



# Ultra-High Molecular Weight Polyethylene Composites for Ballistic Protection: Mechanisms, Modelling, and Performance

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## Abstract

Ultra-high molecular weight polyethylene (UHMWPE) stands as the primary material choice for developing lightweight high-performance composites used in ballistic armour systems. This review provides a complete evaluation of UHMWPE properties which enable its outstanding energy absorption performance when subjected to high-speed impacts. The paper evaluates ballistic test results from projectiles traveling at 250 to 700 m/s speeds and examines three failure modes which include delamination and shear plugging and fibre tensile rupture. The Lambert–Jonas and Reid–Wen formulations serve as analytical and numerical models to evaluate performance predictions through ballistic limit velocity ( $V_{50}$ ) and energy absorption ( $\Delta E$ ) and back-face signature (BFS) assessments. The review examines hybrid material structures which combine aramid with carbon fibre and polyimide and shear-thickening fluids (STF) to improve structural stiffness and multi-hit resistance. The paper examines upcoming technologies such as nano-enhanced UHMWPE and thermoplastic resin systems which represent potential advancements for future lightweight armour development. The synthesis provides design guidelines for ply orientation and layer sequencing and interfacial bonding to achieve optimal performance against diverse ballistic threats.

## 1. Introduction

### 1.1. General

The scientific community has focused research on creating bulletproof jackets through high-velocity impact-resistant composite materials during the last several years. The development of ultra-high molecular weight polyethylene (UHMWPE) stands out as one of the most promising materials for such applications. The molecular weight of polyethylene in UHMWPE exceeds 1 million g/mol and makes it a distinct type of polymer. UHMWPE obtains its exceptional characteristics from its high molecular weight structure that provides both high strength

and high modulus and excellent impact resistance according to Wu et al. (2019). The material UHMWPE serves applications in medical devices and wear-resistant components as well as ballistic protection systems. UHMWPE serves as a core material in hybrid composites for bulletproof jackets because it is used alongside ceramics and fibres. These composites exhibit outstanding capabilities in absorbing and resisting impacts and penetrations according to Lee et al. (2020). The primary benefit of UHMWPE-based composites exists in their ability to absorb and dissipate impact energy. The

polymer absorbs energy due to its extended molecular weight which enables it to deform before breaking.

### 1.2. Properties of UHMWPE

The high modulus of UHMWPE provides exceptional stiffness and resistance to deformation to this material. The material demonstrates optimal suitability for uses that need strong resistance to impact UHMWPE-based composites (1). Multiple bulletproof jackets perform outstanding with the new composite scientific development with performance fibres that have been investigated by various researchers. The hybrid UHMWPE and ceramic composites were developed to resist high speed bullets and demonstrate several benefits. The UHMWPE has an affinity for lower corrosion and Kevlar weight compared bulletproof jackets. UHMWPE-based back face material made resistance of the plain composites susceptible to the conditions due to minimal composite research [1-5].

### 1.3. Characteristics of UHMWPE

UHMWPE represents a thermoplastic polyethylene with exceptionally long molecular chains (molar mass 2–6 million Da) that holds the title of having the highest impact strength among all thermoplastics. The ballistic armour market uses the well-known products Dyneema (DSM) and Spectra

(Honeywell) from renowned brands. UHMWPE serves as a primary component in personal protective equipment because of its unique blend of high tensile strength and low density with exceptional energy absorption properties.

## 2. Material Properties Relevant to Ballistic Protection

### 2.1. Mechanical characteristics

UHMWPE shows superior specific strength and modulus and increased tensile fracture strain than aramid or carbon-based fibres thus enabling it to absorb larger amounts of energy through deformation. The yield strengths of Dyneema SK75 and SK76 reach 2.4 GPa at densities of 0.97 g/cm<sup>3</sup> which results in a strength-to-weight ratio that exceeds aramid by 40%

### 2.2. Thermal and environmental limitations

The low melting point of UHMWPE ranges between 130–136 °C which renders it unsuitable for extended use above 80 °C because high temperatures lead to destructive ballistic property degradation. Ultraviolet radiation together with extended environmental exposure can trigger protective film or coating delamination but carriers provide protection against this effect Shown in Table 1.

**Table 1** Key Properties of UHMWPE for Ballistic Applications

Property	Typical Value	Units	Notes
Density	0.93 – 0.97	g/cm <sup>3</sup>	Lower than Kevlar, aramid, and glass fibres
Tensile Strength (fibre)	2.4 – 3.6	GPa	High-performance grades (e.g., Dyneema®, Spectra®)
Tensile Modulus (fibre)	80 – 200	GPa	Highly oriented fibers, processing-dependent
Elongation at Break	2.5 – 4.0	%	Indicates ductility before failure
Melting Point	130 – 136	°C	Limits use in high-temperature environments
Thermal Conductivity (in-plane)	~1.5	W/m·K	Higher than many thermoplastics
Impact Resistance	Very high	—	Excellent energy absorption capability
Moisture Absorption	<0.01	% (24 h in water)	Practically hydrophobic
UV Resistance	Poor (without additives)	—	Requires stabilizers or coatings

Ballistic Limit ( $V_{50}$ , 9mm FMJ)	450 – 550	m/s	Depends on layup, areal density, backing
Areal Density (typical composite)	5 – 15	kg/m <sup>2</sup>	Used in soft and hard armor panels
Failure Mechanisms	Delamination, back-face deformation, yarn rupture	—	Affected by strain rate, impact energy
Chemical Resistance	Excellent (acids, alkalis, solvents)	—	Advantageous in diverse operational environments
Abrasion Resistance	Excellent	—	Useful for long-term durability in field use

### 3. Ballistic Performance: Mechanisms & Models

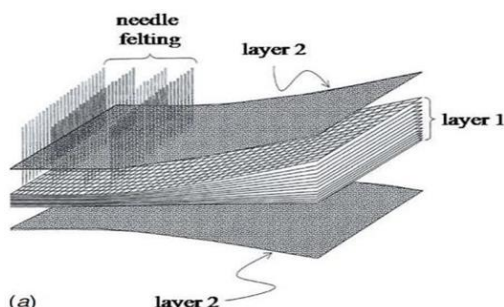
#### 3.1. Experimental observations

UHMWPE laminates with a thickness below 10 mm demonstrate ballistic performance twice better than E-glass laminates at equivalent thickness through their ability to delaminate and undergo large tensile strains. When subjected to steel-core projectiles the material experiences failure through deformation and delamination while bulging occurs at the rear surface while thicker laminates experience two distinct stages of penetration from shear plug formation to tensile breakdown [6-10]

##### 3.1.1. Specific Test-Case Results & Failure Modes

#### Thin Laminates Vs Steel Ball Impact (2)

UHMWPE laminated plates (thicknesses of 1.1 mm, 2.8 mm, and 5.4 mm) were subjected to steel-ball impacts. Recorded ballistic-limit speeds were 233.5 m/s, 415.7 m/s, and 602.9 m/s, respectively. Thinner panels fail via localized bulging and shear plugging, whereas thicker panels transition to tensile-dominated failure mechanisms Shown in Figure 1.



**Figure 1** Combination of Composite Structure

#### Energy Absorption Vs Incident Velocity (3)

UHMWPE laminate energy absorption peaked near 47 J for incident speeds below ~330 m/s. In

the range 327–340 m/s,  $\Delta E$  sharply dropped to ~30 J, then gradually declined to ~20 J at higher velocities (>500 m/s). Multi-stage failure modes observed: initial tensile deformation, transitioning to shear plugging and delamination as speed increased.

#### Soft- vs. Rigid-Matrix Textile Composites (4)

Comparing UHMWPE fibre plain-weave fabrics in different matrix resins revealed that flexible matrices supported membrane-stretching impacts and achieved higher energy absorption per ply, despite showing larger deformations. Rigid matrices performed worse: stress localized, and perforations occurred earlier.

#### Hybrid UHMWPE + Carbon-Fiber Front Face (5)

In a falling-dart test simulating low-velocity impact, hybridization with PE-CF front or rear layers reduced back-face signature (BFS) by ~25% versus pure UHMWPE panels. Carbon fibre increased stiffness and prevented catastrophic bending; UHMWPE contributed ductile energy absorption Bohrium

#### 3.2. Analytical and numerical modelling

The analytical work of Li et al. (6) alongside others developed a model which calculates ballistic limit and determines the energy distribution between fibre tension and delamination effects and matrix failure and mass acceleration while also predicting event duration and residual velocity based on projectile size and mass and composite thickness. Ballistic simulation studies and finite element analyses demonstrate that thicker UHMWPE laminates improve both ballistic limit velocity and energy absorption yet become more prone to delamination and bulge failure. MDPI Poly in 2023 published the simulation results revealed that a reduction of in-plane elastic modulus from 30.70 GPa to 12.28 GPa

led to an increase in  $V_{50}$  from 555 m/s to 575 m/s (4% gain) while an increase of modulus to 36.84 GPa resulted in a decrease of  $V_{50}$  to 545 m/s (2% loss). This means that more deformable panels can take up tensile stresses while too stiff panels do not get time to deform fully before failure. These effects were non-linear; not strictly linear (6) Shown in Figure 2.



**Figure 2** Damage zones in the ceramic tile, backing plate and a projectile (bullet)

Perforation Models (Ogive-Nose Projectile Studies)

**Using energy balance:**

Half  $mv^2 = \text{half } mv^2 + W$  (work of perforation), with  $W \sim \text{constant}$  (~5 kJ around ballistic limit)

**The Lambert–Jonas model:**

$$v_r = \alpha (v^p - v_{bl}^p)^{1/p}$$

When  $p = 2$  and  $\alpha = 1$  then the equation simplifies to

$$v_r = \text{sqrt}(v^2 - v_{bl}^2)$$

It describes the residual velocity quite well above the ballistic limit

**Reid–Wen Reid Ballistic Limit Law (Classic)**

$$V_b = [\pi \Gamma \sqrt{(\rho_t \sigma_e) D^2 T / (4 m)}] \times [1 + \sqrt{(1 + (8 m) / (\pi \Gamma^2 \rho_t D^2 T))}]$$

The formula calculates  $V_b$  with material density  $\rho_t$ , elastic limit  $\sigma_e$ , projectile diameter  $D$ , thickness  $T$  and mass  $m$  using the empirical constant  $\Gamma$  (7)

**4. Specific High-Velocity Impact Resistance Attributes**

**4.1. Rifle-Caliber threat performance**

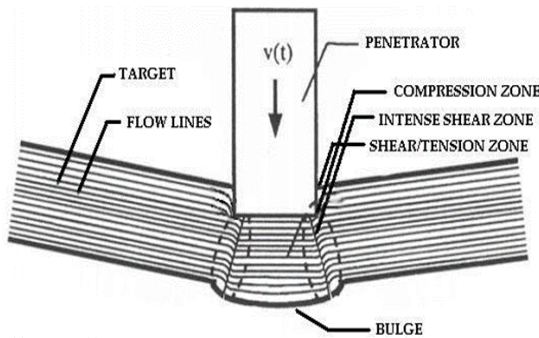
ECO-UHMWPE composites surpass Kevlar-epoxy in tests using 7.62×39 mm projectiles thus enabling panel reduction to 3.5 kg while achieving 25% higher energy absorption and 30% less deformation for equivalent threat levels [10-11]. UHMWPE plates show shear strength values between 13-15 GPa during steel-constrained high-speed blunt projectile impacts when velocities exceed 1150 m/s according to simulation results (8,9) Shown in Table 2.

**Table 2** Main results of the comparative analysis of key parameters (10,11,12)

Sr. No	Sample / Study	Condition	Ballistic Limit ( $V_{50}$ )	Energy Absorption ( $\Delta E$ )	Failure Modes
1	UHMWPE plate (1.1 mm)	Steel ball impact	$\approx 233.5$ m/s	-	Bulging, shear plugging
2	UHMWPE plate (2.8 mm)	Steel ball impact	$\approx 415.7$ m/s	-	Transition tensile + shear
3	UHMWPE plate (5.4 mm)	Steel ball impact	$\approx 602.9$ m/s	-	Tensile-dominated failure
4	UHMWPE laminate (<330 m/s)	Aero-ballistic range	$V_{50} \sim 327-330$ m/s	$\Delta E \sim 47$ J	Shear plugging $\rightarrow$ delamination
5	UHMWPE laminate (340–500 m/s)	Increasing projectile speed	-	$\Delta E$ drops to $\sim 30$ J then $\sim 20$ J	Fiber tensile failure, delamination
6	UHMWPE + carbon front/rear hybrid	Low-velocity dart impact	-	BFS $\sim 25\%$ vs UHMWPE	Controlled stiffness, ductile UHMWPE deformation
7	Flexible matrix textile composite	Gas gun spherical projectile	-	(rigid matrix) energy/ply	Membrane stretching $\rightarrow$ improved resistance

**4.2. Hybrid structures and optimization**

The ballistic resistance of single-material plates improves when UHMWPE laminates contain aramid or carbon fibres and through optimization of ply angles and layer arrangements. The ballistic performance of energy absorption improves when stacking Kevlar in front of UHMWPE core. The arrangement of plies at specific angles ( $45^{\circ}/0^{\circ}/90^{\circ}/-45^{\circ}$ ) enhances low-velocity impact energy absorption by 86% when compared to standard ply sequences while aramid or polyester core-spun yarn hybridization leads to energy absorption increases (13) Shown in Figure 3.



**Figure 3 Schematic View of Failure Mechanisms by Bending and Plugging**

**5. Limitations and Failure Modes**

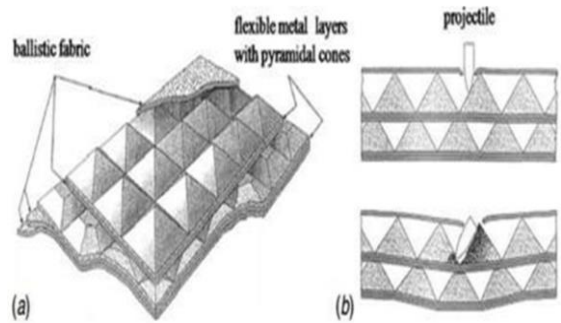
**5.1. Delamination and back face signatures**

When impacted UHMWPE plates expand rapidly due to delamination between layers which helps absorb energy but creates problems for multi-hit functionality and structural stability (14,15) [16-20]

**5.2. Contact-shot vulnerability**

UHMWPE soft armour fails to provide reliable protection against contact shots because of the direct muzzle contact with the vest so manufacturers typically add aramid layers in the backing. FBI contact-shot stoppage panels that combine UD

UHMWPE with aramid backing layers satisfy protocol requirements for the panels Shown in Figure 4.



**Figure 4 Damage propagation through simulations (400 m/s)**

**5.3. Ageing and environmental degradation**

Aging in UV/high-heat environments or film delamination over time (especially in early coatings) can reduce ballistic capabilities; modern panels mitigate this by improved encapsulants, but proper storage/use is critical (16,17)

**6. Emerging Methods & Surface Compatibilization**

- Surface treatments of UHMWPE fibres (chemical functionalization, roughening, grafting) improve fibre-matrix adhesion in composite systems, strengthening mechanical performance and longevity. Alternative reinforcing schemes such as combining UHMWPE with nanomaterials, graded polymer-sand composites, or novel polyurethane-urea elastomers are under investigation to further enhance high-velocity impact resistance and energy dissipation Shown in Table 3.

**7. Synthesis & Design Recommendations (18)**

**Table 3 Engineering Guidelines for Hybrid Composite Armor Design**

Sr. No.	Design Parameter	Recommendation
1.	Material stacking	Use UHMWPE core with aramid or hybrid fiber front/back for contact-shot resilience
2.	Thickness (areal density)	Target $\geq 10$ mm/appropriate areal density to transition from shear to tensile regimes for enhanced energy absorption
3.	Ply orientation	Multi-angle stacking (e.g. $\pm 45^{\circ}$ , $0^{\circ}$ , $90^{\circ}$ ) improves both tensile deformation and impact resistance

4.	Surface treatment	Apply compatibilization or resin treatments to enhance layer bonding and reduce delamination
5.	Environmental constraints	Avoid sustained temperatures >80 °C; shield from UV and moisture
6.	Layer sequencing	Optimize hybrid stacking (carbon, Kevlar, UHMWPE) depending on projectile shape and threat type

### Conclusions & Future Directions

Ultra-high molecular weight polyethylene (UHMWPE)-based composites continue to demonstrate superior ballistic resistance on a per-weight basis, particularly effective against high-velocity threats such as 5.56 mm and 7.62 mm NATO rifle rounds. This performance stems from UHMWPE's high tensile strength, low density (~0.93 g/cm<sup>3</sup>), and ability to dissipate kinetic energy through fibrillation and inter-yarn friction. However, key failure modes—such as interlaminar delamination, transverse cracking, yarn pull-out, and significant back-face signature (BFS) bulging—limit their effectiveness under extreme or repeated impacts. These mechanisms are further exacerbated by thermal softening, moisture absorption, and UV-induced degradation, which can reduce long-term performance in field conditions. To address these challenges, hybrid composite architectures incorporating ceramic strike faces, glass, aramid, or carbon fibre reinforcements are increasingly employed to improve multi-threat protection. Additionally, nanoscale surface treatments—such as plasma modification, graphene oxide grafting, or silane coupling agents—have been shown to enhance interfacial bonding between UHMWPE fibres and polymer matrices, reducing delamination and improving load transfer efficiency. Analytical models, based on energy conservation principles and classical laminate theory, and finite element (FE) simulations incorporating progressive failure criteria (e.g., Hashin, Puck), provide reasonably accurate predictions of ballistic limit velocity ( $V_{50}$ ), penetration depth, and post-impact deformation. However, capturing the highly nonlinear, strain-rate-dependent, and anisotropic behaviour of UHMWPE remains a modelling challenge, especially under conditions of multi-hit loading, oblique impact angles, or variable temperature and humidity. Emerging research directions offer

promising avenues for next-generation armour systems. Functionally graded materials (FGMs), such as polymer-sand gradient layers or ceramic-to-polymer transitions, aim to tailor impedance mismatch and stress wave propagation through controlled material gradation. Polyurea-urethane (PUU) elastomers, known for their hyper elastic energy absorption and rebound behaviour under high strain rates, are being explored as interlayers or backings to further dissipate impact energy. Moreover, nanomaterial integration—including carbon nanotubes (CNTs), graphene nanoplatelets, and nano clay additives—has demonstrated potential for enhancing stiffness, thermal stability, and ballistic resilience without significant weight penalties. In summary, while current UHMWPE composites offer outstanding ballistic protection in single-hit scenarios, future advances in material design, hybridization, and multiscale modelling are essential to meet evolving threats and operational demands. Continued interdisciplinary research is critical for optimizing performance under realistic, complex impact conditions involving multiple strikes, aging effects, and environmental exposure.

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