elucidate the panel response as a function of architecture. Polyethylene materials in the X Hybrid architecture were shown to retain 96-99% of the [0°/90°] architecture's V_{50} ballistic performance, while also reducing the BFD by 36-41%. Higher fiber involvement, increased interaction area, and increased membrane stress and through-thickness compression are proposed as factors for this phenomenon.

1. INTRODUCTION

As the demand for high mass efficiency in personal armor is increasing, it has become apparent that meeting the goals of ballistic effectiveness at a lighter weight is not a trivial task. Ultra-high molecular weight polyethylene (UHMWPE) delivered greater than a 35% increase in ballistic fragment performance over the woven aramid used in the Advanced Combat Helmet (ACH) and has lead to the design of the next generation of ballistic helmet, called the Enhanced Combat Helmet (ECH). However, even UHMWPE on its own has difficulty meeting backface deformation (BFD) specifications for applications where standoff or air space is at a premium (such as in ballistic head protection or personal armor systems). This issue becomes even more apparent when attempting to reduce material to engineer low areal density systems. Utilizing a lower amount of fiber plies leads to lower ballistic resistance and stiffness, which affects the ability of the composite to stay rigid during impact.

Previous research results suggest that varying the fiber orientation and fiber architecture can provide a more desirable combination of ballistic and dynamic deflection behavior in UHMWPE panels. In work with Dyneema® HB25 hybrid panels,[1–2] it was observed that architecture and orientation variations have measurable effects on both ballistic response and backface deformation. By varying the ratio between the oriented and [0°/90°] layers within the composite, and by varying the strike face side, an entire range of BFD/V_{50} relationships were obtained. Since this work, availability of commercial fibers (both aramid and UHMWPE) in various formats (both unidirectional and woven) and in different thermoplastic resin systems has increased. These new grades of UHMWPE and aramids offer new options in developing hybrid composite systems tailored for specific needs (whether ballistic, blast, or blunt impact in nature). It was initially believed that varying ratios of thermoplastic, unidirectional UHMWPE and aramid fibers and varying orientation and layering would be the enabler for developing high performance composite structures at low weight.[2] Several tests were performed to determine the effectiveness of an aramid/UHMWPE hybrid composite. Ultimately, while these aramid/UHMWPE hybrids performed considerably well ballistically, the BFD values were unacceptable for most applications.

Due to the mixed results in the aramid/UHMWPE hybrid work, a study of architecture and orientation effects was proposed, this time utilizing new commercial grades of UHMWPE fiber to determine whether the behavior observed in the previous study by Vargas et al. would be similar in light weight panels (~72% of the typical ACH). In this experiment, UHMWPE and aramid materials will be characterized with ballistic testing (17 grain FSP V_{50} and 9 mm 124 grain BFD) and through use of high-speed imaging and digital image correlation (DIC) methods. Using a method described by Hisley et al.,[3] the instantaneous energy of the panels will be captured and analyzed to help elucidate the effect of structure on the properties of these panels. The goals are to determine the mechanisms affecting the ballistic and BFD performance in the different hybrid composites, and to obtain a hybrid composite structure that meets the performance of currently fielded helmets at a reduced weight.

2. EXPERIMENTATION

2.1 Panel Fabrication

Composite panels were fabricated for this experiment from an array of commercial and developmental materials of various fiber and resin types. Most of the materials were of a thermoplastic matrix and unidirectional nature. Dyneema® HB26 (DSM, Geleen, The Netherlands) and Spectra Shield II® SR-3136 (Honeywell Specialty Materials, Morristown, NJ) were the two UHMWPE materials selected for this study. To use as a reference for current helmet materials, a Kevlar KM2® Style 705 PVB phenolic woven aramid composite was included. A developmental unidirectional thermoplastic aramid fiber, Honeywell Developmental Gold Shield Aramid (HDGA, Honeywell Specialty Materials, Morristown, NJ), was also tested for comparison against the woven thermoset aramid fiber.

Plies of all materials were cut using a cutting table (Gerber Technology, Tolland, CT), hand stacked to the desired areal density, and then consolidated using an industrial uni-axial ram press (Wabash 800 Ton Press, Wabash MPI, Wabash, IN) with a commercial molding cycle driven by the supplied manufacturer's specifications. HB26 was consolidated at 20.8 MPa and 125°C. Both SR-3136 and HDGA were processed at the same consolidation pressure, however at a slightly elevated temperature, 132°C, based on advice from Honeywell. The KM2® woven aramid fiber was processed at a much lower pressure, 1.4 MPa, but a higher temperature, 160°C (necessary for the thermoset matrix). This processing was in accordance with the detailed military specification MIL-DTL-62474F.[4]

Two panel sizes were pressed for each material for ballistic evaluation. Three 0.45 m × 0.45 m square panels of each recipe were pressed for use in the 17 grain (1.1 gram), .22 caliber fragment simulating projectile (FSP) V_{50} determination. For the 9 mm, 124 grain (8 gram) full metal jacket (FMJ) backface deformation studies and DIC work, two 0.38 m × 0.38 m square panels of each recipe were pressed. All the panels were consolidated to a nominal areal density of 7.8 kg/m^2 (1.6 lbs/ft^2). For this areal density, the composite panels consisted of 30 plies for both UHMWPE materials, 36 plies for HDGA, and 28 plies for the woven aramid.

The ARL X Hybrid panel architectures are an incorporation of two layers of panel layup. The strike face side is comprised of a 75% (of net weight of panel) layer of laminate plies laid in typical cross-ply ([0°/90°]) fashion. The remaining 25% of the rear consists of a quasi-isotropic layup where every two succeeding plies are rotated 22.5° clockwise with respect to the preceding layers ([0°/22.5°/45°/67.5°/90°]). There was no regard to symmetry or balancing of the laminate stack. Both HB26 and SR-3136 panels were prepared using the X Hybrid architecture for this testing.

2.2 Ballistic Testing and Post-Processing

To determine the ballistic efficiency of a material or armor system, the standard test method most commonly employed is the V_{50} test, which is performed in the manner specified in the military specification MIL-STD-662F.[5] The value obtained in this test approximates the probabilistic velocity in which 50% of the incoming projectiles will be arrested and the other 50% will completely penetrate the panel. In the test, the panel is impacted repeatedly with a round at varying velocities (since velocity is tied to the impulse of the incoming projectile) until a range of partial penetrations (PP) and complete penetrations (CP) are obtained. The two or three highest velocities of PP and the corresponding two or three lowest CP velocities are taken and averaged together to determine the corresponding V_{50} value. V_{50} determinations were obtained using 17 grain (1.1 gram), .22 caliber fragment simulating projectile (FSP) for this experiment at ARL/SLAD (Army Research Laboratory/Survivability and Lethality Analysis Directorate). Shots were placed on the panel in an unbiased manner, taking care to only impact virgin material (areas that have not been previously delaminated from a preceding shot) for each shot. After each impact, the panel was checked by coin tap and light transmittance to determine and mark the extent of delamination. Two to three velocity values below and above the threshold (within an acceptable range of 38.1 m/s) were selected and averaged to obtain the V_{50} value. A logistic regression analysis was employed to generate a probabilistic curve for all ranges of hypothetical values of V_0 through V_{100}. The curves give an estimated indicator of the performance range; and while not completely accurate, it is infeasible to fully determine these parameters experimentally (time and cost consideration).

Back face deformation analysis was conducted using the NIJ Level IIIA standard, which specifies impacting each panel once in its center with a 9 mm, 124 grain (8 gram) full metal jacket (FMJ) projectile. These tests were conducted under the guidance of ARL SLAD. Digital image correlation (DIC) was employed to characterize the behavior of the panels during the testing. DIC gives the ability to capture the full field displacement and strain of a panel through optical (non-contact) means. Two Photron SA5 (Photron, San Diego, CA) cameras are arranged behind the panel to collect high-speed stereoscopic imagery of the panels. The two cameras (arranged 15° off the centerline) are focused and calibrated on to the center of the back of each panel, where a high contrast dot pattern is applied. In these experiments, the dot patterns were applied through use of a pre-printed temporary tattoo. During the ballistic event, the displacement of the dots were captured by the cameras (between 40,000–50,000 frames/second) and analyzed in a software package provided by the developer of the DIC system employed (Aramis, GOM mbH, Braunschweig, Germany). Due to the nature of the DIC measurement, special care is taken to keep the cameras calibrated and to make sure the noise floor (due to ambient effects such as temperature, vibrations, air flow) is as low as possible to obtain precise measurements. Dynamic deformation, area, volume, and velocity were determined from the processed images.

The data obtained through DIC was further processed to determine the instantaneous energy available in the panel at each time step of the ballistic event. The method, described in Hisley et al.,[3] calculates the energy on the backface of the panel using the instantaneous velocity of the panel backface, the effective area of the delamination, and the areal density of material participating in the event. The ballistic panels were dissected to determine how many plies were penetrated and how many were still active in arresting the projectile. The energy values were determined and collected using MATLAB code. All DIC values (aside from actual BFD) fed into the code were obtained at an initial standoff point of 1 mm, since anything under this threshold had excessive background noise.

3. RESULTS

3.1 Ballistic and Deformation Performance

17 grain V_{50} and 9 mm maximum dynamic BFD were determined for all panel types and are listed in Table 1. All values of V_{50} are normalized with respect to the value for the monolithic SR-3136 sample. The BFD listed is the maximum observed material deformation during the dynamic ballistic event, and is obtained from the collected DIC data.

Table 1. Ballistic Performance of All Panel Hybrids

Sample	V_{50}	V_{50} St. Dev.	BFD	BFD St. Dev.
SR-3136	1.00	0.028	22.2	0.04
HB26	0.97	0.010	21.3	0.00
KM2 705	0.79	0.008	22.0	0.65
HDGA	0.80	0.012	17.4	0.26
HB26 ARL X Hybrid	0.93	0.006	13.5	0.10
SR-3136 X Hybrid	0.99	0.009	13.2	0.35

The combined results for the BFD and V_{50} testing are presented visually in Figure 1. For the graph, the BFD is plotted on the abscissa and the V_{50} on the ordinate. This data is being presented in this fashion, since it gives a clear picture into how each of the two properties (BFD, V_{50}) are related with respect to panel architecture.

The results obtained from the ballistic testing, specifically those of the ARL X Hybrid panels, were staggering. It was presumed that the monolithic UHMWPE samples with the routine ([0°/90°]) cross-ply arrangements would exhibit the highest ballistic performance, since as with most high strain to failure materials in compliant matrices, the fibers are capable of straining through the composite normal to the plane of impact to their point of failure.[6] This was evident in this testing, as the [0°/90°] architectures exhibited the greatest ballistic performance within their respective materials. Previously, it was shown that stiffening UHWMPE panels,

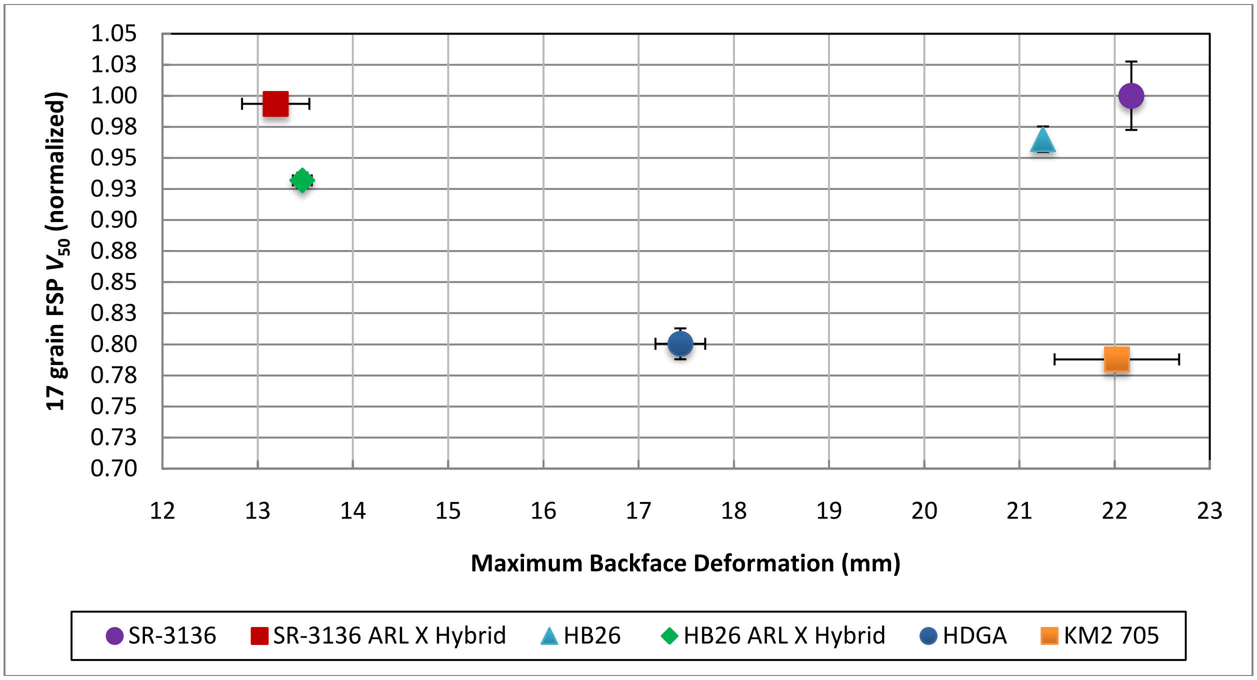

Figure 1. BFD and V_{50} testing for all fiber laminates in this study. The ARL X Hybrid samples exhibit superior levels of BFD, all while maintaining the ballistic performance inherent in the [0°/90°] panels.

by functionally orienting the fibers in the composite, reduced BFD at the expense of ~10% of ballistic efficiency.[2] However, in the lightweight HB26 and SR-3136 ARL X Hybrids, a large reduction in BFD (40.53% in the SR-3136 X Hybrid) was observed with very minimal drop in the 17 grain FSP V_{50} performance. In fact, the V_{50} of the SR-3136 ARL X Hybrid is statistically identical to that of the monolithic [0°/90°] panel. Dyneema® HB26 exhibits similar behavior, albeit at a slightly decreased ballistic level as compared to SR-3136. This seems to imply that any thermoplastic, unidirectional UHMWPE fiber would behave similarly if arranged in the ARL X Hybrid architecture. Thermoplastic, unidirectional aramid samples such as HDGA exhibit better performance all around ballistically, and to a large extent impact wise, than that of the classic woven aramid thermoset composites.

While the values for V_{50} are similar for both SR-3136 panel types, there are very slight differences in behavior for their logistic regression curves. Logistic regression analysis was performed on the V_{50} results, and the resulting statistical curves are shown in Figure 2. Both of the SR-3136 curves seem to intersect almost precisely at the 50% threshold. The SR-3136 ARL X Hybrid sample exhibited a slightly broader curve, meaning that the performance up to V_{50} was statistically higher than that of SR-3136. SR-3136 exhibits higher performance values from V_{50} onwards through V_{100}. The disparity between the HB26 and HB26 ARL X Hybrid is larger, with all of the statistical curve of the X Hybrid lagging behind the [0°/90°] cross-ply, increasingly more so with increasing probability of penetration. Unidirectional cross-ply HDGA generally outperforms its counterpart woven aramid through the entire range of probabilities, probably owing to the inherent advantage unidirectional fibers have in providing tensile strength in the lateral fiber direction, while also being transversely compressed into the succeeding plies.[7]

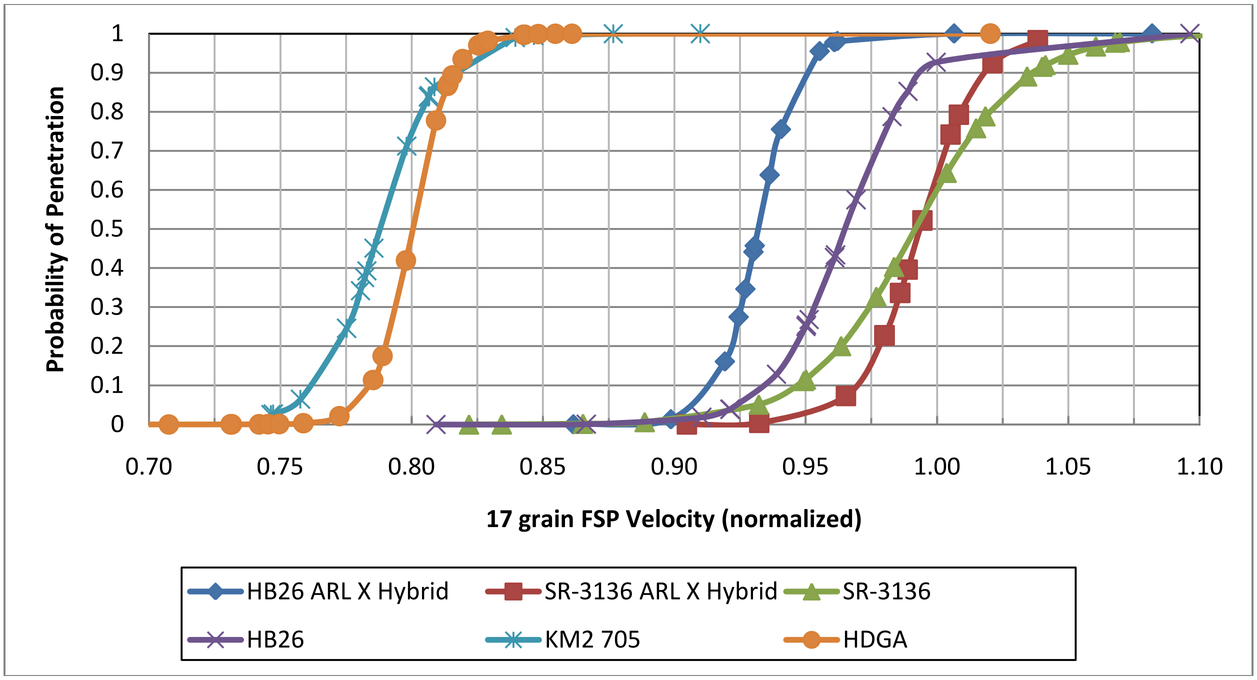

Figure 2. Statistical curves for all panel architectures, as generated through logistic regression of V_{50} values. SR-3136 and SR-3136 ARL X Hybrid split into two performance regimes above and below V_{50}. Thermoplastic unidirectional aramid outperforms woven aramid through most of the range.

3.2 Energy Analysis

The 9 mm BFD data was collected with DIC, analyzed in Aramis, and processed through MATLAB to obtain velocity, area, and energy values. Table 2 lists the results of the maximum energy, displacement, and velocities with their respective timestamps after impact. The deformation as a function of the time during the ballistic event is depicted in Figure 3. BFD increases with similar slope in all panels for the first 60 to 75 microseconds, afterwards, the X

Table 2. Characteristics of Panel Behavior Measured Through DIC (at 1 mm Standoff)

Sample	Maximum Available Energy (J)	Time of Maximum Available Energy (μs)	Time of Maximum Displacement (μs)	Maximum Velocity (m/s)	Time of Maximum Velocity (μs)
HB26	351	60	320	192	60
SR-3136	372	60	320	190	60
HDGA	349	60	240	190	60
KM2® 705	415	80	550	152	75
SR-3136 X Hybrid	639	75	275	166	40
HB26 X Hybrid	642	75	250	159	40

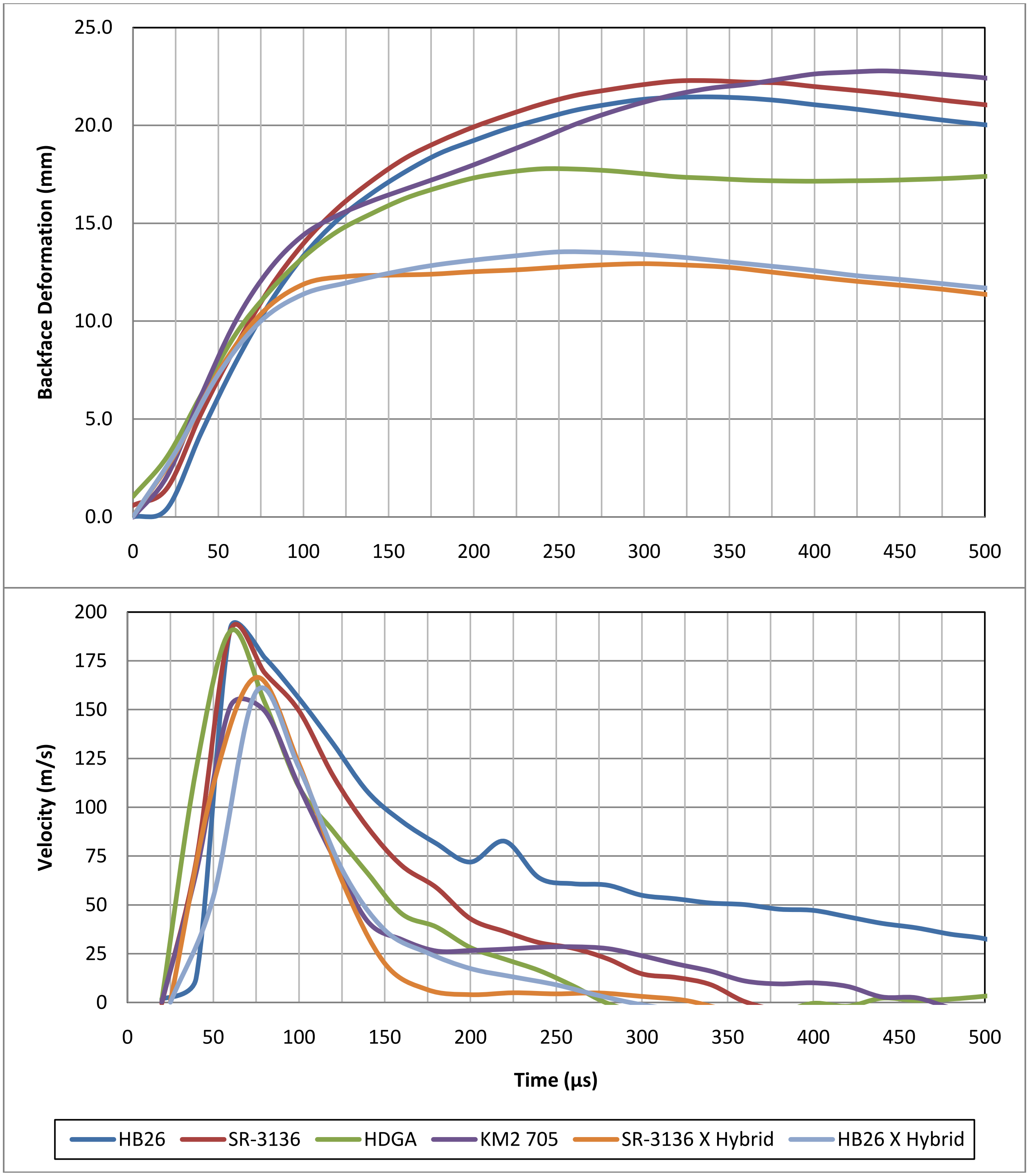

Figure 3. Top) Backface deformation per time during ballistic impact;
Bottom) velocity of backface as a function of time.

Hybrid samples quickly diverge into a relatively flat deformation plateau. The cross-plied panels continue to increase in BFD and converge toward a maximum value more gradually over the time of the event (shown in the velocity graph in Figure 3). The [0°/90°] panels show a slow reduction in velocity over time after the maximum velocity is reached. In contrast, the reduction of velocity in the backface of the X Hybrid panels is more abrupt and approaches zero near the maximum deformation extent. The woven KM2® aramid panel exhibited a lower velocity threshold versus HDGA. The lower velocity threshold initially would suggest that stiffness is greater in the woven aramid panel. However the maximum BFD extent is lower for the HDGA panel, therefore there are other factors that are at work in that panel that reduce BFD.

The total deformation area for each panel was collected as a function of time and is shown in Figure 4. The area and velocity data were then used to determine the instantenous available energy that has been transferred to the bulk of the panel. A standoff plane of 1 mm above the backface of the panel was selected to reduce noise in the measurement. Figure 5 illustrates the instantaneous energy as a function of time, while Figure 6 shows the maximum available energy in the panel as a function of discrete standoff distances from the panel backface. The extent of interaction area involved in each panel shows the differences in how both the [0°/90°] and X Hybrid architectures mitigate the impact impulse. For the SR-3136 material for instance, the interaction area of the X Hybrid at its time at maximum displacement (275 μs) is nearly 44% greater than the SR-3136 cross-ply at its zenith (320 μs). In a traditional unidirectional cross-ply laminate, the principal fibers (the fibers that are directly underneath the impact of the projectile) are at a higher stress than the fibers in the surrounding area of the panel (orthogonal fibers). The orthogonal fibers stressed due to the binding action of the matrix, however, do not experience the amount of stress as the principal fibers. Therefore you see the associated cross-hatch pattern clearly on the back face,[8] which indicates the high strain and displacement of the principal fibers. This is readily evident on the top half of Figure 7, where the DIC image reveals the extent of strain work being imparted to the fibers, mostly in the coordinate directions (0°, 90°, 180°, 270°).

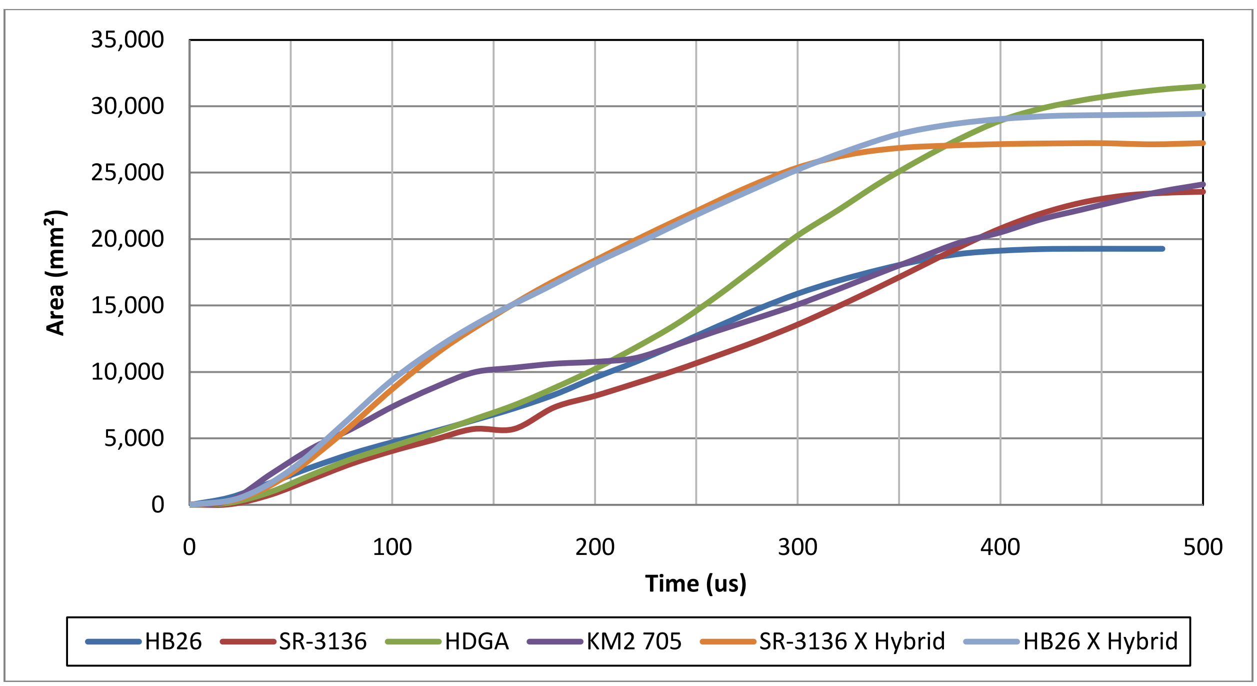

Figure 4. Extent of displacement area as a function of time of impact, based off a 1 mm standoff from panel. Displacement area is more widespread in the X Hybrid architecture in the maximum displacement window (250-340 μs).

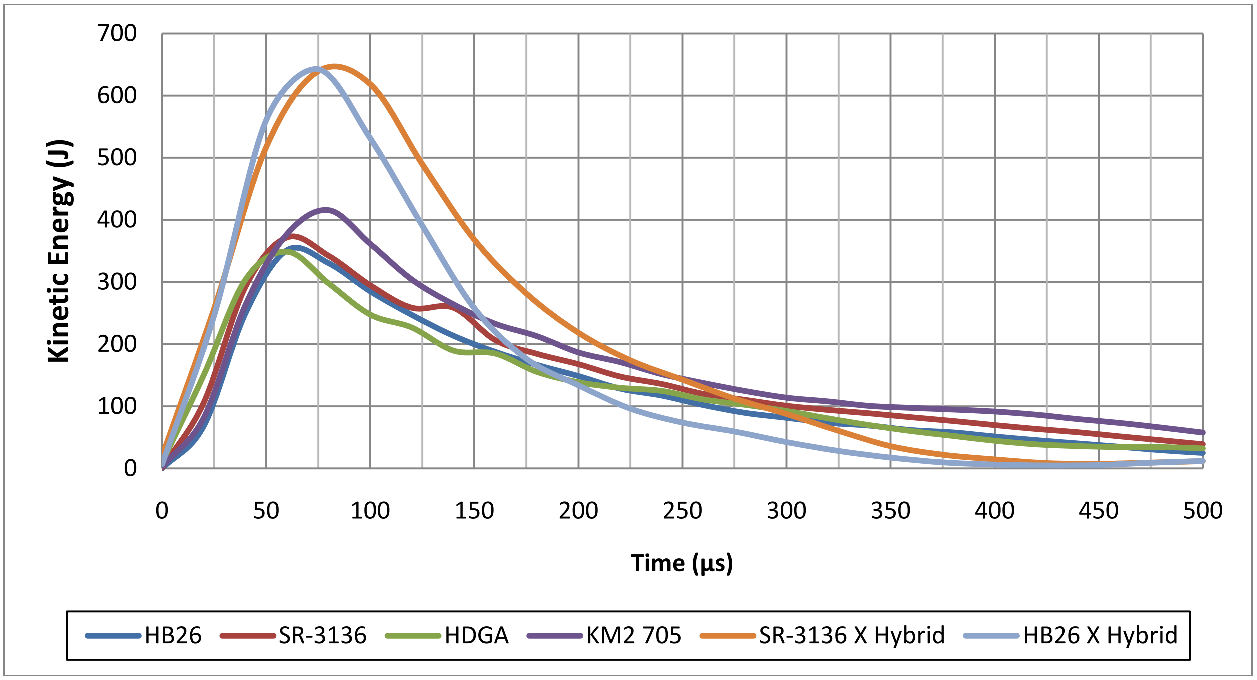

Figure 5. Kinetic energy imparted to the backface of tested panels as a function of time of impact, based off a 1 mm standoff from panel. The maximum energy occurs between 60–80 µs for all panels. The X Hybrid panels exhibit a larger available energy extent than the [0°/90°] cross-plies.

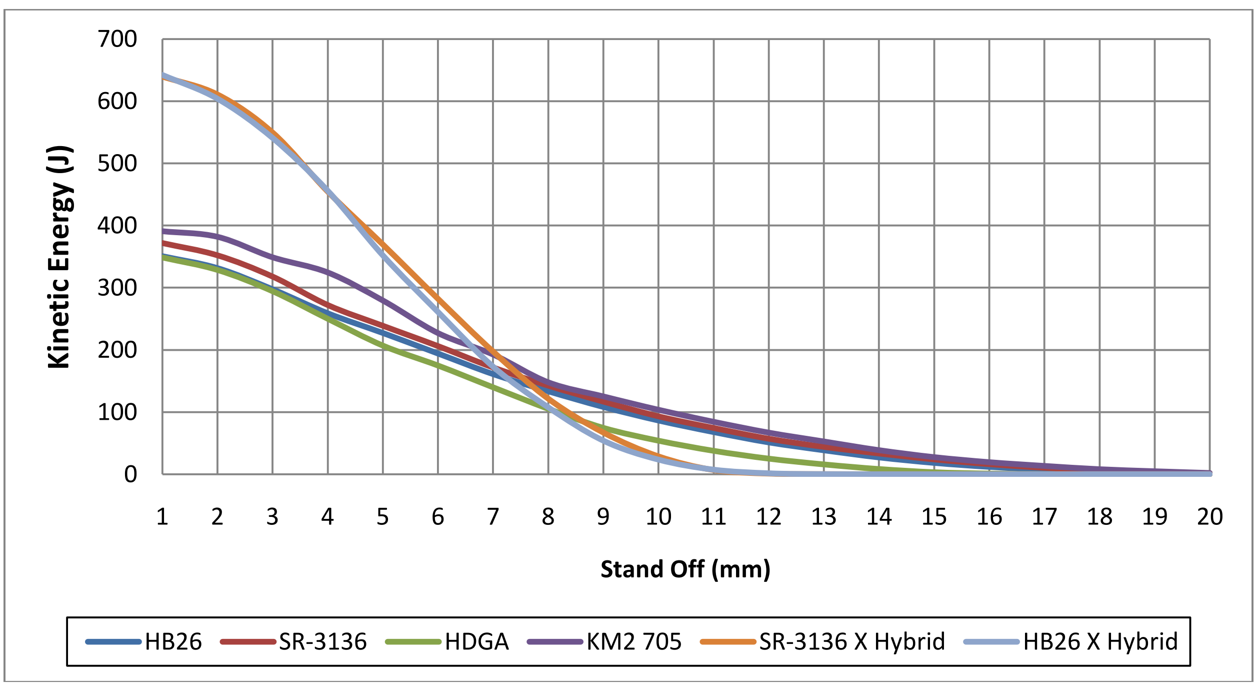

Figure 6. Kinetic Energy imparted into the panel as a function of panel standoff. At a 12 mm standoff, there is very little residual KE left in the X Hybrid panels.

Figure 7 also shows that in the ARL X Hybrid, the orientation of the fibers on the backface works to involve the entire panel in the ballistic event. Since within the back 25% of the panel each succeeding layer is at a different orientation than the layer preceding, the strain induced is transferred into different fiber coordinate directions. Ultimately, the area of fiber interaction develops from the typical cross-hatch shaped pattern into a circular interaction area, involving more of the area of the panel in the energy absorption of the ballistic event. Instead of observing strain only in the 0° and 90° directions, there is a diffuse "halo" of striations revealing the "star" pattern of fibers on the rear of the panel. As shown in Figure 8, the higher involvement of the panels in X Hybrid form leads to the higher instantaneous transfer of energy from the projectile into the panel. The X Hybrid panels exhibit a higher available energy at low standoff distances, and have a larger drop in slope as standoff increases (Figure 6), showing that with the 44% increase of interaction area versus its [0°/90°] counterpart, the X Hybrid panels are able to dissipate more energy into the panel per time. The available energy is higher in the X Hybrid panels as a function of time (Figure 5), however if the ratio of available energy and interaction area is plotted as a function of time, as shown in Figure 9, then it is evident that the energy is more diffuse, which reduces the BFD extent.

In the previous HB25 work,[9] the differences in delamination were seen in images of shot panels on a light table and through DIC work. It was inferred that a panel with all plies oriented in succession would have the largest interaction area and therefore have a high level of energy absorption and stiffness. The testing and characterization did indeed show high area of delamination and high fiber interaction in the panel; however the ballistic properties of the fully oriented composite were very poor, leading to the conclusion that area of interaction, delamination, and stiffness are not necessarily the criteria for a well-performing composite armor. Many variations of panels were tested to determine the effects of mixtures of cross-ply and oriented layers. Panels with an oriented strike face worked hard against the projectile to absorb some of the energy, through high panel interaction and high delamination, in the strike face before the projectile sheared through and reached the more complaint ([0°/90°]) rear. Deformation was reduced a small extent; yet surprisingly, ballistic values actually superseded those of the monolithic [0°/90°] panel (1–3%), owing to the ability of the fibers in the rear to still be compliant and free to strain to failure. With the opposite architecture, it would have been expected that the opposite behavior would have been true; that the stiff rear would inhibit the fibers from being able to have a high degree of transverse deflection, causing the fibers to rupture prematurely, and limiting their ability to absorb energy through transverse strain and through axial tensile loading. Yet, in this study, the ballistic performance levels of the SR-3136 and SR-3136 ARL X Hybrid are statistically equal, with the X Hybrid showing a significant drop in deformation (~40.5%). Recent work by Scott[7] revealed a strengthening effect of thermoplastic unidirectional composite panels through quasi-static confined compression testing. Peak pressures greater than the compressive and shear strengths of the fiber were achieved, which led to the deduction that the tensile failure of the fibers (tensile strengths are much higher than compressive and shear) were being prolonged. It was shown that higher through-thickness compressive forces, hydrostatic pressure, and higher membrane tension all worked to apply a higher retardation force to the projectile. In addition, fibers were observed to be able to plastically deform in the lateral direction while maintaining their tensile strength. It could be inferred that in the case of the ARL X Hybrid, the 25% addition of the stiffened oriented layer provides the backend confinement critical to induce the high level of through-thickness compression and membrane stress, which assists in energy absorption and helps preserve the V_{50}

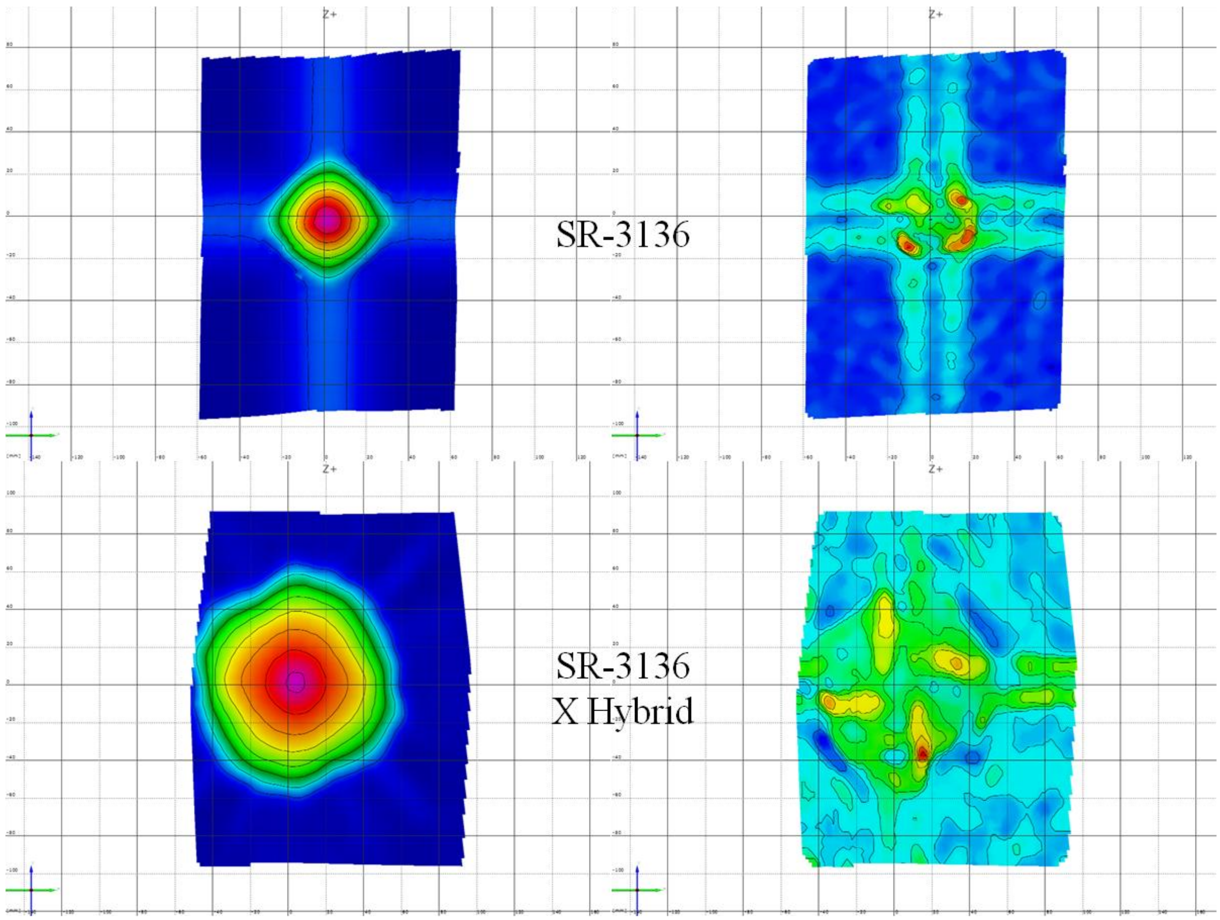

Figure 7. DIC images of both [0°/90°] and X Hybrid architectures of SR-3136 fiber. The left image is of the net displacement and the right image is of the major strain. The images show the rear of the X Hybrid loading on principal fibers in all directions, increasing the area of interaction and the energy absorbing capability of the panel.

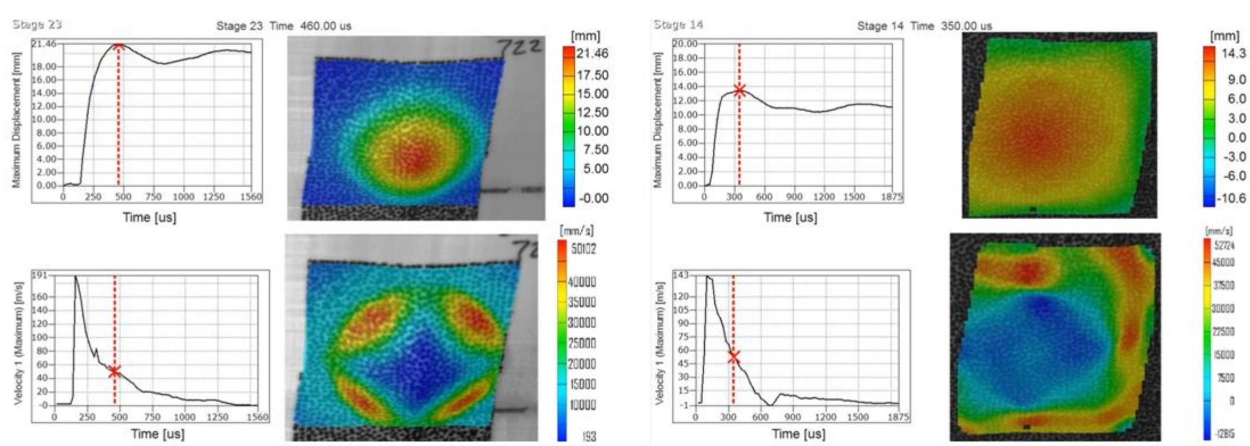

Figure 8. DIC screenshots of [0°/90°] and X Hybrid laminates showing the backface deformation (top) and velocity (bottom) signatures at the maximum deformation extent, highlighting the differences in fiber interaction.

performance. The remaining energy in the panel is then spread over the fibers on the oriented back face, reducing the localized fiber strain and increasing the interaction volume of the panel, leading to reduced BFD.

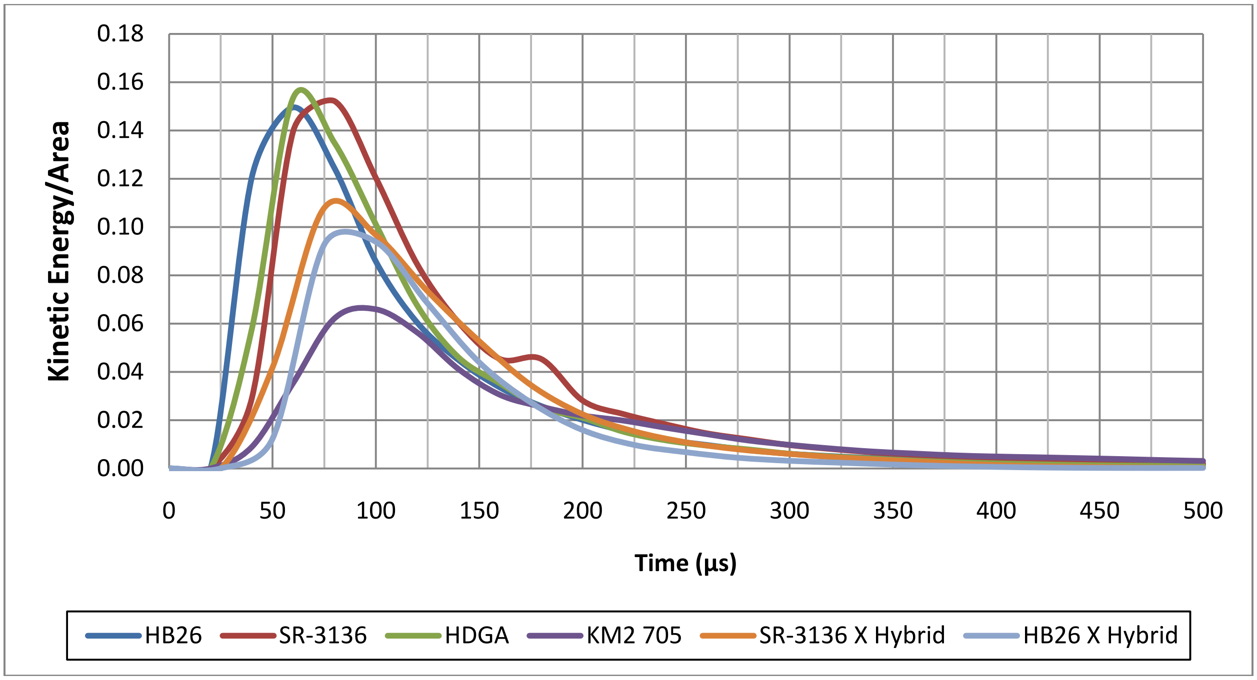

Figure 9. Ratio of kinetic energy/area available in the rear of the panel as a function of time.

4. CONCLUSIONS

Various architectures of UHMWPE and aramid composite structures were ballistically evaluated to determine the trade space between ballistic performance (17 grain .22 cal FSP) and BFD (9 mm 124 grain FMJ), in hopes of finding a balanced tradeoff at a light areal density target (7.8 kg/m^2). The results culminated in the discovery and development of the ARL X Hybrid architecture, which consists of 1) the balance of architecture in the panel being 75% [0°/90°] and 25% oriented, and 2) the use of the [0°/90°] side as the strike face. By implementing the X Hybrid architecture, UHMWPE materials retained 96-99% of the [0°/90°] architecture's ballistic performance, while also reducing the BFD by 36-41%. SR-3136 X Hybrid exhibited a 44% higher interaction area at its maximum extent, increasing the energy spread over a wider area, and increasing the dissipation of energy in the panel over time.

While the high fiber area involvement and the instantaneous energy absorption lead to these results, they are not sufficient to explain the retention of ballistic performance. It is believed that the X Hybrid architecture maximizes the extent of fiber compliance in straining to a high extent, while also providing the benefit of a small amount of orientation providing the energy absorption and back face stiffness. Through this, it is believed that through thickness compression and membrane stress are increased, which provides a retardation force opposite to the force of the projectile.

Future goals will be to determine whether the trends shown here correlate in the transition from flat plate to helmet form. In addition, composites of these architectures will be evaluated for possible inclusion into body armor as ceramic strike face backing materials.

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