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Review **JoPC**

High-Velocity Impact Response of CFRP and Hybrid Composites: A Comprehensive Review on Ballistic Resistance and Damage Mechanisms

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Abstract

This review consolidates recent advances in the study of high-velocity impact response of carbon fiber reinforced polymer and hybrid composites. Carbon fiber reinforced polymer composites are widely applied in aerospace, automotive, and defense due to their high strength-to-weight ratio, stiffness, and durability. However, their susceptibility to impact damage such as delamination, matrix cracking, and fiber breakage limits their performance under dynamic loading. To overcome these challenges, researchers have explored reinforcement strategies including fiber hybridization, sandwich structures, natural fiber incorporation, and nanoparticle modification. This paper critically examines the influence of material composition, stacking sequence, geometrical parameters, and environmental conditions on the dynamic response of composites. Both experimental and numerical methods, including finite element simulations and damage models, are reviewed to understand ballistic limits, energy absorption mechanisms, and failure patterns. The findings highlight hybridization with Kevlar, glass, and basalt fibers, and the use of sandwich and bio-composites, as promising approaches for enhancing impact resistance. The review provides insight into the damage mechanics of composites under high-velocity impact and identifies future research pathways toward designing lightweight, cost-effective, and impact-tolerant structural materials.

Keywords: CFRP, hybrid composites, high-velocity impact, ballistic performance, damage mechanisms

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INTRODUCTION

Composites have increasingly replaced metals in sectors like aviation, marine, and automotive, mainly due to their superior strength-to-weight ratios. In aerospace, the use of these materials reduces structural weight, thereby lowering fuel consumption, which compensates for the initial high manufacturing costs. Furthermore, composites exhibit superior resistance to fatigue, impact, and corrosion, making them highly advantageous for demanding applications [1]. Composite structures are vulnerable to damage under impact, largely due to their relatively weak performance in the transverse direction. This susceptibility arises from the anisotropic nature of composites, where strength and stiffness are typically optimized in the in-plane directions but are often limited in the thickness direction. Consequently, impacts that generate out-of-plane stresses, such as those from dropped tools or high-velocity debris, can lead to delamination, matrix cracking, and fiber pull-out.

Addressing this limitation is crucial for applications in aerospace, automotive, and defense, where impact resistance is essential for maintaining structural integrity and safety [2]. HVI on target occurs when a projectile strikes with a speed typically in the range of several kilometers per second.

The extent of damage sustained by the target material during such an impact depends on multiple factors, including:
(i) The type of impact,
(ii) The material properties of both the target and the Impactor, and
(iii) Characteristics of the impacto, include rigidity, form, and weight.

While low-velocity impacts commonly occur during service or maintenance activities, high-velocity impacts are associated with high-speed, high-energy projectiles or debris that collide with the target. In high-velocity impacts, the energy transferred upon collision can induce complex damage mechanisms, for example delamination, fiber breakage, and matrix cracking in composite materials, making them more vulnerable compared to metals. Analyzing these impacts is crucial for applications in aerospace, defense, and automotive sectors, where even minor impact damage can significantly affect structural integrity. Understanding the influence of projectile dynamics and material response is essential for designing impact-resistant composite structures.

Polymer-based composites are among the most popular, typically consisting of a polymer resin matrix reinforced with fibers. Due to their cost-effectiveness and ease of manufacturing, these materials are extensively produced and applied across various industries. Epoxy resin, commonly used in polymer composites, is especially valued for its strong adhesion, chemical resistance, versatility, and excellent mechanical properties. Understanding the various damage mechanisms associated with impact on composite structures has become essential for investigating their dynamic response under HVI. The damage procedure in composites is complex due to their anisotropic behavior and uneven stress distribution, unlike metals, which exhibit greater ductility and more uniform stress response. Fiber breaking is the primary failure mode in high velocity impacts [3]. Enhancing the impact performance of composite materials is a key focus in composite structural research. Numerous studies have proposed various methods to increase impact resistance and reduce damage. These approaches include hybrid and sandwich composites, adjustments to stacking sequences, varying the number of plies, material selection, fiber stitching, the use of short rods (Z-pinning), external patching, self-healing techniques, incorporation of recovery agents, modifications or additions to matrix materials, integration of natural fibers like particle toughening, jute, hybridization, and the incorporation of carbon nanotubes [4]. The wide use of composites in aerospace and defense sectors has driven significant research into their impact resistance. Fibers offer unique mechanical properties and impact responses, but they also present limitations. Hybridization, or combining different types of fibers, has proven effective for enhancing composite performance, addressing limitations, and improving fatigue resistance, impact durability, and cost-efficiency. A range of hybrid fiber composites has been studied, including E-glass and S2-glass under impact, hybrid Kevlar-glass, Kevlar-carbon, carbon-glass, and woven Kenaf-Aramid, all evaluated for their performance under high-velocity impact conditions [5]. Kevlar, noted for its high elastic modulus, tensile strength, impact, and fire resistance has been widely used in ballistic defense applications. Numerous studies, both experimental and numerical, have explored Kevlar’s behavior under various impact velocities. Despite Kevlar’s excellent longitudinal strength, it has limitations, including poor chemical resistance and low transverse strength. Hybridization with materials such as carbon with other fibers, nanoparticles, and ceramics has proven effective in enhancing Kevlar's properties. Basalt fiber has recently attracted attention due to its favorable mechanical characteristics, heat resistance, and chemical stability. Studies of Basalt and Basalt-carbon hybrids under ballistic impact demonstrate that combining Basalt with Kevlar can significantly enhance composite performance. Various techniques are used to evaluate the performance of polymer matrix composite such as include Scanning Electron Microscopy (SEM), ultrasonic testing, and C-scan imaging, which enable the detailed analysis of micro-cracking, delamination, and fiber-matrix debonding. Additionally, X-ray computed tomography (CT) scans are sometimes utilized to visualize 3D damage distribution within the composite layers [6]. Table 1 reports the various studies conducted on CFRP and Hybrid Composites in past. Table 2 provided systematic literature search and screening process for this review.

Table 1. Various studies conducted on CFRP and Hybrid Composites.

Method of Enhancement	Materials	Results	Reference
Hybrid composites	Jute + natural rubber	Hybrid composites showed superior ballistic performance compared to pure jute and stiff composites.	[7]
Hybrid composites	Kevlar-3D, Basalt-3D (various configs)	The B3K3 configuration was more impact resistant than H3B3, and Kevlar absorbed more energy after baking.	[8]
Hybrid composites	Ceramics, metals, fabric laminates	A 7.62 mm round was stopped by 5 out of 25 panels, with velocity ranging between 806–887.5 m/s.	[9]
Hybrid composites	CFRP + aramid fiber	AF/CFRP hybridization demonstrated superior resistance to ballistic impact compared to CFRP/AF.	[10]
Hybrid composites	Carbon + date palm + Kevlar	The hybrid composite absorbed more impact energy than Kevlar alone.	[11]
Hybrid composites	Basalt + Kevlar polypropylene	Hybridization did not increase ballistic limit, but natural fibers performed better than synthetic ones.	[12]
Natural composites	3D Kevlar/basalt	The B3K3 configuration provided superior ballistic performance among the designs tested.	[13]
Hybrid composites	Jute-rubber-jute-epoxy	Maximum energy absorption was observed when impacted by a conical projectile.	
Hybrid composites	Glass/epoxy + carbon/epoxy [G-C-G-C-G]	The stacking sequence improved performance under impact loads due to enhanced perforation resistance.	[15]
Hybrid composites	Kevlar-glass CFRP	An optimized laminate layup increased energy absorption without adding mass.	[16]
GFRP	Curved GFRP plates	Increased plate thickness improved anti-penetration, while flat impactors produced the highest force.	[17]
Sandwich structure	CFRP + Al foam	More kinetic energy was dissipated through delamination, and oblique impacts showed greater resistance than vertical ones.	
CFRP	CFRP + Al honeycomb	The front CFRP panel absorbed the highest share of impact load in the mixed structure.	[19]
CFRP	CF/PEEK composites	Impact performance was enhanced, although higher velocities caused more severe damage.	[20]
Hybrid composites	IM7/8552 pseudo-woven CFRP	Hybridization reduced back face damage by 45%, deflection by 19.5%, and increased V50 velocity by 5.5%.	[21]
Metal matrix	CFRP + aluminum laminate (CRALL)	CRALL exhibited a high ballistic limit, with strain rate having a significant effect on flat-nosed projectile resistance.	[22]
Natural composites	Aramid helical lay-ups	Helical lay-ups showed lower perforation resistance compared to cross-ply and quasi-isotropic laminates.	[23]
CFRP	T700/TDE-85	Hygrothermal aging caused cracks at the fiber/matrix interface and interlayer surfaces.	[24]
GFRP	GFRP laminate	Laminates with 0°/90° and ±45° orientations showed higher ballistic resistance.	[25]
GFRP	Woven GFRP	A continuum model successfully predicted the performance under high-velocity impact.	[26]
Hybrid composites	Aged woven GFRP	Hygrothermal aging reduced the ballistic limit by 14.9%.	[27]
GFRP	Glass/epoxy + PE-SMA	Anchored PE-SMA composites showed a 72.7% higher ballistic limit and improved CAI resistance.	[28]
Sandwich material	Foam core + FML	A numerical model predicted residual velocity and perforation energy with 88.8% and 97.4% accuracy.	[29]
Hybrid composites	Kevlar + S2-glass	Predictive modeling effectively reduced the need for experimental trials.	[30]
Hybrid composites	Carbon, glass, basalt	Basalt/epoxy absorbed the maximum ballistic energy, while carbon/epoxy had the highest flexural strength.	[31]
Natural composites	Veneer-aramid (2:1	Panels absorbed 78.6% of ballistic energy at 354.7 J.	[32]

	ratio)		
Hybrid composites	SiC + CFRP	The combination of SiC face plates and CFRP rear plates produced the best armor performance.	[33]
Hybrid composites	Al foam + fillers	The addition of micro- and nano-fillers enhanced energy absorption and ballistic resistance.	[34]
Hybrid composites	Carbon + UHMWPE	Increasing UHMWPE content improved specific energy dissipation.	[35]
Natural composites	Multilayer natural fiber armor	The use of natural fibers reduced both weight and cost by up to 95%.	[36]
Natural composites	Graphene-epoxy + luffa	Addition of 2 wt% graphene improved tensile, flexural, and impact strength.	[37]
Natural composites	Polycarbonate + aramid	The matrix percentage significantly affected performance, with yarn breakage governing ballistic response.	[38]
Natural composites	STF + aramid fabric	STF and polyurea coatings improved impact resistance and energy absorption.	[39]
Natural composites	2D braid vs. 3D weave	2D braids failed globally with yarn debonding, while 3D weaves caused localized damage.	[40]
CFRP	Carbon–epoxy laminates	Low temperatures increased fiber breakage and shear matrix cracks.	[41]
GFRP	Woven S2-glass/epoxy	An anisotropic model accurately predicted stress–strain fields.	[42]
Metal matrix	Fiber Metal Laminates	Oblique hits caused projectile deflection, and higher velocity reduced the deflection angle.	[43]
CFRP	AS4/8552 carbon–epoxy	Six mechanisms contributed to energy absorption, including fiber failure, delamination, and matrix cracking.	[44]

Table 2. Systematic literature search and screening process adopted in this review.

Search Terms	**Initial search**	**First filter**	**Second filter**	**Third filter**	**Fourth filter**
	Initial number of articles searched from Scopus database	Articles left after exclusion criteria based on document type	Articles left after exclusion other than English	Articles left after duplication (title-wise)	Articles left after meticulous abstract analysis based on keywords
CFRP and Hybrid Composites under High-Velocity Impact	420	260	220	120	32
High-Velocity Impact Response of Composite Materials	100	80	60	30	8
Ballistic Performance of Composite Structures	50	35	25	15	4
Failure and Damage Mechanisms in Composite Impact	120	90	70	35	12
Fabrication Techniques for Impact-Resistant Composites	350	250	200	90	15
Design Strategies for Ballistic-Resistant Composite Systems	60	30	20	10	4
Total number of papers used in the review	1100	745	595	300	75

This paper reviews historical data and recent studies on fiber-reinforced hybrid polymer composites, focusing on performance factors and failure mechanisms under high-velocity impacts. It examines the ballistic characteristics of composites reinforced with glass, carbon, Kevlar, and hybrid textiles with nanophases. Key findings from past research on impact response and resistance enhancement methods are discussed.

The study reviews impact velocity effects, analytical approaches, and damage assessment, along with factors improving impact resistance, such as material composition, hybridization, sandwich structures, biocomposites, and geometric considerations. Experimental, numerical, and analytical studies provide insights into impact behavior and optimization strategies.

FACTORS INFLUENCING THE IMPACT ANALYSIS COMPOSITE

Figure 1 illustrates the parameters affecting the dynamic response of the composite structure under HVI loading. High-velocity impact testing on composite materials is primarily conducted using gas gun apparatus, where projectiles are launched at controlled, high speeds to simulate real-world impact scenarios such as ballistic and aerospace applications.

This setup allows researchers to evaluate the composite's response to extreme conditions, including the effects of strain rate sensitivity and energy dissipation mechanisms. Figures 2 and 11 illustrate the comprehensive configuration for HVI testing. During experimentation, multiple sensors are often incorporated to capture real-time data on impact force, displacement, and velocity, providing a comprehensive view of the material's initial response. After the impact, advanced non-destructive techniques are employed to examine the internal damage without altering the specimen's integrity.

Influence of Constituent Materials

The influence of constituent materials on improving the impact damage resistance of various composites has been extensively explored in the literature, offering numerous optimized solutions to better understand material mechanics and dynamic behavior. Composites are primarily composed of reinforcements, matrix materials, and the interface region, with the mechanical and chemical properties of these components playing a critical role in the damage and fracture mechanisms of the composite.

Factors such as loading, impact velocity, and the inclusion of supplementary materials substantially influence the dynamic response of composites during high-velocity impacts. This thorough examination facilitates the advancement of more robust and effective composite materials for many applications.

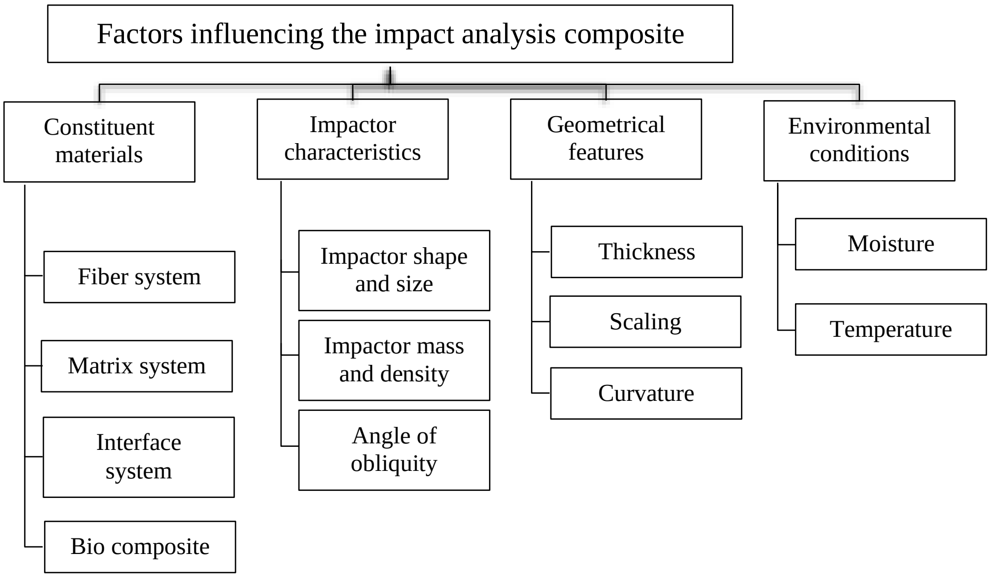


Figure 1. Factors influencing the impact response of the composite structure under High velocity.

Based on Fiber Reinforced Composites

Alkhatib et al. [11] studied improving the energy absorption capability of ballistic plates using a three-phase approach. The first phase analyzed the effects of three fiber types (carbon, date palm, and Kevlar), while the second focused on hybridization within layers. Numerical simulations using LS-DYNA optimized the hybrid composite for maximum energy absorption, demonstrating superior performance compared to non-hybrid Kevlar plates of the same density. The lighter-weight plates offer enhanced protection and ease of movement. Simulation results were validated through ballistic testing, confirming conservative but reliable predictions. Shih et al. [39] used ballistic testing to evaluate the impact behaviour of aramid fabric reinforced with polyurea elastomers, epoxy, and shear-thickening fluids (STFs). Results reveal that polyurea elastomers provide the highest energy absorption and impact resistance, while epoxy-treated composites suffer from stress concentration, reducing their performance. STF impregnation enhances structural protection but adds weight and lowers specific energy absorption. The findings offer insights into energy absorption, deformation, and damage characteristics for advancing protective equipment design.

Khodadadi et al. [45] investigated the energy absorption and behavior of neat Kevlar fabric and PMCs under HVI. It explores the influence of two matrix types, rubber and thermoset epoxy, on energy absorption, with a focus on how the hardness of the rubber matrix (high and low) affects performance. Ballistic tests revealed that the rubber matrix improves energy absorption and flexibility, whereas the thermoset matrix reduces flexibility, adversely impacting ballistic performance. The study also analyzes the damage mechanisms for each type of sample. Zhang et al. [46] studied the impact resistance of 2.5 mm thick carbon fiber/resin composite laminates under various impact conditions. The results show that oblique impacts at 300 m/s lead to higher energy absorption than normal impacts. Differences in failure modes are observed for center and edge impacts, with center impacts causing buckling and edge impacts leading to compression and buckling failures. The findings provide insights into the residual strength of laminates after impact. Mou et al. [47] investigated the ballistic behavior of plain-woven aramid fabric containment systems through experiments and LS-DYNA simulations. Ballistic tests revealed energy absorption via deformation and inter-yarn friction, with strain rate significantly enhancing peak stress and modulus. Simulations accurately replicated deformation and failure modes, validating the method for analyzing ballistic impacts. Insights into interlaminar contact and projectile effects are also discussed.

Zhu et al. [40] examined the impact resistance and damage tolerance of two distinct composite types: two-dimensional triaxially braided composites (2DTBC) and three-dimensional angle-interlock woven composites (3DAWC). Both materials show similar impact resistance, but their damage patterns differ. 3DAWC exhibits higher damage tolerance in compression after impact due to binder yarns preventing buckling. The study additionally reveals a distinctive trend in residual compressive strength associated with impact energy, taking into account both penetration and rebound.

Based on Matrix Oriented Systems

The dynamic response of composite structures to high-velocity impacts is primarily dictated by the fiber system, whereas damage tolerance is considerably affected by the matrix material and interface region. The matrix material stabilizes the reinforcement and facilitates load transfer to the fibers, thereby impacting the overall mechanical performance of the composite. Kosedag et al. [48] examined the impact behavior of SiC-reinforced Al6061 MMCs at varying Fiber volume fractions. Low-velocity and ballistic impact tests reveal that increased SiC content enhances ballistic resistance but reduces impact energy absorption. Notable damage patterns include cracking at 30% SiC and complete failure at 40%. The findings highlight the trade-offs in performance with varying reinforcement levels. Akbari et al. [49] examined the ballistic performance of ceramic-reinforced aluminum matrix composites (AA6061, AA7075, and AA5083) against 7.62 × 39 mm bullets using numerical models and experimental tests. Key parameters include alumina content (15%, 30%, 45%) and target thickness (20, 25, 30 mm). Results reveal AA5083 as the best matrix material, with an optimal armor configuration of

25 mm thickness and 30% alumina, offering superior resistance to penetration and projectile erosion. Dong et al. [50] examined the ballistic impact response of fiber-reinforced composite/metal composite targets (FMCT) against spherical projectiles by experimental and numerical approaches. Significant findings encompass the effects of impact velocity and target areal density on residual velocity, failure mechanisms, and energy absorption. Targets featuring Kevlar composite front plates and steel back plates demonstrate enhanced anti-penetration efficacy. Improving the protective attributes of the target can be accomplished by optimizing the thickness of the Kevlar front plate and minimizing the thickness of the steel back plate.

Kumar et al. [51] evaluated the ballistic performance of ZrSiO4 particle-reinforced Al-Si12Cu (LM13) aluminum alloy composites fabricated via stir casting. Ballistic tests using AK-47 bullets reveal that composites with finer particles (20 µm) offer superior resistance to penetration, reducing bullet residual velocity by ∼34%, compared to ∼29% and ∼22% for 60 µm and 120 µm particles, respectively. The spall diameter also decreases with larger particle sizes. Microstructural analysis highlights the composite's behavior under high-impact loads. Fiber-metal composite targets, especially those with Kevlar front plates and steel back plates, offer enhanced anti-penetration performance. Additionally, finer reinforcement particles in aluminum alloys significantly reduce residual bullet velocity.

Based on Interfaced Oriented System

Localized impact damage reduces the residual compressive strength of composites. Carbon fiber demonstrates inadequate toughness, which can be enhanced by incorporating more durable materials like glass, Kevlar, and aramid. Hybridization techniques combine ductile, impact-resistant fibers with high-stiffness reinforcements to improve mechanical properties. Studies demonstrate that hybridization enhances the impact resistance of carbon-epoxy composites. Extensive research has been undertaken on hybrid composites, including carbon/glass, carbon/Kevlar, and carbon/aramid [52]. Mousavi & Khoramishad [16] investigated the energy absorption capabilities of hybridized CFRP composites incorporating Kevlar and glass layers under HVI, utilizing experimental validation, FE modeling, and ANN. The results show that optimizing the laminate layup can enhance energy absorption by 135% with only a 9% mass increase. This methodology provides a safe and economical technique for the creation of impact-resistant hybrid composites.

Figure 2 compares the simulation and experimental damage morphologies. Ahmed et al. [53] established a novel numerical model to predict the ballistic impact behavior of hybrid 3D woven composites, validated through experiments. It captures interply and intraply damage mechanisms using simple finite elements, with Z-yarns modeled as 1D connectors. The approach accurately estimates residual velocities and failure mechanisms. It provides reliable results while minimizing computational costs. Tang, Yin et al. [18] examined the protective efficacy of CFRP/aluminum foam sandwich constructions subjected to high-velocity impacts via ABAQUS/Explicit simulation.

A VUMAT user subroutine is applied to model the CFRP panel with Hashin's damage criterion, and aluminum foam's behavior is simulated using an elastic model. Results reveal that with increasing impact velocities (172–450 m/s), the an increase in kinetic energy loss, but the rate of increase slows down as velocity rises. Additionally, higher velocities result in greater delamination and fiber breakage in the sandwich structure, leading to more energy dissipation through these damage mechanisms. Figure 3 illustrates the geometry of a three-dimensional orthogonal woven representative volume element featuring three sets of fiber tows. Ahmadi et al. [29] investigated the high-velocity impact characteristics of sandwich constructions featuring syntactic foam cores and fiber metal laminate skins using both experimental and numerical approaches.

A finite element model utilizing ABAQUS/Explicit integrates proprietary VUMAT subroutines for the simulation of GFRP composites and syntactic foam. Multiscale modeling estimates the effective characteristics of woven composites by Python-based homogenization. Gas-gun experiments validate the model, showing accuracies of 88.8% for residual velocity and 97.4% for perforation energy.

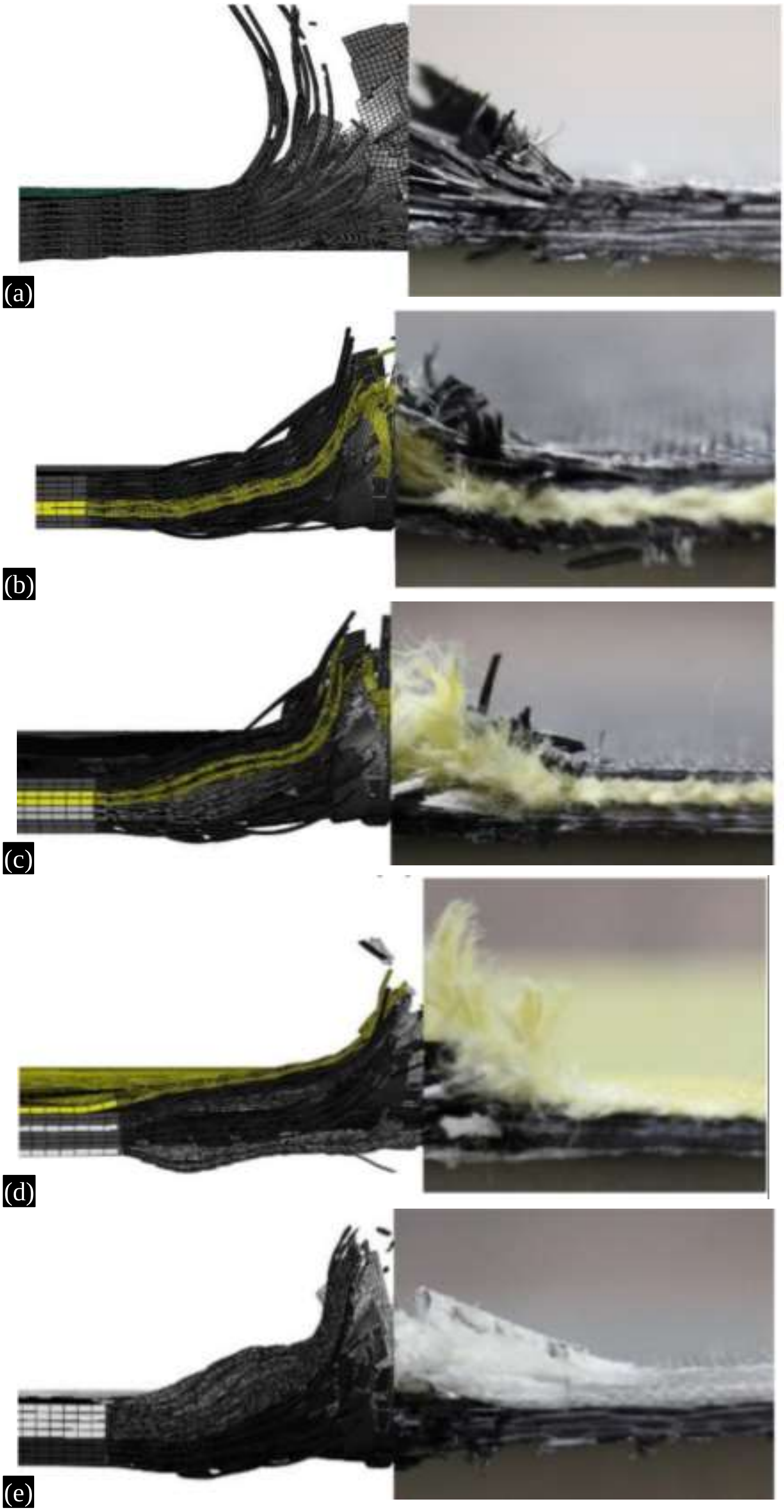


Figure 2. Comparison of simulated (left) and experimental (right) damage morphologies of a) [C_8] b) [$C_2K_2C_4$] c) [$C_2G_4K_2C_2$] d) [$G_2C_3G_2C_2K$] e) [C_4G_4] [16].

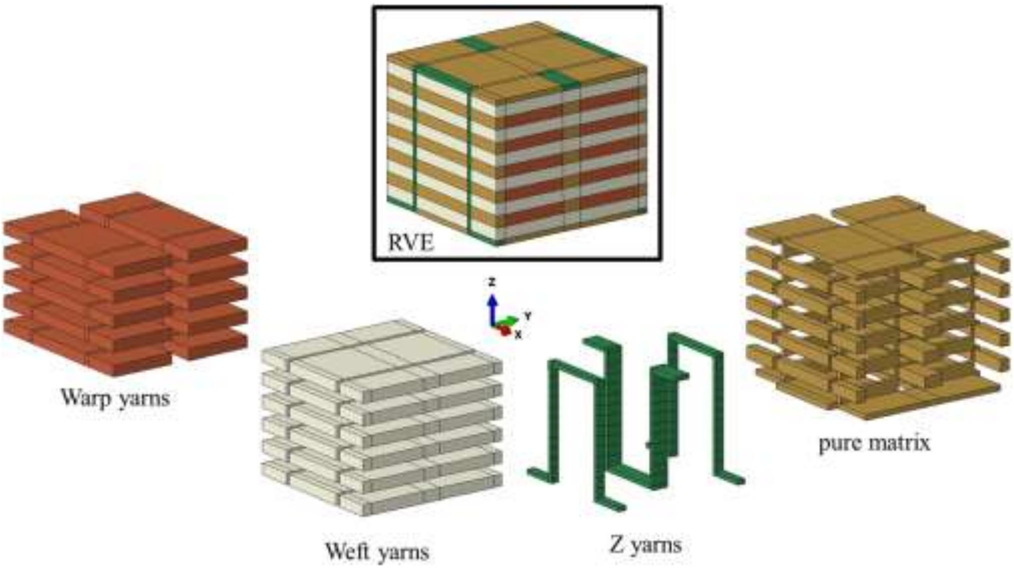


Figure 3. 3D orthogonal woven RVE with warp, weft, and z-yarns and pure matrix region [53].

The validated model further explores the effects of impactor mass, shape, and stacking sequence on impact response. Doğru et al. [31] examined the flexural and ballistic properties of glass fiber, carbon, and their hybrid composites, as well as basalt (natural fabric). For possible applications in ballistic load-carrying structures, this study investigated the utilization of natural basalt fiber in inter-ply hybrid sequences with carbon and glass fibers. Nine-layer composite plates with cross-ply stacking sequences ($[0/90]_9$) were fabricated and tested. Three-point bending flexural testing and ballistic impact tests indicated that basalt/epoxy composites exhibited the best energy absorption under ballistic loading, whereas the basalt-glass-basalt/epoxy composite showed a similar energy absorption capability. Xu et al. [54] performed an investigation into the ballistic performance, failure mechanisms, and energy absorption properties of hybrid fiber-reinforced polymer targets (HFRPT) composed of carbon and aramid fiber composites.

A finite element model was established to assess the effects of layer thickness and stacking sequence, corroborated by a theoretical approach that forecasted ballistic limits with an error margin of less than 10%. Four failure modes: compression, tensile, shear plugging, and tension-shear coupling were identified, with hybridization affecting their prevalence. The study further examined the influence of stacking sequence and layer thickness on energy absorption.

These studies collectively highlight advancements in hybrid composite materials for ballistic protection, emphasizing the role of material selection, layup optimization, and numerical modeling in enhancing impact resistance. By integrating experimental validation with finite element simulations, researchers have improved the predictive accuracy of impact behavior, energy absorption, and failure mechanisms.

Based on Biocomposite Oriented System

Bio composites are advanced materials that integrate natural fibers with a polymer matrix, providing an environmentally sustainable alternative to conventional composites. The performance of bio composites during high-velocity impact is determined by the nature of the natural fibers, the matrix material, and the fiber-matrix contact. These materials exhibit unique energy absorption characteristics due to the viscoelastic properties of natural fibers and their ability to dissipate impact energy. High-velocity impacts, such as those encountered in ballistic applications, can result in localized damage, including fiber breakage, delamination, and matrix cracking. Research into bio composites under high-velocity impact focuses on enhancing their toughness, reducing delamination, and improving their structural integrity for applications in aerospace, automotive, and defence industries.

Mahesh et al. [7] experimentally determined the ballistic limit of compliant composites, neat jute fabric, hybrid composites, and stiff jute epoxy composites. Ballistic impact assessments were performed utilizing a gas gun and a conical bullet. Results indicate that compliant hybrid composites exhibit superior energy absorption and ballistic performance compared to other configurations. The inclusion of natural rubber significantly enhances ballistic response while maintaining composite flexibility. Damage mechanisms governing these materials were also analyzed. Wang et al. [23] investigated the impact behavior of bio-inspired composite laminates, including helicoidal fiber architectures, in comparison to cross-ply controls and quasi-isotropic configurations, under high-velocity impacts. Helicoidal laminates with small rotation angles exhibited superior perforation resistance and energy absorption compared to quasi-isotropic and cross-ply configurations, with cross-ply being the most effective. Failure processes differed with lay-up, exhibiting fewer fragmented fibers and decreased delamination at small inter-ply angles, which facilitated wedge-in mechanisms. Helicoidal layouts with minimal angles are therefore not advisable for impact-resistant applications. Doddamani et al. [36] reviewed to examine the ballistic impact response of NFRP used in armor systems, focusing on material properties, kinetic energy absorption, and projectile parameters. It highlights internal (fiber/matrix composition, failure modes) and external (projectile angles, residual velocity) factors, along with strategies to enhance performance and the economic viability of replacing synthetic fibers with natural ones. Mohan Kumar et al. [14] explored the ballistic impact response of eco-friendly JRJ-ES-JRJ hybrid sandwich composites with varying core thicknesses (10–20 mm) and filler compositions (0–40%) under 350 m/s impacts using flat, conical, and hemispherical projectiles. Numerical simulations employing Taguchi's design of experiments demonstrate that filler mix and core thickness substantially affect ballistic resistance. Conical projectiles lead to maximum energy absorption, while flat projectiles cause the most immediate damage, demonstrating the composite's potential for defense applications. Figure 4 shows the Schematic sketch of the Gas-gun apparatus. Satkar et al. [15] examined the ballistic impact performance of hybrid composite laminates comprising glass and carbon layers through numerical analysis in ANSYS-Explicit Dynamic. The stacking sequence [G-C-G-C-G] exhibited enhanced energy absorption across various impact velocities (400–500 m/s). Furthermore, DOE methodologies were utilized to assess the effect of various parameters on the impact resistance of the laminate. These studies highlight advancements in the ballistic response of natural fiber and bio-inspired composites, emphasizing their potential for impact-resistant applications. Experimental and numerical analyses demonstrate the influence of material composition, fiber architecture, and projectile characteristics on failure mechanisms and energy absorption. While compliant hybrid composites and cross-ply laminates exhibit superior performance, small-angle helicoidal configurations are less effective. The economic feasibility of replacing synthetic fibers with natural alternatives is also explored, paving the way for sustainable armor solutions. These findings advance the creation of lightweight, high-performance ballistic materials for defense-related objectives.

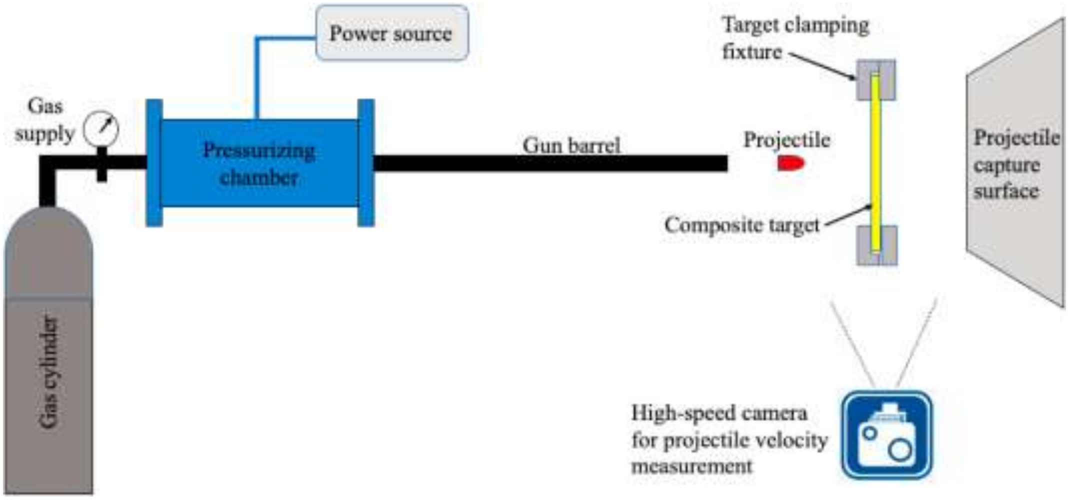


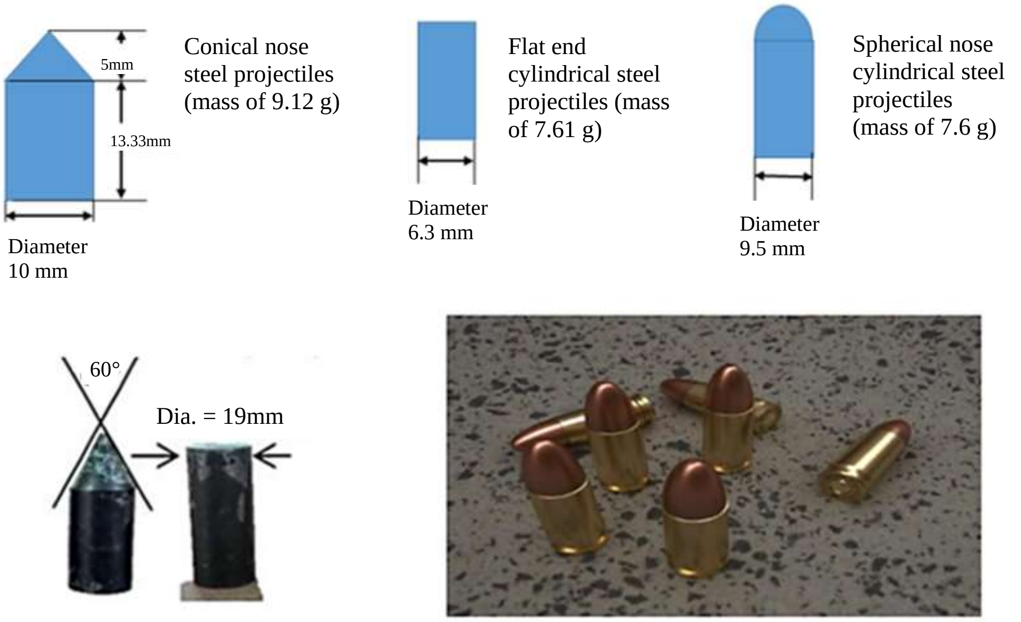
Figure 4. Schematic sketch of the gas-gun apparatus [55].

INFUENECE OF IMPACTOR CHARATERISTICS AND GEOMETRICAL FEATURES

The response of materials and structures to high-velocity impacts is predominantly influenced by impact velocity. The influence of impact velocity can be classified according to material properties, energy dissipation, and failure modes. Depending on different impact velocity ranges, the material deformation, failure mode, energy absorption mechanism, stress wave propagation, strain rate sensitivity and penetration behavior change. Therefore, the impact velocity is a critical factor in determining the types of impact responses exhibited by the material [56]. Sah et al. [8]conducted a numerical analysis on the ballistic impact of six hybrid composite panels (B3H3, K3B3, H3B3, K3H3, H3K3, B3K3) made of Basalt-3D, Kevlar-3D, and Hybrid-3D fabrics, impacted by a 9 mm bullet at a velocity of 240–350 m/s. The B3K3 panel had the highest ballistic limit (332 m/s), while H3B3 had the lowest (251 m/s), highlighting Kevlar's superior energy absorption. Figure 5 illustrates the schematic representations and digital photographs of various projectile types.

Figure 6 represents different zones of TTT laminate with a micrograph. Peng et al. [9] fabricated 25 hybrid ballistic panels using ceramics, Kevlar, Dyneema and compressed wood, testing them with 7.62 mm bullets at 806–887.5 m/s. Energy absorption, rear face signature, and failure modes were all examined in the analysis of five panels that successfully stopped bullets. Pathak et al. [10] modeled three advanced hybrid ceramic composite plates in finite element software using a custom material model (VUMAT) for body armor applications. The B8K8 panel achieved a ballistic limit of 416 m/s, while the SB2K2 panel reached 606 m/s, demonstrating significant improvements in ballistic resistance. Francesconi et al. [59] conducted 45 experiments under hypervelocity impact on CFRP samples of varying thicknesses.

Aluminum spheres were used in impact testing, and the velocity ranged from 2 to 5 km/s. Projectile entrance craters were analyzed to create a new method for estimating failure uncertainty. In cases of perforation and fragment ejection, high-speed shadowgraphs were used to study the impact damage evolution and characteristics. Andrew et al. [60] reviewed the damage behavior of FRP composites, focusing on their use in aerospace and other dynamic loading applications. It analyzes impact velocity's effect on failure modes and four structural performance parameters: material, event, geometry, and environmental circumstances.



9 × 19 mm parabellum bullets

Figure 5. Schematic shapes and digital images of different types of projectiles [57].

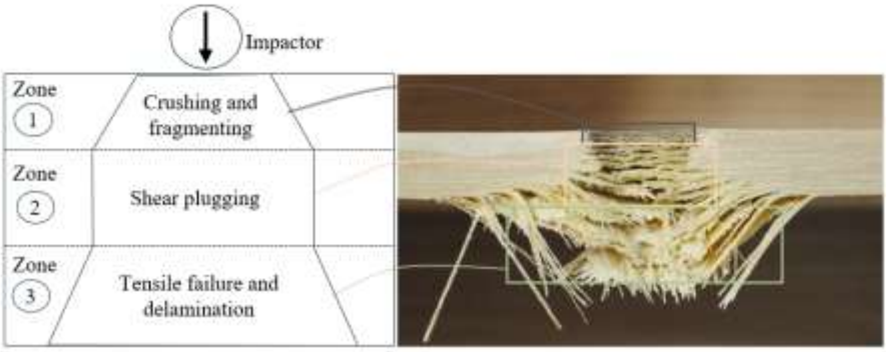


Figure 6. Various TTT zones of a laminate subjected to HVI; schematic on the left and micrograph on the right [58].

The performance of hybrid composites under HVI is significantly influenced by both geometrical and environmental factors. Geometrical aspects such as thickness, shape, and stacking sequence play an important role in determining impact resistance. Increased thickness generally enhances energy absorption, while optimized stacking sequences can mitigate delamination and improve structural integrity. Fiber orientation also affects performance, with cross-ply or angle-ply configurations often distributing impact loads more effectively than unidirectional arrangements. On the environmental side, factors like temperature, humidity, and exposure to UV radiation or chemicals can degrade the composite material. Elevated temperatures may soften the matrix, reducing its energy dissipation capacity, while moisture ingress weakens the fiber-matrix interface, leading to premature failure. Furthermore, hybrid composites exhibit strain rate sensitivity, where the rate of energy application influences their resistance to penetration and deformation. Prolonged exposure to harsh environments can exacerbate damage mechanisms such as fiber breakage, matrix cracking, and delamination, especially in regions with poor interfacial adhesion. These factors collectively determine the structural performance and durability of hybrid composites under extreme impact conditions, underscoring the importance of tailored designs to enhance their resilience [61]. Gaur et al. [22] examined the ballistic performance of carbon fiber-reinforced aluminum laminates (CRALL), an advanced fiber-metal laminate with high specific strength, under high-velocity impacts. Using dynamic explicit analyses in ABAQUS, the effects of strain rates and projectile nose shapes (flat, hemispheric, and sharp) on ballistic limits were evaluated. Progressive damage models for CFRP and aluminum layers, in conjunction with cohesive surface models for interlaminar delamination, indicated that CRALL exhibits a significant ballistic limit, particularly at elevated strain rates and for flat-nosed projectiles. The strain rate considerably affects the ballistic limit velocities of flat-nosed designs. L. Liu et al. [24] investigated the effects of cyclic hygrothermal aging on T700/TDE-85 composites used in military aircraft. Aging cycles resulted in resin surface degradation, fiber/matrix interface fractures, and interlayer interface damage due to the interplay of heat and swelling pressures. While ILSS initially increased by 12.4% due to plasticization, it later decreased with further interface damage. Ballistic impact resistance improved, with critical energy absorption increasing by 15.6% after 280 cycles, and the highest energy absorption was observed at 70 cycles. Aging also altered damage morphology, enhancing energy absorption and impact resistance capabilities compared to unaged composites. Trellu et al. [62] addressed the limitations of the traditional pyramid of tests for aeronautical composite structures, which are costly, conservative, and unrepresentative of actual structural behavior. A new methodology has been developed that uses a complex loading test rig for CFRP plates under combined loading after impact. The study reveals unique behavior different from conventional Compression After Impact (CAI) responses, investigating the interaction between impact damage and post-buckling behavior under compression, shear, and combined loadings. X. Yang and Jia [27] assessed the influence of hygrothermal aging on the impact resistance of woven GFRP subjected to high-velocity impacts. Results indicate that hygrothermal aging lowers the ballistic limit by 14.9%; however, it exerts minimal impact near the ballistic limit velocity. Aging-induced structural deformation and mechanical degradation lead to consistent failure modes at lower velocities. Analytical models predict ballistic limits and energy absorption reasonably well, though they slightly underestimate total energy absorption efficiency.

Nugroho et al. [32] investigated the application of densified wood, particularly laminated veneer, as an armor material and its capacity to absorb ballistic energy. Teak Platinum veneer underwent densification through hot pressing and pre-treatment techniques such as bacterial cellulose self-assembly. Hybrid and non-hybrid panels were tested, with hybrid panels incorporating aramid fabric and densified veneer. Ballistic tests using 9mm Luger ammunition showed that non-hybrid panels performed better, but the hybrid panel with a 2:1 aramid to veneer ratio and aramid fabric on the inside absorbed 78.64% of ballistic energy, making it the most effective configuration. KG & K [37] studied the ballistic, mechanical, and moisture absorption properties of luffa fiber reinforced with graphene-modified epoxy composites. Graphene nanofillers (20 nm) were incorporated in varying weight percentages (0–4%) using mechanical stirring and tested. Results revealed enhanced tensile, impact, and flexural strength up to 2 wt% graphene, improved energy absorption in ballistics tests, and reduced water intake in composites with fillers. SEM analysis highlighted defects like fiber pullout, voids, and internal cracks in tested specimens. J. Pernas-Sánchez et al. [41] examined the behavior of CFRP laminates subjected to high-velocity impacts (70 to 500 m/s) at ambient and cryogenic (-150°C) temperatures. The analysis investigates damage patterns across several laminate orientations, demonstrating that cryogenic temperatures result in an increased frequency of fiber fractures and shear matrix cracks, although the overall damaged area remains same.

The results demonstrate that these damage patterns are unrelated to temperature-induced effects, as verified by interlaminar shear strength assessments and ply thermal stress computations. Key & Alexander [42] validated an anisotropic multiple constituent model in the CTH hydrocode for composite materials used in military vehicles and airplanes. The model and EOS simulate composite microstructure stress and strain for damage analysis. Recent validation includes striking woven glass/epoxy composite panels with steel spheres at varied speeds and angles. Sandia National Laboratories experiments compared CTH MCM forecasts to damage and projectile residual velocity. Results show model robustness under oblique impact situations. C. Zhang et al. [43] created a nonlinear dynamic finite element model to examine the ballistic performance and damage mechanisms of fiber metal laminates subjected to oblique impact. The model, confirmed with experimental data, explores the influence of impact velocity and angle on deflection, residual velocity, and energy absorption. Results show that deflection decreases with higher impact velocity. The simulation approach offers valuable insights for future oblique impact studies in fiber metal laminates. Factors such as strain rate, aging effects, projectile shape, and environmental conditions play a crucial role in determining ballistic efficiency. Experimental and numerical approaches, including finite element modeling and hydrocode validation, provide deeper insights into material behavior under high-velocity impacts. These findings contribute to the development of lightweight, high-performance armor and aerospace structures, paving the way for future innovations in protective materials.

DAMAGE AND FAILURE ASSESSMENT UNDER HIGH-VELOCITY IMPACT

Damage analysis Methods

The method of analyzing composite structures is crucial in the field of impact analysis. This section reviews the literature that is currently available on the analysis, numerical, and experimental methodologies used to investigate their impact response [63, 64]. The design of composite structures necessitates a thorough understanding of dynamic responses, damage mechanisms, and damage resistance [65, 66]. Therefore, foundational aspects of impact analysis have been reviewed, employing a range of different approaches to provide comprehensive insights into these crucial factors. Figure 7 for boundary condition and meshed laminate.

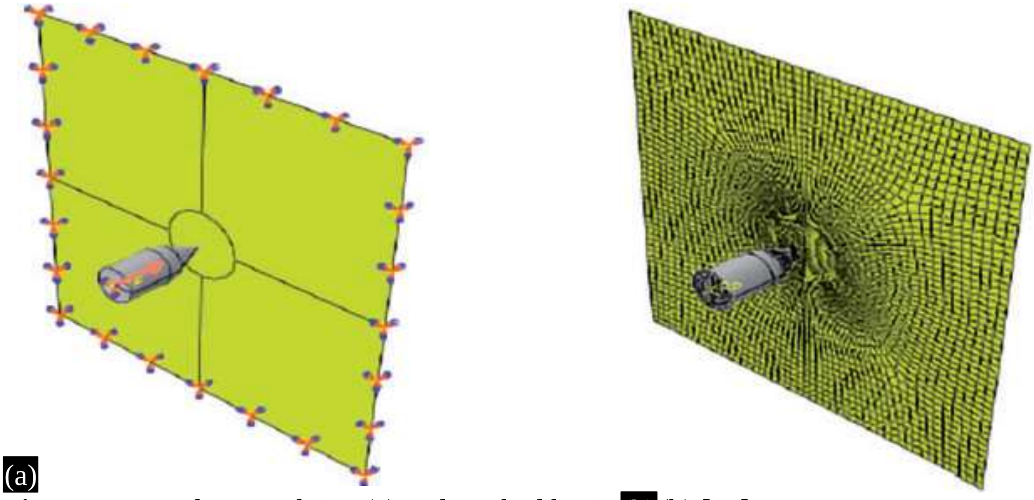


Figure 7. Boundary condition (a) and meshed lamin(b) [67].

Using both experimental and numerical methods, Stephen et al. [55] investigated the HVI resistance of FRP composites composed of carbon, glass, and Kevlar in both hybrid and non-hybrid stacking sequences. Glass as the intermediary layer in Kevlar-based hybrid composites, according to their results, reduces material costs by 21% while offering impact protection on par with Kevlar/epoxy composites. Sandwich composites made of Kevlar and glass-based fabric also show great promise for protective applications, surviving impacts at up to 200 m/s. These materials could be utilized to create light, inexpensive defensive armor. Peng et al. [68] studied ballistic impact on hybrid composite by numerical approach. Hybrid composite composed of compressed wood, Kevlar, ceramics, and Ultra-High-Molecular-Weight Polyethylene (UHMWPE).

The ballistic responses of the constituent materials and hybrid constructions were captured through the use of several constitutive models and the associated failure criteria. Lightweight composite armor with reduced self-weight and optimal ballistic resistance can be made using the established FE models. Liu et al. [20] studied the analytical and experimental modeling of the behavior of continuous CFRP composites under LVI and HVI utilizing a rigid iron impactor. Low-velocity impact experiments utilize drop-weight tests, whereas high-velocity impact testing employs a gas-gun apparatus. The carbon fiber composites employed in these tests have a uniform fiber architecture and are reinforced with either a thermoplastic poly(ether–ether ketone) (CF/PEEK) matrix or a thermoset toughened epoxy (CF/Epoxy) matrix. The results clearly demonstrate that CF/PEEK composites possess enhanced impact resistance. Chen et al. [25] examined the ballistic resistance of GFRP laminates subjected to high-velocity impact using experimental testing and 3D simulation models that integrated strain rate effects and the Hashin failure criterion. Factors such as layer angle, stacking sequence, and layer angle ratio were evaluated by an orthogonal testing method, optimizing simulations while maintaining accuracy.

The results indicate that the stacking sequence considerably influences ballistic resistance, with 0°/90° and ±45° layer orientations providing enhanced performance. An equivalent ratio of varying layer angles further improves impact resistance.

Alonso et al. [26] established an FE model to predict the ballistic behavior of woven GFRP laminates using a CDM based constitutive model. Material parameters were obtained from both literature and original experiments, and the model was validated using experimental impact tests. It was then employed to investigate the effect of laminate thickness on energy absorption mechanisms near the ballistic limit, highlighting critical deformation and failure processes during perforation. Vescovini et al. [30] simulated ballistic impacts for woven Kevlar-S2-glass interply hybrid composites. LS-Dyna MAT_162, which models progressive intra- and inter-laminar failure modes, is used in this investigation. Testing establishes the softening parameters, strain rate, and mechanical properties. This study investigates the effects of target thickness and stacking sequence on target energy absorption, limit velocity, and ballistic curves. The numerical models reliably predict residual velocity, ballistic limit, and damage. Sivakumar et al. [33] examined ceramic/thermoset composites for bulletproof armor against AK-47 bullets, finding that a silicon carbide face plate with a carbon-epoxy back plate offered optimal performance. Reddy et al. [35] analyzed Carbon/UHMWPE hybrids against 7.62×39 mm projectiles, concluding that higher UHMWPE content improved energy absorption and reduced deformation. Gao et al. [69] investigated CFRP/Aluminum Honeycomb Sandwich Panels under HVI, demonstrating that over 70% kinetic energy is absorbed by the front panel and core. Numerical simulations and experimental results closely matched, confirming the reliability of the findings. In addition to experimental approaches, mathematical and analytical modeling plays a crucial role in understanding the high-velocity impact behavior of composite materials. These models are designed to simulate the impact process, predict damage evolution, and optimize composite structures for different applications such as defense, automotive, and aerospace industries.

Analytical models typically involve simplifying assumptions about material behavior, such as considering composites as layered or homogeneous structures. Classical approaches, like the energy balance method and the wave propagation model, are often used to predict parameters like ballistic limit, residual velocity, and energy absorption. These models also help estimate the onset of damage modes such as matrix cracking, fiber breakage, and delamination by applying theories of elasticity and plasticity. Carrasco-Baltasar et al. [44] developed a mathematical model to simulate the perforation of woven AS4/8552 laminate plates under in-plane preload and oblique impact. Six energy absorption modes are included in the model: matrix cracking, shear plugging, fiber failure, laminate acceleration, and elastic deformation. It is confirmed against experimental and numerical data by analyzing the impact of oblique and perpendicular impacts on laminates regardless of in-plane preload. More sophisticated numerical modeling methods, such as Finite Element Analysis (FEA), offer a more thorough and precise comprehension of impact behavior. Software like LS-Dyna and ABAQUS is commonly used to simulate complex phenomena like high strain rates, inter- and intra-laminar failure modes, and strain rate dependency. Specific material models, such as MAT_162 in LS-Dyna, account for progressive failure modes and help simulate how the composite responds to high-speed impacts. These simulations are calibrated using material properties obtained experimentally and adjusted for factors like strain rate sensitivity, softening, and plasticity. Karthick et al. [70] used LS-DYNA simulations to investigate ballistic performance of hybrid composite armors.

Different stacking sequences of KFRP, E-Glass (GFRP), and CFRP were evaluated for energy absorption and ballistic resistance. Results show that hybridization and stacking order significantly impact performance, with KFRP as the outer layer and GFRP in the middle offering superior protection. Numerical findings closely align with experimental data, highlighting the sensitivity of ballistic resistance to projectile nose shape. The combination of experimental testing and mathematical modeling allows for a highly accurate representation of impact dynamics, enabling engineers to design composite structures with optimal impact resistance. Analytical and numerical models also reduce the need for extensive physical testing by providing initial insights and enabling virtual prototyping, thus saving time and resources in the development process. V. Sivakumar et al [33], 38 Mousavi & Khoramishad [16] carried out many tests and employed NDT methods to investigate the composite's post-impact behavior.

Damage Properties Analysis

Enhancing the structure necessitates comprehension of the damage resistance and dynamic properties of composite materials. Upon impact, impact loads generate elastic waves that may result in degradation via energy dissipation, target vibration, and wave propagation. Recognizing the various damage mechanisms and their evolution after impact is crucial for assessing the performance of composite materials. This review study seeks to consolidate essential data from many studies regarding the impact mechanics of polymer matrix composites, offering a thorough overview of the latest advancements in this field. By synthesizing existing research, it aims to provide significant insights into impact damage mechanisms, underscore recent achievements, and provide future avenues for enhancing the impact resistance of composite materials. Figure 8 illustrates the failure in a multi-layered composite laminate. The primary determinant of the impact behavior of composite materials is the resin system's fracture toughness. Systems made of brittle resin show little resistance to the onset and spread of fractures. Enhancing the fracture toughness of the matrix improves the material's capacity to resist fracture propagation, hence enhancing the composite's resistance to interlaminar delamination resulting from resin cracking. Intraply failure mechanisms can induce interlaminar delamination, especially when there is a disparity in characteristics between layers composed of varying fiber kinds or orientations. As a crack advances to the interface between neighboring layers, shear stress escalates significantly because to the sudden alteration in material characteristics, prompting the fracture to redirect and propagate along the contact as interlaminar delamination. The interlaminar fracture toughness in both Mode-I (crack opening) and Mode-II (shearing) are essential parameters influencing the impact response of composite laminates. This phenomenon arises as delamination initiates through crack opening (Mode-I), while its progression is influenced by shearing (Mode-II) resulting from bending. Composite materials can absorb and disperse significant impact energy through multiple degradation mechanisms under impact loading. Figure 9 illustrates the Failure Modes in the affected plate.

Othman et al. [72] conducted experimental investigations on the damage of CFRP laminates featuring toughened interlayers subjected to LVI and HVI. Low-velocity impacts result in global deformation, whereas high-velocity impacts induce localized damage absorption. X-ray radiography and Optical microscopy observations proved that toughened interlayers reduce delamination at lower energy but may induce a shift to intralaminar damage at elevated fracture toughness levels. Figure 10 shows the X-ray photographs of the laminates after HVI. Pathak et al. [12] conducted a numerical analysis of the impact resistance of hybrid basalt/Kevlar polypropylene composites subjected to HVI utilizing a bespoke simulation tool (VUMAT).

Different configurations of basalt/Kevlar and pure Kevlar laminates were tested with a 9 mm bullet to assess their energy absorption and ballistic limit. While hybrid basalt/Kevlar composites did not surpass pure Kevlar in ballistic limit, they demonstrated cost-effectiveness and promising mechanical properties, making them valuable for applications requiring economical alternatives with reliable performance. The simulation results aligned well with existing literature, confirming the model's accuracy. Pathak et al [13] examined damage initiation and propagation in hybrid composite panels under impact, using the Yen criteria to identify failure modes.

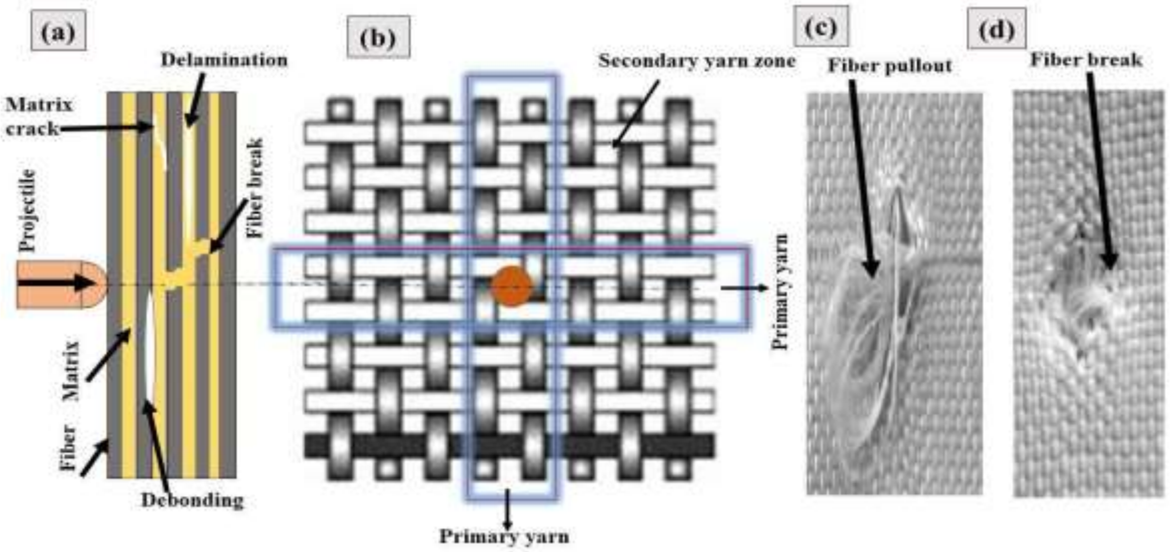
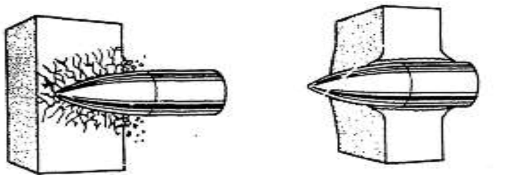
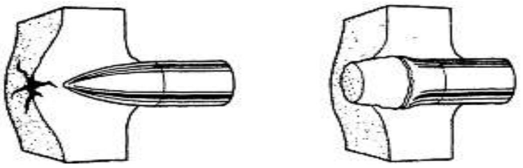


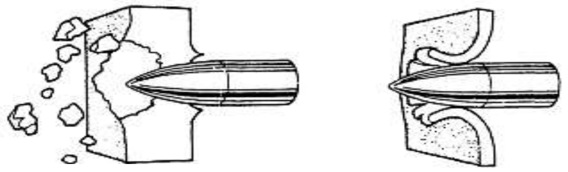
Figure 8. Illustration using diagrams of a multi-layered composite laminate's failure under HVI [57].



Brittle fracture Ductile hole growth

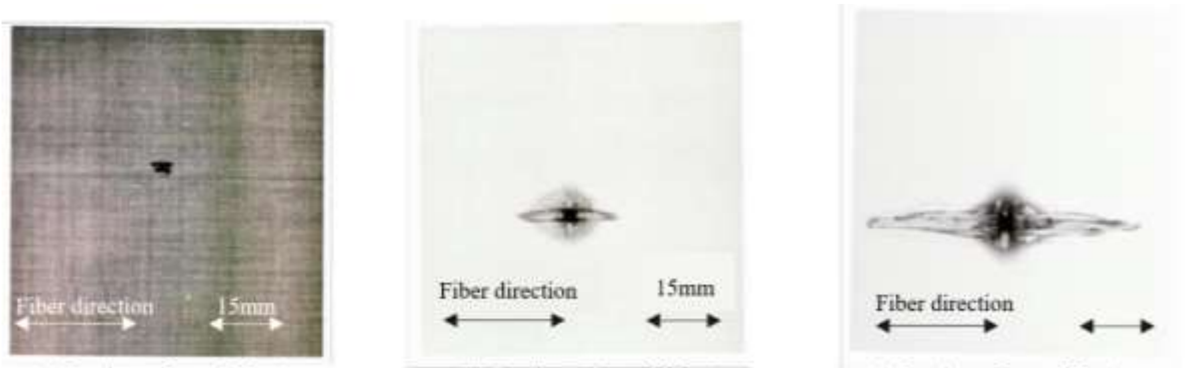


Radial fracture Plugging



Fragmentation Petaling

Figure 9. Failure Modes in Impacted Plate [71]



(a) Specimen 5; v – 160 m/s (b) Specimen 6; v – 327 m/s (c) Specimen 7; v – 160 m/s

Figure 10. Soft X-ray photographs of the laminates after high-velocity impact [72]

Yang et al. [17] explored the impact response of curved GFRP composites, used in rail vehicles, through experimental testing and finite element (FE) simulations. Initial material tests established the composites' mechanical properties, followed by HVI tests on GFRP plates cut from rail vehicle components. Using the Lambert-Jonas equation and LS-DYNA simulations, the study examined factors like impact velocity, target thickness, and projectile shape. Findings indicated that while thicker GFRP plates offer better penetration resistance, a 4-mm thickness showed the highest specific energy absorption among tested variants, balancing impact resistance with efficiency. B. Yang et al. [73] proposed a FE model to forecast the performance of woven carbon fiber-reinforced polymer (CFRP) composites subjected to LVI and CAI scenarios. The model, corroborated by experimental LVI and CAI testing, precisely emulated force-displacement relationships and failure mechanisms, including fiber breaking, matrix cracking, and delamination.. Scanning electron microscopy (SEM) analysis confirmed these damage mechanisms, and additional simulations explored how impactor size and energy levels influenced impact damage and post-impact strength. Cuomo et al. [74] introduced a baseline-free method to identify HVI locations on complex structures and assess damage using only the signals captured during the impact. The approach eliminates common limitations like dependency on material properties, wave direction, and sensor placement. It employs acoustic emission power estimation and reconstructs power distribution using a radial basis function network for impact localization. Damage assessment uses a novel technique based on the Hilbert–Huang transform. Experimental tests on CFRP specimens confirmed the method's accuracy in impact localization and damage evaluation under different velocities.

Haro et al. [34] developed hybrid composite armors by impregnating closed-cell aluminum foam with shear-thickening fluids that contain different micro and nano-fillers, such as gamma alumina, colloidal silica, Kevlar micro-fibers, and silica carbide. The armors, which were compression-molded using AA 5086-H32 aluminum sheets, underwent ballistic resistance testing with a 9 mm rifle. Findings indicate that impact energy absorption and ballistic resistance are greatly improved by nano-fillers, with Kevlar microfibers providing the maximum energy absorption but adding thickness and weight. The best energy absorption and the least amount of weight gain were provided by gamma alumina and silica carbide, indicating that the technique may improve interfacial bonding and performance. Tang et al. [19] investigated the effects of HVI (300 m/s) on Carbon Fiber Reinforced Plastics (CFRP)/Aluminum Honeycomb Core (Al HC) sandwich panels using experiments and simulations. The total interaction duration of 164.5 μs is divided among the front CFRP panel (32.5 μs), Al HC core (91.7 μs), and rear CFRP panel (40.3 μs). Experimental and simulation results align well, showcasing damage patterns like cracks, delamination, and carbon fiber filament fractures. Scanning electron microscopy (SEM) analysis and ABAQUS simulations provide insights into the impact dynamics and microscopic damage characteristics. Verma et al. [28] analyzed the CAI characteristics of pseudo-elastic shape memory alloy (PE-SMA) integrated glass/epoxy composites subjected to high-velocity impacts. Anchored PE-SMA composites with reduced embedment lengths demonstrate markedly enhanced ballistic limitations. PE-SMA composites are more damage tolerant at lower velocities, but homogenous glass/epoxy composites have higher compressive strength at higher velocities due to localized damage. Han et al. [38] studied the effect of matrix content on the ballistic performance of aramid FRP composites (AF/PCC).

In conclusion, this review consolidates key findings on the impact behavior of PMCs, highlighting the influence of material properties, structural configurations, and reinforcement strategies on energy absorption and damage resistance. Various studies demonstrate the effectiveness of hybrid composites, toughened interlayers, and novel reinforcements in improving ballistic performance. Experimental and numerical analyses provide valuable insights into damage mechanisms such as delamination, fiber breakage, and matrix cracking, contributing to the development of more resilient composite materials. Advanced modeling techniques and innovative impact localization methods further enhance the understanding of impact dynamics. These findings offer a foundation for future research aimed at optimizing composite structures for high-performance impact resistance in defense, aerospace, and transportation applications.

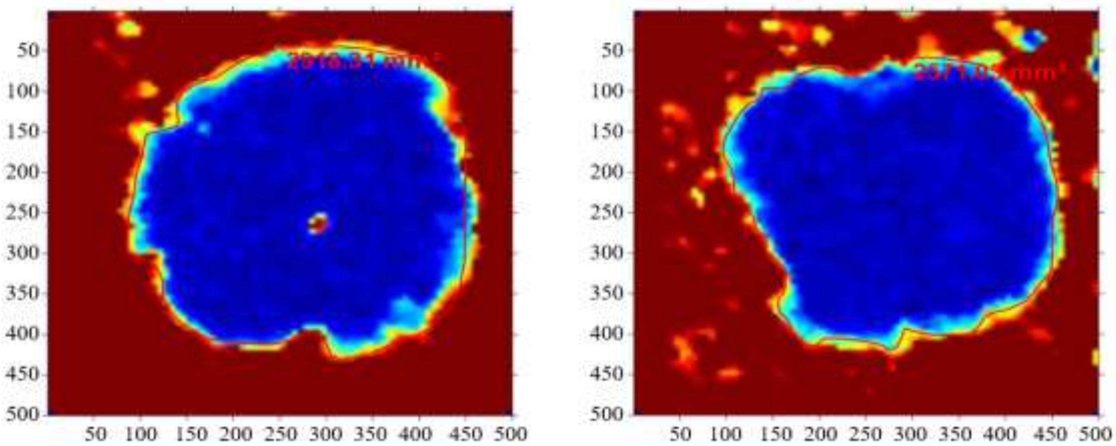


Figure 11. C-scan Images of damage areas. (a) Specimen of Kevlar impact to 231 m/s and (b) specimen of Kevlar + cork powder impacted to 230 m/s [75]

Damage Analysis Based on Stacking Sequence

Proper placement of fibers in a composite plays an essential role in enhancing impact resistance, strength, and overall material performance. The orientation, distribution, and alignment of Fibers substantially affect the composite's capability. To withstand external loads and environmental conditions. This review paper compiles and analyzes various studies on fiber orientation, highlighting its effect on properties such as fracture toughness, tensile strength, and energy absorption. Additionally, the paper discusses recent advancements in fiber reinforcement techniques and their potential applications in high-performance composite materials. Rad et al. [21] investigated the high-velocity impact response of hybrid pseudo-woven IM7/8552 carbon/epoxy composite laminates produced via automated fiber placement (AFP). The study compares three 24-ply laminate configurations: a quasi-isotropic control laminate, hybridized pseudo-woven sub-laminates, and traditional layups. Experimental findings show that hybrid configurations significantly reduce back face surface damage (45%) and back face deflection (19.5%) while improving the V50 velocity by 5.5% compared to traditional laminates. Kazemi et al. [58] developed a zone-based hybrid laminate design to improve CFRP composites' HVI performance while maintaining weight and in-plane mechanical properties. Tailoring materials in three lamination zones optimizes impact response. Fiber reinforcements, shape memory alloys, and ceramics were tested. The hybrid laminates provided up to 95% better energy dissipation than the baseline CFRP design, proving their efficacy for HVI applications.

FUTURE SCOPE

Future research in the high-velocity impact response of CFRP and hybrid composites can explore novel material systems, advanced manufacturing techniques, and sophisticated modeling methods to enhance ballistic resistance, refine damage prediction, and optimize material performance.

- *Bio-inspired & Auxetic Designs:* Develop composites mimicking natural structures (nacre, bone) and incorporate nanofillers like CNTs and graphene to enhance toughness.
- *Advanced Hybridization:* Explore novel fiber-metal and polymer-foam hybrids, including self-healing matrices, to improve energy dissipation.
- *Optimized Manufacturing:* Use 3D printing for architected cores, optimized fiber orientation, and stacking sequences to maximize absorption and reduce deformation.
- *Modeling & Simulation:* Implement multi-scale, multi-physics, and data-driven models to predict damage mechanisms efficiently.
- *Real-time Monitoring:* Embed sensors to track impact damage and create digital twins for structural health insights.
- *Environmental & Lifecycle Focus:* Study effects of moisture and temperature, and develop recyclable or sustainable composites for real-world reliability.

CONCLUSION

Carbon fiber reinforced polymers and hybrid composites are increasingly used in aerospace, automotive, and defense applications due to their high strength-to-weight ratio and excellent mechanical properties. However, their susceptibility to high-velocity impact damage such as delamination and fiber breakage limits their reliability. Recent research has focused on hybridization, sandwich structures, and natural fiber reinforcements to enhance impact resistance and energy absorption.

- Hybridization with Kevlar, basalt, glass, and natural fibers improves energy absorption and damage tolerance compared to pure CFRP.
- Sandwich structures with foam or honeycomb cores enhance delamination resistance and shock absorption.
- Environmental effects such as hygrothermal aging and stacking sequence significantly influence ballistic performance.
- Advanced modeling and simulation approaches provide accurate predictions and reduce reliance on costly experiments.
- Future research should explore bio-composites, nano-modifications, and multi-scale designs for sustainable high-performance materials.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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