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Hybridized composite architecture for mitigation of non-penetrating ballistic trauma

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ABSTRACT

Ultra-high molecular weight polyethylene (UHWMPE) fiber-based composites are employed in a variety of Soldier protection systems due to their impressive specific strength and elastic wave speed. However, as UHMWPE composites rely on their tenacity to decelerate the projectile impact, even in successfully arrested impacts issues arise with the blunt deformation trauma generated due to high deformation of the material into the Soldier. In this experiment, UHMWPE composite laminates employing two widely different laminate architectures, [0°/90°] and ARL X Hybrid, were evaluated to assess the effect of panel architecture on impact pressures generated in non-penetrating ballistic impact events. Panels were impacted with 7.62 mm lead core projectiles on a testing platform designed for the physics-based evaluation of BHBT of helmet materials. Composite panel deformation for the [0°/90°] configuration impacted the testing frame at velocities 2.2× higher than the ARL X Hybrid specimens, leading to a 526% higher average maximum pressure amplitude measured on the BHBT platform (45.5 ± 19.1 MPa and 7.3 ± 3.3 MPa for [0°/90°] and ARL X Hybrid, respectively), demonstrating the effectiveness of ARL X Hybrid in mitigating non-penetrating ballistic impact stress. The experiment has provided critical insight into non-penetrating small arms impact stresses and the role materials, materials processing, and materials design influence non-penetrating blunt trauma response.

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1. Introduction

Dismounted Soldier protection systems utilizing ultra-high molecular weight polyethylene (UHMWPE) fiber composites have been replacing para-aramid based fiber composites in an increasing number of Soldier protection platforms, such as ballistic helmets and the backing materials for ceramic-faced small arms protective inserts (SAPI). In 2013, the Army and Marines began low-rate production and fielding the Enhanced Combat Helmet (ECH), which will be replacing the Army Combat Helmet (ACH) and Lightweight Helmet (LWH) used by the Army and Marines, respectively. While the ACH and LWH utilized a KM2 Kevlar woven-fiber based composite impregnated with a 1:1 mixture of polyvinyl butyral (PVB)/phenolic resin epoxy matrix, the ECH system is manufactured entirely out of UHMWPE fiber composite with thermoplastic-based matrix chemistries. This helmet yields a significant increase (>35% overall) to fragmentation resistance, and the first U.S. based helmet qualified for a specific small arms penetration specification.

The combination of material properties of the UHMWPE fiber is what yields its impressive ballistic efficiency. A valuable metric that has been derived to rank the ballistic performance of composite fibers is a scaling law that correlated the performance to a parameter called the Cunniff velocity, c^* [1]. The parameter related the ballistic limit to tensile fiber tensile strength, failure strain, elastic modulus and fiber density. Comparing UHMWPE to other engineering fibers, UHMWPE fibers exhibit impressive strength ($\sigma^{UTS} = 3.3–3.9$ GPa) [2]. While other high performance fibers, such as carbon and aramids, exhibit higher strengths, the low density of UHMWPE ($\rho = 0.97$ g/cm^3) yields specific strength values that are unmatched by Kevlar or carbon. Fiber strains for UHMWPE have been reported to be as high as 3.5–4.0% [2], however, UHMWPE was shown to exhibit strain-rate sensitivity at low strain rates. At higher rates (10^{-2}–10^3 s^{-1}), the fibers are strain-rate insensitive and strains of around 2.0% were reported [3]. Even with the lower fiber strains incorporated in the calculation, the predictions show that the specific strength of UHMWPE and the high speed of sound

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in the highly crystalline longitudinal fiber direction (ν = 1922 m/s) [3] are the main drivers to the high ballistic efficiency of UHMWPE fibers [4,5]. As the UHMWPE fiber composites are impacted by projectiles, the longitudinal wave travels through the fiber at high elastic wave speed, promoting transfer of strain through the yarn, and in-plane to adjacent yarns through matrix strain transfer. The high transverse membrane stretching serves to promote energy absorption in the composite. These transverse membrane bulging and tension mechanisms have been shown to be dominant for energy absorption and projectile deceleration during high-rate ballistic impact [4–8].

The transverse deflection ability, driven by the tenacity of the fiber, leads to impressive ballistic efficiency, or resistance to penetration (RTP). However, this ability of the fiber to strain and decelerate projectile energy inherently leads to extensive back face deformation (BFD). Given that the interior spacing between the helmet shell and the Soldier's head is relatively sparse (~20 mm, adjusting for a small compression of the helmet pad for fitment), there is little room for allowable BFD. This is problematic, as UHMWPE derive their ballistic efficiency from this transverse behavior. While previous helmets were designed to decelerate and resist penetration of fragmentary and handgun rounds within the 20 mm spacing, the demand for even lighter helmet materials and higher threats will push performance requirements into a regime where penetration resistance is possible, however doing so in the confines of the system spacing will not be possible. There are no definitive medical criteria for correlation of armor deformation to blunt trauma in the event of a non-penetrating impact in where the deformation strikes the wearer's skull [9]. This is primarily because these mechanisms are not well under-stood to begin with. Evidence suggests that two mechanisms are generally responsible for Behind Helmet Blunt Trauma (BHBT) injuries – direct contact of the deforming armor material with the head, and stress waves transmitted through the material from the ballistic impact [10]. However, the link between the amount of ballistic, blunt or blast insult and the physiological injury caused by those forces are not well known at this time. Therefore, there is a large impetus for not only developing physiologically based criteria for helmet blunt trauma [9], but also developing physics-based helmet materials solutions that work to mitigate the extent of forces reaching the Soldier's head during impact.

On the composite manufacturing level, fiber manufacturers have been able to provide varying UHMWPE fiber composites with varying resin chemistries to assist in tailoring the deformation response for Soldier applications. It has been shown that the interlaminar shear strength affects the energy absorption capability of the composite [11], and that matrix materials with high shear strengths (such as the PVB/phenolic epoxy) reduce ballistic performance of those with lower shear strength [7,12,13]. The ballistic performance has been attributed to ease of deflection of composite fibers in the transverse direction, and to low interfacial shear strengths between layers, causing higher level of delamination between ply interfaces, contributing to further energy absorption. To ensure high performance from UHMWPE ballistic composites, thermoplastic-based elastomers are commonly used, such as synthetic rubbers (such as Kraton®), silicones, thermoplastic polyurethanes (TPU), and polyethylene [14]. These composite products are typically resin starved (generally in the range of 12–20% by volume), ensuring high ballistic efficiency due to higher level of the fiber present. The UHMWPE composite products are supplied as unidirectional sheets of fiber stacked orthogonally in a repeating [0°/90°] configuration. The orthogonal fiber construction maximizes the ductility of the fibers under ballistic impact for absorbing high amounts of the projectile kinetic energy [5,15]. Most of the high-performance fiber composites exhibit this common orthogonal fiber arrangement. It is worth nothing that many of these variables, such as the effect of shear strength [16] and composite fiber orientation (fiber stacking ratio, ply size, matrix content, etc.) are not accounted for in the Cunniff scaling law, therefore there is still extensive ongoing research in this area.

Though the decrease in interlaminar shear strengths leads to better ballistic performance in composites, armor manufacturers have typically utilized UHMWPE composites with higher shear strength thermoplastic matrix resins (such as the polyurethane-based matrix on the composite fiber used in this experiment), as they provide higher resistance against deformation at a significant, yet acceptable cost to the ultimate ballistic efficiency.

Army Research Laboratory (ARL) and others have been pursuing materials, processing, and materials design strategies for balancing RTP and BFD in Soldier protection materials. These thrusts have included strategies for optimization of laminate processing variables [17–20], and hybridization of dissimilar composite fibers/matrix chemistries or laminate architectures [21], the most promising of these being the engineering of hybridized composite laminate architectures. Researchers at ARL proposed the benefit of using hybridized laminate architectures for optimizing the ballistic and impact response of UHMWPE. One laminate architecture in particular, called ARL X Hybrid, yielded a 40.5% reduction in BFD against 9 mm 124 grain (8.0 g) full metal jacket (FMJ) handgun rounds with no drop to ballistic efficiency against fragmentary threats [21]. The ARL X Hybrid architecture was shown to also be highly effective when used in body armor applications [22], lowering deformation extent by 20–35% in both first and second impacts.

The aim for this work is to characterize and understand the physics-based effects composite laminate architecture has on blunt trauma and impact stress against non-penetrating ballistic blunt impact. Two laminate architectures, [0°/90°] and ARL X Hybrid were evaluated against a 7.62 lead-cored rifle projectile. To develop insight in these phenomena, researchers from the ARL Survivability/Lethality Analysis Directorate (SLAD) built a first generation testing system, based on previous research efforts in behind armor blunt trauma [23–28]. The purpose of the testbed is to analyze the impact stresses generated during non-penetrating ballistic impacts. The configuration is shown in Fig. 1. This testbed was designed to simulate a combat helmet condition, in which a flat composite panel is stood off 20 mm from the head (in this case simulated by an acrylic plate and ballistic gelatin block) with ACH-specification padding. Variables assessed during testing included deformation velocity, impact damage, and impact stresses. These results were analyzed in combination with freely backed plate testing of the two UHMWPE laminate architectures to help guide the understanding of the deformation behavior modification due to the change in laminate architecture, and to determine whether the performance improvements shown by ARL X Hybrid translate to reduction of blunt trauma in non-penetrating ballistic impacts.

2. Experimental

Composite panels were processed using a commercial UHMWPE fiber composite from Honeywell® – Spectra Shield® II SR-3136 (Honeywell Specialty Materials, Morristown, NJ). The UHMWPE fiber composite consists of a unidirectional cross-ply configuration with four plies per layer (in a 0°/90°/0°/90° arrangement) coated with a TPU-based resin system. The material was cut into 30.48 × 30.48 cm square sheets from the material roll using a cutting table (Gerber Technology, Tolland, CT) and stacked to three areal densities (AD): 10.7, 12.6, and 14.6 kg/m^2 (2.2, 2.6, and 3.0 PSF). These laminates were consolidated using a uniaxial press (Wabash 800 Ton Press, Wabash MPI, Wabash, IN) with a slightly