Mechanisms of projectile penetration in Dyneema® encapsulated aluminum structures

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Abstract

Polymer composites comprising ultra-high molecular weight polyethylene (UHWMPE) fibers in a compliant matrix are now widely used in ballistic applications with varying levels of success. This is primarily due to a poor understanding of the mechanics of penetration of these composites in ballistic protection systems. In this study, we report experimental observations of the penetration mechanisms in four model systems impacted by a 12.7 mm diameter spherical steel projectile. The four model targets designed to highlight different penetration mechanisms in Dyneema® UHWMPE composites were: (i) a bare aluminum plate; (ii) the same plate fully encased in a 5.9 mm thick casing of Dyneema®; (iii) the fully encased plate with a portion of the Dyneema® removed from the front face so that the projectile impacts directly the Al plate; and (iv) the fully encased plate with a portion of the Dyneema® removed from the rear face so that the projectile can exit the Al plate without again interacting with the Dyneema®. A combination of synchronized high speed photography with three cameras, together with post-test examination of the targets via X-ray tomography and optical microscopy was used to elucidate the deformation and perforation mechanisms. The measurements show that the ballistic resistance of these targets increases in the order: bare Al plate, rear face cutout target, fully encased target and front face cutout target. These findings are explained based on the following key findings: (a) the ballistic performance of Dyneema® plates supported on a foundation is inferior to Dyneema® plates supported along their edges; (b) the apparent ballistic resistance of Dyneema® plates increases if the plates are given an initial velocity prior to the impact by the projectile, thereby reducing the relative velocity between the Dyneema® plate and projectile; and (c) when the projectile is fragmented prior to impact, the spatially and temporally distributed loading enhances the ballistic resistance of the Dyneema®. The simple model targets designed here have elucidated mechanisms by which Dyneema® functions in multi-material structures.

1. Introduction

Many mechanisms are utilized to arrest the penetration of projectiles incident upon a target, including deformation and fragmentation of the projectile on the target strike face, projectile deceleration with controlled momentum transfer to the target, and spall shield capture of partially defeated projectile/target debris at the rear of a target. Different materials are used to exploit each mechanism; hard (and ideally tough) materials are utilized to deform and fragment projectiles, high strength but fracture resistant materials for deceleration (by plastic dissipation) and ultra-high strength fibers in the form of textiles or composites are used for spall shields to catch debris. In a well-designed protection concept, synergies are sought between the three material components to further enhance performance. For example, a high strength ductile metal that resists penetration can also be used to confine a ceramic, and increase the effectiveness of interface defeat.

To maximize performance, the fibers used in spall shields need to have a balanced combination of properties including: (i) a high tensile strength to resist the significant stretching forces during (end restrained) fiber deflection, (ii) a high strain-to-failure to convert debris kinetic energy to (stored) potential energy, (iii) a high elastic modulus to reduce dynamic out-of-plane (transverse) displacements and (iv) a low density if intended for mobile

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Many studies have investigated the transverse impact of fibers [1–6]. Cunniff [7] has used scaling arguments to rationalize the selection of ballistic resistant fibers. Cunniff [7] argued that the ballistic limit of fiber composites scales linearly with a material property index called Cunniff velocity $c^*$ of the fiber defined by:

$$c^* = \left( \frac{\sigma_f \epsilon_f}{2p} \sqrt{\frac{E}{\rho}} \right)^{1/3}$$

(1)

where $\sigma_f$ and $\epsilon_f$ are the tensile strength and failure strain of the fibers respectively, $E$ is the tensile modulus of the fibers and $\rho$ their density. The two material properties that make up the definition of $c^*$ are the specific energy absorption $\sigma_f \epsilon_f / (2p)$ and extensional wave speed $c_L = \sqrt{E/\rho}$ of the fibers. A material property map with axes of these two properties is given in Fig. 1(b), along with contours of the Cunniff velocity $c^*$. Based on the index $c^*$ the three highest ballistic limit materials are all polymers; SK76 Dyneema®, Zylon and the M5 fiber. The M5 fiber remains under commercial development, and Zylon is susceptible to environmental degradation, and so here we explore the penetration mechanisms of the Dyneema® SK76 fiber which has been combined with 17 wt.% polyurethane resin to form $[0^\circ/90^\circ]$ cross-ply HR26 grade tape that can be hot pressed to create laminated plates. The composites are highly anisotropic, having tensile strengths of a few GPa but a shear strength on the order of only a few MPa [8].

Many impact studies have been performed on UHMWPE fiber reinforced composites [9–14,5,15–17]. Such measurements have been used to develop continuum models (e.g. Refs. [18–20]) to enable the modeling of the penetration resistance of UHMWPE composites. Penetration calculations performed using such constitutive models typically have a narrow range of validity in terms of projectile type, armor geometry, etc. and more importantly give little insight into the physical basis of the scaling relation proposed by Cunniff [7]. In an elegant analytical study, Phoenix and Porwal [21] demonstrated that the ballistic limit of composite plates can scale with $c^*$ by assuming a membrane stretching deformation and failure mode of the impacted plate as illustrated in Fig. 2. In this model they included the fast moving extensional wave at a speed $c_L$ followed by a hinge moving at a slower velocity $c_H$ (Fig. 2(b)), which bounds the transversely deflected region of the Dyneema® plate; membrane stretching of the Dyneema® engulfed by the extensional wave is assumed to cause tensile fiber failure under the projectile.

A recent experimental investigation by Karthikeyan et al. [15] has investigated the transverse deflection dynamics and impact site damage mechanisms of a 6 mm (96 ply) thick, Dyneema® HB26 plate impacted by a 12.7 mm diameter hardened steel spherical projectile. The plates had an areal density of 5.89 kg m$^{-2}$, and were bolted between annular steel plates with an inner radius of 100 mm. The ballistic limit was measured and found to be about 445 ms$^{-1}$. They confirm the formation of a pyramidal deflection structure following impact (Fig. 2(a)) and measured the transverse hinge velocity in the fiber directions to be $c_H \approx 316$ ms$^{-1}$. However, examination of the laminate after impact revealed that penetration of the laminate was progressive, with the number of failed plies increasing with impact velocity. No plug formation was observed, and the observation of progressive failure appeared to be inconsistent with the Phoenix and Porwal [21] model of binary failure in a membrane-stretching mode (a non-progressive mode of failure). Woodward et al. [22] have suggested an alternate failure mechanism for fiber composites under indentation type loading. They argue that the compressed laminate under the indenter is stretched applications. Many fibers have been (or are being) developed for ballistic applications, and Fig. 1(a) plots the quasi-static tensile strength and Young’s modulus of many of these materials. However, the material property chart does not address the role of fiber density, which is critical in some applications, nor the influence of the failure strain, which governs the mechanical work that can be stored.

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1 The sources of the material data are tabulated in Appendix A.
but unable to flow laterally (confined) due to the surrounding laminate material. The stress field underneath the punch intensifies with indentation depth until the group of plies closest to the punch, which are stretched the greatest, fail in tension (Fig. 2(c)). While the mechanics underlying the hypothesis of Woodward et al. [22] are not clear, the sequence of events leading to failure suggested by Woodward et al. [22] more closely resembles the observations of Karthikeyan et al. [15].

The application of Dyneema® laminates in composite protection systems has been accomplished with varying degrees of success. For example it is well known that the placement of Dyneema® within a composite (multi-material) structure and the type of projectile being resisted both greatly affect the efficacy of the Dyneema® [9,13,23]. For example, a study by Karthikeyan et al. [16] impacted the 6 mm thick HB26 laminate beams with 28.5 mm diameter aluminum foam projectiles. Now in contrast, to the progressive failure under the projectile observed in Ref. [15] for impact by a steel projectile, failure in this case occurred by stretching at the grips. No clear understanding of the mechanisms of failure of Dyneema® composites when used in multi-material structure currently exists.

The focus of this study is to elucidate the different mechanisms of perforation and failure of Dyneema® composites in model systems designed to reveal the fundamental micromechanisms. The outline of the paper is as follows. First we describe four different model systems including the materials and fabrication methods. Next, the response of the four different systems to impact by a hard steel sphere is described and contrasted. Finally, these observations are assembled to elucidate the different perforation mechanisms of Dyneema®.

2. Materials and sample fabrication

We probe the dynamic response of Dyneema® by utilizing variations in the penetration mechanism of an aluminum plate when impacted by a hardened (low ductility) chrome steel sphere of diameter 12.7 mm at various impact velocities. The baseline target investigated in this study comprises a 6061T6 aluminum alloy plate wrapped in grade HB26 Dyneema® (DSM, The Netherlands) as sketched in Fig. 3(a). This is the same Dyneema® grade used by Karthikeyan et al. [15], and this study uses a similar thickness laminate to allow for appropriate comparisons. However, unlike in Ref. [15] the wrapping of the Dyneema® employed here allowed us to avoid using bolts for attaching the Dyneema® plates. Three additional variants of the baseline targets are also investigated within this study in order to gain further insights into the deformation and penetration mechanisms. The four types of targets were:

(i) The **baseline fully encased target**: this target comprised a 31.6 mm thick 6061T6 aluminum alloy plate wrapped in HB26 Dyneema® cross-ply composite (Fig. 3(a)).

(ii) The **bare Al plate**: a 31.6 mm thick 6061T6 aluminum alloy plate used to characterize the ejecta impacting the rear laminate of the front face cutout target (Fig. 3(b)). A 63.5 mm thick 6061T6 aluminum alloy plate was additionally characterized to understand the projectile/target interaction during high impact velocity penetration.

(iii) The **front face cutout target**: a 30 × 30 mm central section was cut out from the impacted face of the baseline target to understand the role of the Dyneema® on the impacted face (Fig. 3(c)).
(iv) The rear face cutout target: an 80 × 80 mm central section was cut out from the distal face of the baseline target to understand the role of the Dyneema® on the rear, or non-impacted, face (Fig. 3(d)).

These four target designs enable us to (i) probe the behavior of both an edge supported Dyneema® plate and a Dyneema® plate supported on a foundation when impacted by a spherical projectile, and (ii) investigate the behavior of an edge supported Dyneema® plate impacted by a fragmented projectile. We proceed to first describe the materials used in each of these targets and then describe the manufacturing processes and the geometrical details.

2.1. Materials

HB26 Dyneema®: The HB26 grade composite comprises Dyneema® SK76 fibers in a polyurethane matrix. The 17 μm diameter SK76 fibers are made by gel spinning an ultra-high molecular weight polyethylene (UHWMPE) suspended in solution, evaporating the solvent and hot drawing the fibers. The resulting fibers are crystalline with the extended molecular chains highly aligned in the fiber axis. These fibers are then formed into yarns arranged in collinear sheets, coated with a polyurethane resin and formed into a [0°/90°]₂ (0.27 mm thick) laminated pre-preg tape with a fiber fraction of 83 vol.% (Fig. 4(a)). The HB26 tapes can be stacked and hot pressed to create a panel of arbitrary thickness.

Fig. 4(b) shows a high resolution micro-X-ray tomographic image of the cross section of a consolidated laminate. The images clearly show the 0° and 90° plies as well as the presence of small tunnel cracks [24] between the fibers in the 0° plies that are thought to form as a result of anisotropic thermal contraction in the longitudinal (fiber) and transverse directions of the plies and the very low transverse tensile strength of the composite. A higher resolution SEM micrograph of the cross section of a tape is shown in Fig. 4(c) and reveals the tight packing of the fibers and the pockets of resin.

The tensile response of SK76 yarn (a bundle of 780 fibers) was measured at ambient temperature (23 °C) by sandwiching each end of a yarn between two pieces of highly adherent tape, clamping the tapped yarn ends in wedge-action grips equipped with serrated jaw faces and pulling the yarn at a nominal strain rate of 5 × 10⁻³ s⁻¹. A typical measured tensile stress versus applied nominal tensile strain curve is plotted Fig. 5 and is consistent with a large body of data (see for example [8,25–27]): the tensile response is elastic-brittle with a tensile modulus of about 110 GPa and a tensile strength around 3.1 GPa. Furthermore measurements by Russell et al. [8] demonstrated that the response of the SK76 fibers is strain rate insensitive over the strain rate range 10⁻² s⁻¹ to 10⁻¹ s⁻¹ at ambient temperature. The tensile response of the [0°/90°] HB26 laminate in the direction of one fiber sets was measured using the dog-bone target developed by Russell et al. [8]. A representative measurement is included in Fig. 5. In contrast to the yarn response, the composite displays some “plasticity” prior to complete fracture.
at a strength of about 850 MPa. Given that the matrix contribution to the strength is negligible, laminate plate theory predicts that the $[0^\circ/90^\circ]_{14}$ laminate with 83% volume fraction fiber should have a strength of about 1.3 GPa based on the yarn measurements reported above. The reduction of strength may be a consequence of fiber waviness developed during laminate fabrication: the fibers straighten out during the loading which gives rise to the apparent plasticity of the composite and non-uniform loading of the constituent fibers of the composite. This non-uniform loading is also the likely reason why the composite strength is below the predictions of laminate plate theory. The inter-laminar shear strength of the HB26 composite was measured to be about 2 MPa using the double-notch shear sample introduced in Ref. [15].

Aluminum plate: In all the Dyneema® wrapped targets, we used 31.6 mm thick aluminum 6061 alloy plate solutionized and aged to the T6 condition. Quasi-static tensile tests were conducted on the 6061 plate material in the T6 condition. The measured Young’s modulus and yield strength were 66 GPa and 305 MPa, respectively, and the alloy had an ultimate tensile strength of 325 MPa at a tensile failure strain of 14%. Readers are referred to Ref. [28] for the dynamic behavior of this alloy, including a Johnson Cook model fit of its mechanical behavior.

2.2. Sample fabrication

The three types of Dyneema® encapsulated samples are sketched in Fig. 3 and we briefly describe the manufacturing process. All three target types first involved the manufacture of the baseline target as follows.

**Step I:** The 136 mm $\times$ 132 mm $\times$ 31.6 mm thick rectangular Al plate had its edges chamfered to a radius of 3 mm to reduce stress concentrations on the Dyneema® wrapping (Fig. 6(a)).

**Step II:** Two strips of the HB26 pre-preg tape, one 136 mm wide (strip 1) and the other 132 mm wide (strip 2), were cut in the $0^\circ/90^\circ$ fiber orientation to a length of 4 m. The surface of strip 1 was bonded with a Lord grade 7542 A/B urethane adhesive (Lord Corp., Cary, NC) to the rear surface of the aluminum plate, and strip 2 was adhesively bonded to the surface of strip 1, but rotated $90^\circ$ to the wrapping direction of strip 1; see Fig. 6(b). The fibers in the outer ply of each strip were oriented parallel to the sides of the rectangular aluminum plate. Each strip was then alternatively wrapped around the aluminum plate eleven times without applying significant tension to the tapes.\(^2\) Referring to the outer ply of strip 1 as the $0^\circ$ orientation, the lay-up from the aluminum surface on both the 136 mm $\times$ 132 mm faces was $[(90^\circ/0^\circ)]_2/[(0^\circ/90^\circ)]_{11}$ with a thickness of 5.9 mm. The lay-up on the four smaller sides was either $[90^\circ/0^\circ]_{22}$ or $[0^\circ/90^\circ]_{22}$ and

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\(^2\) The length of applied pre-preg material per strip was $\sim$5 cm longer than calculated for a perfectly tight wrap.

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Fig. 4. (a) Schematic illustration of a Dyneema® HB26 pre-preg tape. (b) Micro-X-ray computed tomogram of a consolidated HB26 laminate showing the presence of tunnel cracks. (c) SEM micrograph of a ply from a consolidated laminate cut normal to the filament direction. The $0^\circ$ filament ends were slightly smeared during sample preparation.

Fig. 5. The measured tensile stress versus strain response of the SK76 yarn and the HB26 cross-ply laminate in the direction of one of the set of fibers.
thus only half the thickness of that on the 136 mm × 132 mm faces.

**Step III:** The Dyneema® wrapped samples were consolidated in a hot press using a die, Fig. 6(c). The sample was inserted into a die that had been pre-heated to 100 °C. Aluminum shims were tightly fitted along the sample’s sides, and a Baldwin 1.4 MN universal testing machine was used to load the die at a loading rate of 110 kN min⁻¹ until the applied pressure over the 136 mm × 132 mm faces reached 20.6 MPa. The temperature was then increased to 127 °C and maintained for 20 min. The die/sample assembly was then cooled to 100 °C, the pressure released and the sample allowed to cool to ambient. The final dimensions of the fully encased panel are indicated in Fig. 3(a).

The front and rear face cutout targets as indicated in Fig. 3 were prepared by first manufacturing the baseline targets as described above and then removing a central square of Dyneema® from one of the 136 mm × 132 mm faces using an abrasive wheel attached to a rotary cutting tool. The front and rear face cutout samples had 30 mm × 30 mm and 80 mm × 80 mm regions of Dyneema®, respectively removed as shown in Fig. 3. The aim was to cutout the minimum amount of Dyneema® wrapping so that the projectile did not make contact with the Dyneema® casing on the impacted face in the front face cutout targets. The rear face cutout had to be large enough to ensure that the wrapping on the rear face did not interact with the deformation of the rear surface of the aluminum plate or projectile/target ejecta.

**Fig. 6.** Fabrication of the Dyneema® encased aluminum panels using two strips of HB26 Dyneema® pre-preg tape. All leading dimensions are given in mm.

**Fig. 7.** Schematic illustration of (a) the test fixture used to grip the targets and (b) the dynamic testing facility at Chesapeake Testing (Belcamp, MD) used to perform the ballistic experiments.
A black ink square grid pattern of grid size 12.7 mm was applied to the (white) front and rear surfaces of all the Dyneema\textsuperscript{C210} encased samples. The grid was aligned with the 0° and 90° fiber orientations and permitted dynamic tracking of Dyneema\textsuperscript{C210} displacements via high speed photography during the impact events.

### 3. Impact test protocol

High speed ballistic impact tests were conducted by firing a hardened 52100 chrome steel sphere (CCR Products LLC, West Harford, CT) measuring 12.7 mm in diameter and 8.4 g in weight at the test targets described above. The measured Vickers hardness and compressive strength of the projectile material were 7.6 GPa and 3.4 GPa, respectively. The projectile impacted the targets normally and centrally at velocities in the range 110–3300 ms\textsuperscript{-1}. The penetration response of targets at these high velocities was not sensitive to the edge gripping conditions; the fixture sketched in Fig. 7(a) was employed to hold the targets in position during the tests.

All impact tests with projectile impact velocities $V_i \leq 1700$ ms\textsuperscript{-1} were performed at Chesapeake Testing (Belcamp, MD) using the setup sketched in Fig. 7(b). Two paper break screens were used to measure the projectile impact velocities, and three v. 7.3 Phantom high speed cameras (Wyane, NJ) were used to obtain simultaneous high speed images of the profile, front and rear views of the sample. The images were recorded using 1 μs exposure durations at a 20 μs inter-frame interval. In case the projectile penetrated the target, the residual velocities $V_r$ were estimated from the images of the profile camera to an accuracy of ±2.5%. A debris catcher, consisting of compliant un-consolidated Dyneema\textsuperscript{C210} pre-preg tape, was placed behind the targets in order to arrest the projectile with minimal additional damage to the projectile. Recovered projectiles were analyzed for damage and fragmentation. A few select tests at impact velocities in excess of 1700 ms\textsuperscript{-1} were performed at the University of California, Santa Barbara using a light gas gun\textsuperscript{29} with instrumentation and fixtures similar to those used at the Chesapeake testing facility.

After impact, most of the samples were water jet sectioned along a central plane to reveal internal damage. For any laminate that was partially perforated, the number of surviving plies below the projectile was counted. Some samples were also examined by high resolution X-ray computed tomography (XCT).

![Graph](image)

**Fig. 9.** The measured depth of penetration and crater diameter as a function of impact velocity for impacts against a 63.5 mm thick Al 6061-T6 plate.

![Image](image)

**Fig. 10.** Photographs of 31.6 mm thick bare aluminum plates impacted at (a) $V_i = 1090$ ms\textsuperscript{-1}, (b) $V_i = 1360$ ms\textsuperscript{-1}, (c) $V_i = 1530$ ms\textsuperscript{-1} and (d) $V_i = 1647$ ms\textsuperscript{-1} and sectioned along a central plane.
4. Impact response of targets

The measured impact velocity $V_i$ versus residual projectile/target ejecta velocity $V_r$ responses of all four target types investigated are plotted in Fig. 8. In all cases the targets show a typical ballistic behavior wherein the projectile does not fully penetrate the target up to a critical velocity referred to as the ballistic limit $V_{bl}$, and $V_r = 0$ for $V_i < V_{bl}$. Just above the ballistic limit the residual velocity of the projectile rises sharply and then $V_r$ increases more gradually with further increases in $V_i$. The ballistic limit $V_{bl}$ increases in the order: bare Al target, rear face cutout target, baseline fully encased target, and front face cutout target (with highest ballistic resistance). While it would have been anticipated that the bare Al target would be the worst performing in terms of the ballistic limit, there are some non-intuitive observations from these measurements:

(i) The front face cutout target has a higher ballistic limit compared to the baseline fully encased target.
(ii) The rear face cutout target has a significantly lower ballistic limit compared to the fully encased target. In fact the ballistic limit of the rear face cutout target was only about 100 ms$^{-1}$ higher than the bare Al target, and ejecta had a higher residual velocity than the bare aluminum plate for $V_i > 1500$ ms$^{-1}$.

These observations suggest that the Dyneema® on the front and rear of the Al plate has profoundly different effects on the ballistic resistance of the targets. We proceed to first describe in detail the penetration responses of the four target types and then use these observations to explain the apparently anomalous behavior listed above and thereby gain insight into the ballistic penetration mechanics of Dyneema® composites.

4.1. The bare Al plate

The ballistic limit of the 31.6 mm Al plate was significantly lower than the Dyneema® encased targets. In order to characterize the deformation/fracture of the projectile and aluminum plate over the larger impact velocity range investigated for the encased targets, we first performed ballistic tests on 63.5 mm thick bare Al targets made from the same 6061T6 aluminum used for the 31.6 mm Al plates. These thicker Al plates had the same in-plane dimensions as

![Fig. 12. High speed image sequences showing the deformation of the bare 31.6 mm thick Al target impacted at (a) $V_i = 1300$ ms$^{-1}$ and (b) $V_i = 1610$ ms$^{-1}$. The images in (a) are of a profile view of the rear of the target while (b) shows an oblique view of the rear surface. Time $t = 0$ corresponds to the instant that the projectile impacts the front face.](image)
the 31.6 mm plates and were impacted normally and centrally by the same spherical steel projectile as described in Section 3 at velocities $V_i$ in the range 700–3300 ms$^{-1}$. After the tests, the targets were water jet sectioned through the center of the impact crater, and the depth of penetration (DOP) measured from the bottom of the crater to the pre-impact location of the impact surface. In addition, the crater diameter was measured at the original location of the impact surface.

The DOP and crater diameter are plotted in Fig. 9 as functions of the projectile impact velocity $V_i$. The DOP initially increased with impact velocity reaching a local maximum of 42 mm at a $V_i$ of about 1700 ms$^{-1}$. It then declined to a minimum of 30 mm at an impact velocity of $\sim 2100$ ms$^{-1}$ before starting to rise once again and reaching its previous maximum DOP value (attained at $V_i \approx 1700$ ms$^{-1}$) at a $V_i$ of about 3300 ms$^{-1}$. Dehn [30] observed the same phenomena while investigating the DOP into semi-infinite plates and rationalized them as follows. The impact generates dynamic stresses within the projectile that scale with impact velocity and, at a sufficiently high impact velocity, termed the fracture threshold, the stresses surpass the strength of the projectile resulting in projectile fracture. Further increases in $V_i$ increase the number of the fragments and these fragments begin to spatially spread. Above a critical velocity, termed the shatter threshold, the increased loading area from the severely fragmented projectile causes the DOP to rapidly decrease with increasing impact velocity, and is accompanied by increases in the crater diameter. Eventually the DOP begins to rise once again, as the impact becomes a...
predominantly hydrodynamic event, and the $V_i$ range over which the DOP shows a dip is referred to as the shatter gap. We observe from Fig. 9 that our projectile/aluminum system has a shatter threshold at $\sim 1700$ ms$^{-1}$. Examination of the recovered projectiles revealed a fracture threshold velocity in the range of 1100 ms$^{-1}$ to 1150 ms$^{-1}$ after a DOP of $\sim 25$ mm. Therefore, we will be able to exploit the fragmentation of the projectile, and accompanying fragment dispersion, with our 31.6 mm plate when impacted at velocities above $V_i \sim 1150$ ms$^{-1}$.

With the understanding of the projectile fragmentation gained from the DOP measurements on the thick Al targets, we now revisit the ballistic measurements of the 31.6 mm thick Al targets in Fig. 8. Sections through the tested targets at four selected impact velocities $V_i$ are included in Fig. 10. At $V_i = 1090$ ms$^{-1} = V_{fr}$, Fig. 10(a), the section shows that the spherical projectile is intact within the target and a small plug is ejected from the target with a residual velocity of about 65 ms$^{-1}$. With increases in $V_i$, the spherical projectile exits the target and a cylindrical cavity is left behind in the target. The diameter of this cavity increases with $V_i$ as evident from Fig. 10 and this is quantified in Fig. 11 where the measured crater diameter at mid-plate thickness is plotted as a function of $V_i$. Note that the crater diameter was equal to the projectile diameter at low impact velocities but increased quadratically for velocities above the projectile fracture threshold of $\sim 1150$ ms$^{-1}$; we attribute this to the spreading of the loading caused by the fragmentation of the projectile. Moreover, the cavity develops an increasingly 'hour glass' profile and the inner surface of the cavity changes its texture; below this shatter threshold the inner surface of the cavity is smooth (see Fig. 10(a) and (b)) but at the higher impact velocities we observe scaling of the inner surface of the cylindrical cavity. We attribute this scaling to abrasion from the fragmented projectile as it penetrated the target. A second effect of projectile shattering was the leveling-off of the projectile/ejecta residual velocity (Fig. 8) as the shatter threshold, $V_i \approx 1700$ ms$^{-1}$, was approached. It is thus evident that projectile fragmentation is a potent mechanism to defeat an incoming projectile, and the application of Dyneema$^\text{SM}$ to exploit this will be made evident in the analysis of the Dyneema$^\text{SM}$ encased targets.

A sequence of high speed images showing the dynamic deformation and penetration of the 31.6 mm thick Al plate impacted at $V_i = 1300$ ms$^{-1}$ and 1610 ms$^{-1}$ are shown in Fig. 12(a) and (b), respectively. Fig. 12(a) shows a profile view, and the view in Fig. 12(b) is the so-called dead man's view (i.e. normal to the rear face). Time stamps are included in Fig. 12 with $t = 0$ corresponding...
to the instant that the projectile impacts the target. In both cases, a bulge is seen to form on the rear surface of the Al plate prior to the exit of the projectile/projectile fragments. The diameter of this bulge is significantly larger than the diameter of the projectile and increases from about 20 mm in the $V_i = 1300$ m/s to approximately 34 mm in the 1610 m/s case. This suggests that the bulging Al plate can serve as an effective load spreader. This effect too will be exploited in the Dyneema® encased targets to help increase the ballistic resistance of the targets.

4.2. The front face cutout target

In this design the projectile directly impacts the Al plate and then penetrates through the Al plate before interacting with the rear Dyneema® face. The impact versus residual velocity plot in Fig. 8 shows that targets with the front face cutout have the highest ballistic limit of all the targets considered here. Moreover after a sharp rise in the residual velocity just above the ballistic limit, $V_r$ plateaus-out, or even decreases, with increasing $V_i$ over the range of impact velocities considered here. As the projectile directly impacts the bare Al plate and penetrates through this plate before interacting with the Dyneema® it is unsurprising that the crater diameter versus $V_i$ relation for this target is identical to that for the bare Al target, Fig. 11. We also anticipate that similar to the bare Al target, the projectile incident upon this target shatters upon impact with the Al front face for impact velocities in excess of about $V_i \sim 1150$ m/s.

The superior performance of this target design is understood by considering the case of impact at $V_i = 1430$ m/s, which is just below the ballistic limit. X-ray computed tomographic (XCT) reconstructed images of the center of the rear Dyneema® face are shown in Fig. 13; in Fig. 13(a) a sketch illustrating the region being imaged is shown while in Fig. 13(b) and (c) the XCT images on two orthogonal planes are included. It is clear that (i) the projectile that has impacted the rear Dyneema® face is fragmented, (ii) this fragmented projectile is arrested after it has broken/penetrated more than half of the Dyneema® plies of the rear face laminate and (iii) the impacted area of the fragmented projectile with the rear laminate is larger than that of an intact projectile. In Section 4.3 we will show similar levels of penetration of the rear Dyneema® laminate occur in the fully encased target, but at a lower impact velocity $V_i = 1360$ m/s. However, in this case the projectile remained intact when it exited the Al plate and impacted the rear Dyneema® face. Thus, we argue that fragmentation of the projectile caused by the direct impact of the projectile against the high impedance Al face is the primary cause for the superior performance of the front face cutout targets.

High speed images of the deformation of the front face cutout target impacted at $V_i = 1430$ m/s are shown in Fig. 14 with the images in Fig. 14(a) showing the deformation of the rear face via a side profile, while Fig. 14(b) and (c) shows oblique views of the rear and front faces, respectively. The images are time synchronized, and time marks are indicated on the images, with $t' = 0$ corresponding to the instant that the deformation of the rear Dyneema® face commenced. Recall that prior to the projectile breaking through the Al plate, the Al plate bulges and petals, Fig. 12. This bulging of the Al plate initiates the motion of the rear Dyneema® face and we thus surmise that $t' = 0$ corresponds to the initiation of the bulging of the rear of the Al plate rather than the impact of the projectile/projectile fragments on the rear Dyneema® face. The side profile of the rear Dyneema® face shows a triangular profile with the base of the triangle and the height of the triangle increasing with time. The two hinges at the base of the triangle each moved outwards towards the edge of the plate at a speed of approximately 300 m/s. From the oblique rear view, Fig. 14(b), the deflected profile is seen to be pyramidal in shape, with the ridges of the pyramid deflection (lines of pyramidal face pair contact) aligned with the 0°/90° fiber orientations. Thus, the deformation of the Dyneema® laminate is highly anisotropic with the hinges traveling significantly faster along the fiber directions (which are aligned with the black marker lines) compared to their velocity at 45° to these lines. These observations are all consistent with those reported in Ref. [15] for a Dyneema® laminate directly impacted by a spherical projectile.
We note that very large transverse deflections of the Dyneema® rear face are seen in Fig. 14. In Section 4.3.1 we shall show that these large out-of-plane deflections of the Dyneema® laminate are not primarily due to the straining of the Dyneema® laminate, but rather to pull-in of the Dyneema® from the sides and front of the target. This pull is evident in oblique front view images, Fig. 14(c),\(^3\) where the grid lines curve near the cutout section of the Dyneema® (within the region indicated by the arrows) as the Dyneema® is pulled to accommodate the transverse deflection of the rear face.

4.3. The baseline fully encased target

The measured residual velocity of the projectile/ejecta versus projectile impact velocity plotted in Fig. 8 shows that fully encasing the Al plate in Dyneema® results in a ballistic performance superior to the bare Al plate but inferior to the front face cutout target. Moreover, unlike the bare Al plate and the front face cutout targets, the residual velocity does not plateau out, but continues to increase approximately linearly with \(V_i\) up to the highest (1600 ms\(^{-1}\)) impact velocity investigated here. Further, the crater diameter plotted as a function of \(V_i\) in Fig. 11 clearly shows that for a given impact velocity, a cylindrical cavity with a smaller diameter is formed in the fully encased targets compared to the bare Al plates or the front face cutout targets; a difference that increases with increasing \(V_i\).

These observations are rationalized by noting that the Dyneema® on the front face acts as a low impedance “soft” surface to the incoming projectile. This results in the shatter threshold increasing significantly beyond the \(V_i \approx 1150\) ms\(^{-1}\) value of the bare Al plate (as in the case of the bare Al plate or the front face cutout targets). This increase in the shatter threshold is confirmed in Fig. 15 where photographs of sections through the mid-plane of the fully encased targets are shown for three \(V_i\) values below the ballistic limit. It is clear that even for the case of \(V_i = 1360\) ms\(^{-1}\) the projectile remains intact in the fully encased target while the projectile had fragmented at a lower impact velocity for the front face cutout target (recall Fig. 13). The retention of a spherical projectile has three consequences:

(i) A cylindrical cavity of smaller diameter is created in the Al plate as the loading remains concentrated.
(ii) The loading on the rear Dyneema® laminate is mainly via the intact spherical projectile compared to the distributed loading by the fragmented projectile in the front face cutout target. This reduces the ability of the Dyneema® rear face to arrest the projectile.
(iii) Since the projectile remains intact, the residual velocity does not plateau out for the values of \(V_i\) reached here. We do anticipate that at higher impact velocities, where the shatter threshold for a Dyneema® faced Al plate is attained, a plateauing of the residual velocity would be observed.

By comparing the ballistic performance of the front face cutout and fully encased targets it is clear that while the Dyneema® on the front face aids in reducing the velocity of the incoming projectile,\(^4\) this front face Dyneema® effectively reduces the ability of the rear face Dyneema® to catch the projectile by keeping the projectile intact. Overall, this detrimental effect of the front face Dyneema® is larger and hence the fully encased targets have a lower ballistic performance compared to the front face cutout targets.

\(^3\) The bright flash in the front face high speed photographs is due to impact luminescence when the projectile impacts the bare Al plate.

\(^4\) The role of the Dyneema® on the front face in reducing the velocity of the incoming projectile will be made explicit in Sections 4.4 and 5.1 where the rear face cutout target is discussed.
4.3.1. Extension of the Dyneema® plies

The transverse deflection $\delta$ of the mid-span of the Dyneema® rear face is plotted in Fig. 16(a) as a function of time $t$ for three select values of the impact velocity $V_i$. The very large transverse deflections (maximum deflections $\delta_{\text{max}} \approx 30$ mm over a span of $L_0 \approx 130$ mm) suggest that the extensional strains in the Dyneema® plies are $\approx 2(\delta_{\text{max}}/L_0)^2 = 46\%$ which is far in excess of the dynamic Dyneema® fiber failure strains reported in Ref. [8]. The reason for this discrepancy is that in making the above extensional strain estimate we assume that the rear Dyneema® face is rigidly held at the edges of the plate and does not pull-in. However, the oblique high speed images in Fig. 14(b) (note the deformed grid pattern near the sample edges) show that the grid pattern on the rear face near the edges translates and that the Dyneema® is pulled inwards from the edges by the mechanism sketched in Fig. 17(a). This pull-in needs to be corrected for in order to make an accurate estimate of the actual extensional strain within the plies of the rear Dyneema® face.

Consider the cross-sectional sketch of the rear Dyneema® face in Fig. 17(b), where we have indicated the position of a fiducial marker near the edge of the plate in both the undeformed and transient deformed configurations. The grid lines on the rear face serve as these fiducial markers, and we choose grid lines that are initially spaced a distance $L_0$ apart. As the Dyneema® is pulled-in from the front face towards the rear, these fiducial markers move inwards by $\xi_1$ and $\xi_2$, respectively such that the total pull-in distance $\xi = \xi_1 + \xi_2$. The section of the Dyneema® rear face of initial length $L_0$ has changed to a length $L$ in the deformed configuration where $L$ is the arc-length between the fiducial markers in the deformed configuration. The technique used to measure $\xi$ and $L$ from the oblique and profile high speed image views is detailed in the Appendix B.

The measured values of $L$ and $\xi$ as a function of time $t$ are plotted in Fig. 16(b) and (c), respectively, for three values of the impact velocity $V_i$. It is clear that within experimental error $L \leq 1.03L_0$ throughout the deformation history. This clearly shows...
that the extension of the Dyneema\textsuperscript{\textregistered} plies is no more than the measured dynamic failure strain of the Dyneema\textsuperscript{\textregistered} yarns by Russell et al.\textsuperscript{[8]. However, it increases monotonically with $V_i$ (Fig. 16(c)), and thus we conclude that the large deflections of the rear face are largely accommodated by pull-in at the edges rather than just elastic extensional straining of the Dyneema\textsuperscript{\textregistered} plies.

4.4. The rear face cutout target

The rear face cutout targets had a significantly lower ballistic performance compared to the fully encased or front face cutout targets (Fig. 8). In fact, the ballistic limit was only 100 m\,s\textsuperscript{1} higher than the bare Al plates. This can be understood in terms of the insights gained from the discussions in Sections 4.1–4.3. Recall that the key to the superior performance of the front face cutout targets stemmed from the projectile fragmenting upon impacting the bare Al plate at high velocities. These spatially and temporally dispersed fragments then penetrate through the Al plate and subsequently impact the rear laminate. When Dyneema\textsuperscript{\textregistered} was added on the front face, as seen with the fully encased target, the projectile did not fragment, and thus the aluminum plate and rear laminate of this target were loaded by the intact projectile, which applied a highly localized pressure to the Dyneema\textsuperscript{\textregistered} laminate. This resulted in a reduced ballistic performance compared to the front face cutout target.

The rear face cutout target does not invoke any of the mechanisms that enhance the ballistic performance of the targets, viz. it has Dyneema\textsuperscript{\textregistered} on the front face that prevents the fragmentation of the projectile and it does not have a Dyneema\textsuperscript{\textregistered} rear face to catch the projectile that exits the Al plate. This is clearly seen in the high speed images of Fig. 18 which show an oblique view of the rear face of the rear face cutout target impacted at $V_i = 1420$ m\,s\textsuperscript{1}. An intact projectile exits the target after penetrating through the Al plate.

5. Discussion of Dyneema\textsuperscript{\textregistered} penetration mechanisms

The three different types of Dyneema\textsuperscript{\textregistered} encased targets investigated above have revealed that Dyneema\textsuperscript{\textregistered} on the front and the rear face have rather contrasting effects on the ballistic resistance of the targets. In order to better understand these effects we proceed to quantify the ballistic performance of the Dyneema\textsuperscript{\textregistered} faces in these samples using a methodology introduced by Karthikeyan et al.\textsuperscript{[15] which quantifies the progressive failure of the Dyneema\textsuperscript{\textregistered}.

We begin by first summarizing the results of Karthikeyan et al.\textsuperscript{[15] who impacted 150 mm square, $\sim$6 mm thick, edge clamped HB26 Dyneema\textsuperscript{\textregistered} plates by a 12.7 mm diameter spherical steel ball as sketched in Fig. 19. Karthikeyan et al.\textsuperscript{[15] observed that penetration of the Dyneema\textsuperscript{\textregistered} plate by this spherical projectile occurred in a progressive manner such that an increasing number of plies fractured directly under the impact site with increasing impact velocity until all plies fractured at the ballistic limit to allow the projectile to perforate the plate. The measurements of Karthikeyan et al.\textsuperscript{[15] are replotted in Fig. 20(b) in terms of the fraction of perforated plies in the laminate versus the projectile impact velocity $V_i$. Ply fracture in the edge clamped plate initiated at an impact velocity $V_i = 250$ m\,s\textsuperscript{1}, and the fraction of plies perforated then increased with $V_i$ until all plies had fractured under the projectile at the ballistic limit of about 445 m\,s\textsuperscript{1}. We emphasize that in the experiments of Karthikeyan et al.\textsuperscript{[15]} no measurable deformation of the projectile occurred over the entire velocity range investigated.

The HB26 plates investigated by Karthikeyan et al.\textsuperscript{[15] are comparable in terms of size and areal mass to the Dyneema\textsuperscript{\textregistered} front and rear face laminates of the targets studied here. Moreover, the projectile used by Karthikeyan et al.\textsuperscript{[15] was identical to the projectile used in this study, and we can therefore directly compare our measurements with those of Karthikeyan et al.\textsuperscript{[15] In order to make these comparisons we note that the Dyneema\textsuperscript{\textregistered} faces in the targets used here fall into two categories:

(i) The Dyneema\textsuperscript{\textregistered} on the front face (in the fully encased and rear face cutout targets) is back supported by the Al plate and cannot undergo significant transverse deflection as illustrated in Fig. 21(a).

(ii) The Dyneema\textsuperscript{\textregistered} on the rear face (in the fully encased and front face cutout targets) can deflect under the projectile and pull-in from the edges as illustrated in Fig. 21(b); this case is
expected to be very similar to the situation in the experi-
ments of Karthikeyan et al. [15].

We shall thus consider each of these in turn.

5.1. Dyneema® plates resting on a strong foundation

Impact experiments on the fully encased and rear face cutout targets at impact velocities much below the ballistic limit were used to measure the penetration response of the Dyneema® on the front faces of these targets and thereby infer the response of Dyneema® plates resting on a strong foundation. The measured fraction of plies penetrated in these tests as a function of $V_i$ is included in Fig. 20(b). It is clear that the projectile penetrates the supported Dyneema® plate with relative ease. The plies of the plate begin to perforate by $V_i = 110 \text{ m s}^{-1}$ with complete perforation of the plate (i.e. ballistic limit) being attained at $V_i = 200 \text{ m s}^{-1}$. These values are at least a factor of two less than those measured by Karthikeyan et al. [15] for an edge clamped plate as seen clearly in Fig. 20(b).

A photograph of the central section through the fully encased specimen impacted at $V_i = 110 \text{ m s}^{-1}$ showing the partial perforation of the Dyneema® front laminate.

Fig. 21. (a) Schematic showing the sequence of events for the perforation of the Dyneema® on the front face of the model targets. (b) Schematic illustrating the pull-in of the Dyneema® as the projectile impacts the rear Dyneema® face of the model targets. Magnified views of this impact event by either an intact or fragmented projectile are included. (c) A photograph of the central section through the fully encased specimen impacted at $V_i = 110 \text{ m s}^{-1}$ showing the partial perforation of the Dyneema® front laminate.
been activated during this impact event as the Dyneema® plate was unable to deflect in a string-like mode as sketched in Fig. 2. Rather, fracture of the Dyneema® plies seems to have occurred under compressive loading by the projectile via the indirect tension mechanism analyzed in a forthcoming publication by Attwood et al. [31] (and initially hypothesized by Woodward et al. [22]). In this mechanism the applied transverse compressive stress results in shear stress forming between the alternating 0° and 90° plies due to the anisotropic deformation nature of these plies. These shear stresses generate fiber tension via a shear lag mechanism, and it is this fiber tension that we hypothesize causes the perforation of the plies as indicated in Fig. 21(a).

5.2. Edge supported Dyneema® plates

The rear faces of the fully encased and front face cutout targets are impacted by the projectile/ejecta that comes through the Al plate. Thus, in order to make a fair comparison we define $V_i^*$ to be the velocity of the projectile/ejecta that impacts this rear Dyneema® face. For a given projectile velocity $V_i$ the corresponding velocity $V_i^*$ is estimated as follows:

(i) Fully encased targets: The projectile in these targets first penetrates the Dyneema® on the front face and then the Al plate before it impacts the Dyneema® rear face. Thus for a given $V_i$, $V_i^*$ is given by the residual velocity of the projectile as it exits the rear face cut-out targets. We thus calculated $V_i^*$ by interpolating the residual velocity data for the rear face cutout targets in Fig. 8.

(ii) Front face cutout targets: The projectile impacting these targets only penetrates the Al plate before it impacts the Dyneema® rear face. Thus for a given $V_i$, $V_i^*$ is given by the residual velocity of the projectile as it exits the bare Al targets. We thus calculated $V_i^*$ by interpolating the residual velocity data for the bare Al targets in Fig. 8.

The measurements of the fraction of the perforated plies of the rear Dyneema® faces as a function of $V_i^*$ are included in Fig. 20(b) for both the fully encased and front face cutout targets. Intriguingly the two sample types do not overlap and also differ from those of Karthikeyan et al. [15]. We thus discuss them in turn to clarify the mechanisms responsible for these discrepancies.

**Fully encased target:** The ballistic response is very similar to that observed by Karthikeyan et al. [15] until approximately 40% of the plies are penetrated. Subsequently, the rear Dyneema® face of the fully encased target seems to have an enhanced ballistic performance compared to the plates of Karthikeyan et al. [15], i.e. the rear Dyneema® face of the fully encased target needs to be impacted at a higher velocity to achieve the same level of perforation as in Ref. [15]. To rationalize this, consider the sketch in Fig. 22(a) where the penetration of the projectile through the fully encased target is illustrated. Following the high speed images in Fig. 18, we expect that the Al plate bulges at the rear prior to the projectile breaking through. This large radius of curvature bulging of the Al plate results in the rear Dyneema® face acquiring a velocity and deflecting prior to impact by the projectile that emerges through the bulge. This is indicated in Fig. 22(b) where we sketch the mid-span deflection $\delta$ of the rear Dyneema® face as a function of time $t'$. The point at which the projectile impacts the Dyneema® face is also indicated (red circles) and the slope of the $\delta$ versus $t'$ curve at this instant is the velocity of the Dyneema® face at the instant of impact; we refer to this velocity as $\delta_0$. With increasing $V_i$ (and consequently $V_i^*$), $\delta_0$ increases and the relative velocity between the projectile and plate at the instant of impact, $V_i^* - \delta_0$ increases at a slower rate in these fully encased specimens compared to that in the Karthikeyan et al. [15] experiments where the Dyneema® plate was always stationary prior to impact. The key driver to perforation of the Dyneema® plate is the relative velocity between the projectile and the Dyneema® plate. Recall that we have plotted the perforation of the Dyneema® in terms of the impact velocity $V_i$ or $V_i^*$ rather than relative velocity between the Dyneema® and the
portions of the Dyneema\textsuperscript{\textregistered} removed from the rear face so that the projectile can exit the Al plate without again interacting with the Dyneema\textsuperscript{\textregistered}. The measurements show that the ballistic performance of these targets increases in the order: bare Al plate, rear face cutout plate, fully encased plates, and the front face cutout plate having the highest ballistic resistance. A combination of synchronized high speed photography (with three cameras) together with post-test examination of the target via high resolution X-ray tomography was used elucidate the deformation and perforation mechanisms and explain the above mentioned ballistic performance rankings. The primary mechanisms revealed by the analysis are as follows:

(i) Penetration of Dyneema\textsuperscript{\textregistered} plates supported on either a foundation or edge restrained occurs by the progressive fracture of fiber plies under the projectile. The number of fractured plies increases with impact velocity.

(ii) The ballistic performance of Dyneema\textsuperscript{\textregistered} plates supported on a foundation is significantly lower (ballistic limit is lower by nearly a factor of two) compared to edge restrained plates.

(iii) When Dyneema\textsuperscript{\textregistered} plates were pre-accelerated to an initial velocity prior to the impact of the projectile (in our case by the large radius of curvature bulge of the Al plate against the rear Dyneema\textsuperscript{\textregistered} face), the apparent ballistic performance of the Dyneema\textsuperscript{\textregistered} plate was enhanced. This was due to a lowering of the relative velocity between the plate and the projectile (and thus the applied pressure) for a given projectile velocity.

(iv) Fragmentation and concomitant spatial and temporal dispersion of the projectile by an intervening aluminum plate increased the ballistic limit of the laminate by distributing the interfacial forces between the projectile and laminate over a larger area, thereby reducing the contact pressure.

(v) Placement of the low impedance Dyneema\textsuperscript{\textregistered} on the front face of the targets delays the onset of projectile fragmentation. This resulted in targets with Dyneema\textsuperscript{\textregistered} on their strike faces having a reduced ballistic performance at higher impact velocities.

Finally we conclude by noting that the simple model targets designed here have elucidated mechanisms that show how Dyneema\textsuperscript{\textregistered} can have both beneficial and detrimental effects on the ballistic resistance of targets. A fuller understanding of these mechanisms may provide better insight into how best to deploy Dyneema\textsuperscript{\textregistered} in a multi-material structure.

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Appendix A. Tensile properties of high performance fibers

The data used to generate the material maps in Fig. 1 is listed in Table A1 along with the details of the sources of the information.
Consider the square grid as shown in Fig. B1. When this square grid is observed at an angle a distorted image is obtained on the plane of view. We use the projective transformation in the “maketform” function in MATLAB to construct the transformation by providing the actual and observed 2D co-ordinates of the four corners of one of the grid squares. This transformation is then applied to the oblique images using the “intrapform” function in MATLAB so as to correct the image for the parallax. The measurements of $\varepsilon$ are made by counting pixels to measure the movement of the fiducial markers between consecutive transformed high speed images.