

Article

The Effect of Material Arrangement Order on Ballistic Resistance of Ceramic Composite Armor Structure

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Abstract

This study investigates the ballistic performance and energy-absorption behavior of advanced multilayer ceramic composite armor systems composed of silicon carbide (SiC) ceramics, composite metal foam (CMF), rolled homogeneous armor (RHA), ultra-high-molecular-weight polyethylene (UHMWPE), aluminum, and rubber interlayers. The objective is to enhance impact resistance and optimize energy dissipation efficiency against armor-piercing (AP) projectiles. Ballistic tests were performed following the NIJ Standard 0101.06 Level IV specifications using .30" caliber AP M2 rounds with an impact velocity of 784–844 m/s. Experimental results revealed that the SiC front layer effectively fragmented the projectile and dispersed its kinetic energy, while the CMF and UHMWPE layers were the primary energy absorbers, dissipating approximately 70% of the total impact energy (≈ 3660 J). The aluminum and RHA layers provided additional reinforcement, and the rubber interlayer significantly reduced stress-wave propagation and suppressed crack growth in the ceramic. The most efficient configuration 0.5 mm RHA + 7 mm SiC + 7 mm EPDM + 7 mm CMF + 5 mm UHMWPE achieved an areal density absorption of $77.2 \text{ J}\cdot\text{m}^2/\text{kg}$ and a unit thickness absorption of $190.6 \text{ J}/\text{mm}$. These findings establish a quantitative layer-wise energy dissipation framework, highlighting the synergistic interaction between brittle, porous, and ductile layers. This work provides practical design principles for developing lightweight, high-efficiency composite armor systems applicable to defense, aerospace, and personal protection fields. Moreover, this study not only validates the NIJ Standard 0101.06 ballistic performance experimentally but also establishes a reproducible methodology for quantitative, layer-wise energy analysis of hybrid ceramic-CMF-fiber armor systems, offering a scientific framework for future model calibration and optimization.

Keywords: ballistic silicon carbide; armor-piercing; composite metal foam; ultra-high molecular weight polyethylene; rolled homogeneous armor; aluminum plate; energy absorption



Academic Editor: Michael A. Beckett

Received: 12 September 2025

Revised: 5 November 2025

Accepted: 12 November 2025

Published: 17 November 2025

Citation: Chen, Y.L.; Chu, C.K.; Chang, Y.C. The Effect of Material Arrangement Order on Ballistic Resistance of Ceramic Composite Armor Structure. *Solids* **2025**, *6*, 64. <https://doi.org/10.3390/solids6040064>

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1. Introduction

Advancements in modern armor protection technology have significantly transformed the design of combat and tactical vehicles. The latest trends in armor development emphasize lightweight construction, multi-functionality, enhanced toughness, and high energy absorption efficiency. Among candidate materials, ceramics play a pivotal role due to their low density, high hardness, wear resistance, and thermal stability. In composite armor systems, ceramics typically serve as the front strike face, while metal foams act as

the energy-absorbing core, and fibrous or metallic plates function as the backing layer to prevent penetration and mitigate rear-face deformation.

In 2015, García Ávila et al. introduced a novel composite metal foam (CMF) structure made of 2 mm steel hollow spheres, which served as an efficient kinetic energy absorbing layer in ceramic-based armor [1]. When paired with a SiC ceramic front plate and a Kevlar or aluminum alloy backing, this configuration met NIJ 0101.06 Level III–IV ballistic standards [2], dissipating up to 60–70% of projectile kinetic energy [3,4]. Subsequent research by Liu et al. (2016) on fiber metal laminate (FML) sandwich panels demonstrated that variations in core and skin thickness strongly influence ballistic response and energy absorption behavior [4]. Marx et al. (2020) further optimized CMF-based sandwich armor systems, reporting up to 70% kinetic energy absorption under 7.62 mm to 12.7 mm AP projectile impacts [5]. Alkhatib et al. (2021) compared hybrid composites using carbon, palm, and Kevlar fibers, confirming that stacking order and material combination significantly affect impact mitigation [6].

Recent investigations have continued to refine multilayer ceramic composite systems. Hu et al. (2021) developed a metal/UHMWPE/SiC multilayer armor with improved energy dissipation [7], while Xie et al. (2022) performed numerical simulations on SiC/TC4/UHMWPE laminates, revealing that layer sequence and thickness determine energy absorption efficiency [8]. Chen et al. (2024) analyzed structurally optimized spliced ceramic panels [9], and Xiang et al. (2024) experimentally verified that fiber-constrained SiC/UHMWPE plates achieve enhanced resistance to 7.62 mm AP threats [10]. Together, these studies confirm the growing importance of multilayer and functionally graded architectures in advanced ballistic protection.

However, previous works have primarily focused on two- or three-layer combinations, often neglecting quantitative layer-by-layer energy analysis and stress-wave modulation mechanisms. As a result, the precise contribution of individual layers to the total absorbed energy remains insufficiently characterized. The present study therefore fills this key gap by providing a quantitative, layer-wise energy analysis of ceramic–composite metal foam (CMF) fiber armor systems.

The goal is to enhance ballistic energy absorption and stress-wave attenuation under NIJ Level IV impact conditions. The novelty of this work lies in its quantitative layer-wise energy distribution analysis, which integrates experimental and theoretical approaches to clarify the mechanical contribution of each component. Moreover, the comparative evaluation of CMF thicknesses (7 mm vs. 10 mm) and UHMWPE backing thicknesses (3 mm vs. 5 mm) provides insight into the optimal configuration for lightweight, high-efficiency composite armor.

Unlike previous studies that mainly focused on two-layer ceramic–metal armors, this work systematically examines the effects of stacking sequence, CMF and UHMWPE thickness, and stress-wave modulation on overall energy dissipation, thereby providing new insights for the design of lightweight, high-efficiency armor systems.

2. Experimental Methods

The study examines different approaches to energy absorption, categorizing them into two primary groups. It evaluates the ballistic performance of composite structured specimens by analyzing the projectile's initial velocity during ballistic tests and its residual velocity after traversing the material. The energy absorption capacity, as described by Dr. Roylance [11], is determined by calculating the kinetic energy dissipated within the target throughout the process. The methodology follows the NIJ 0101.06 ballistic standard testing procedure, involving the launch of a .30" caliber Armor-Piercing (AP) M2 armor-piercing projectiles at its original velocity to impact the test specimen. After pene-

tration, the residual velocity of the projectile is recorded to determine the energy absorbed by the material. This approach enables an evaluation of the material's structural efficiency in managing and dispersing kinetic energy [12]. The second study explores scenarios in which the material completely stops the bullet's movement. While no penetration occurs, the energy transmitted by the impact wave can still pose risks to individuals or structures located behind the barrier. To mitigate this, it is crucial to incorporate highly efficient shock-absorbing materials at the rear, minimizing the influence on the surrounding environment [12]. This research utilizes dent volume analysis to quantify changes in clay volume, enabling a more comprehensive evaluation of the kinetic energy dissipation performance of different interlayer materials. By integrating the results derived from both methodologies, the study determines the most effective combinations of internal materials for such systems, thereby improving overall energy absorption efficiency.

2.1. Materials

The specimen plate is composed of various materials, including a 0.5 mm layer of rolled homogeneous armor steel (MIL-A-12560 RHA), a silicon carbide-based ceramic plate made entirely of SiC, foam steel layers with thicknesses of 7 mm and 10 mm, and ultra-high molecular weight polyethylene (UHMWPE) HB 50 composite fiberplate available in 3 mm and 5 mm thicknesses. Additionally, the configuration is completed with a 3 mm thick aluminum backing. Collectively, these materials form the test sample. To investigate performance under varying conditions, different experimental configurations are employed, as outlined in Table 1. Specifically, the variations include foam steel thicknesses of 7 mm and 10 mm and ultra-high molecular weight polyethylene plate thicknesses of 3 mm and 5 mm. Control samples are also prepared to facilitate a comparative analysis of the experimental results.

Table 1. Experimental configuration.

Specimens	Thickness (mm)	Areal Density (kg/m ²)
S7C10A3	20.0	53.6
R0.5S7C7A3	17.5	48.9
R0.5S7E1C7A3	18.5	58.0
S7C10X3	20.0	49.0
R0.5S7C7X5	19.5	48.3
R0.5S7E1C7X5	20.5	53.6

1. S = silicon carbide (SiC); C = composite metal foam (CMF); A = aluminum plate; R = rolled homogeneous armor (RHA); E = EPDM rubber interlayer; X = UHMWPE fiber reinforced plate. 2. The number following each symbol indicates layer thickness (mm). 3. Areal density values represent mean results from measured samples.

The ceramic components employed in bulletproof plates are predominantly composed of silicon carbide ceramics, produced at a processing temperature of 2140 °C, based on hot pressing data provided by HCG. Co. Ltd. (Taoyuan, Taiwan) The ceramic plates are manufactured from 100% silicon carbide material to ensure optimal performance.

The composite metal foam (CMF) material, supplied by Taiwan Porite Co., Ltd. (Zhu-nan, Taiwan), is developed based on the method proposed by Wang [13]. The foam panels are produced in square units, each with a side length of 150 mm, but differ in thickness, with variations of 7 mm and 10 mm. This metallic foam steel incorporates a layered structure formed during the casting process. Such a structure elongates the crack propagation path during fracture, thereby improving durability. Additionally, this design enhances the composite material's energy absorption capabilities while maintaining a robust bond with the matrix, resulting in a stable transition layer. When subjected to pressure, the layered structure greatly boosts the material's stress resistance, thereby increasing its overall strength under stress.

EPDM rubber and plastic are widely used elastomeric materials known for their ethylene propylene diene monomer composition. These synthetic materials exhibit exceptional resistance to weathering, ozone, and chemicals, along with superior electrical insulation properties. Thanks to these qualities, EPDM is a preferred material for diverse applications in industries such as automotive, construction, consumer goods, and appliances. In the military sector, it is frequently utilized in vehicles where it serves as a protective layer, offering reliable defense against temperature fluctuations and ultraviolet radiation.

AP bullet: The .30" Armor-Piercing (AP) M2 projectile, with a mass of 9.6 g (150 gr), represents a specialized form of ammunition engineered for penetrating armored targets, predominantly employed in military applications. As defined by the NIJ Level IV standard, this classification pertains to projectiles that adhere to the specifications established by the National Institute of Justice. Notably, this ammunition delivers a minimum muzzle velocity of 2740 fps (835 m/s).

The silicon carbide ceramics used in this study were supplied by HCG Co., Ltd., a domestic manufacturer, and were fabricated via atmospheric-pressure sintering. The production process involved adding a binder, dispersant, lubricant, and water, followed by ball mill mixing to obtain a homogeneous slurry. The slurry was spray granulated and poured into molds. According to the required size and thickness of the ceramic plates, the granulated powder was compacted into green bodies using a powder pressing machine, bisque-fired to remove organics and increase strength, and finally sintered to obtain dense SiC plates, as shown in Figure 1a. The assembled ballistic target, consisting of nine individual SiC plates arranged in a 3×3 grid, is shown in Figure 1b. Figure 1 also illustrates the distinction between a monolithic ceramic plate and a tiled plate structure. The monolithic configuration represents a single continuous ceramic slab, whereas the tiled structure comprises multiple smaller SiC tiles joined in a 3×3 array. This design enhances crack arrest capability and improves multi-hit tolerance compared with a monolithic plate. To confirm material purity and homogeneity, microstructural and compositional analyses were performed. The results are presented in Figure 1c,d. The SEM micrograph in Figure 1c reveals uniformly distributed fine SiC grains with no visible porosity or impurity phases, indicating a dense microstructure and high sintering quality. The corresponding XRD pattern in Figure 1d shows sharp diffraction peaks corresponding exclusively to β -SiC, confirming a SiC content of approximately 99%, and thereby validating the material's purity and phase uniformity.

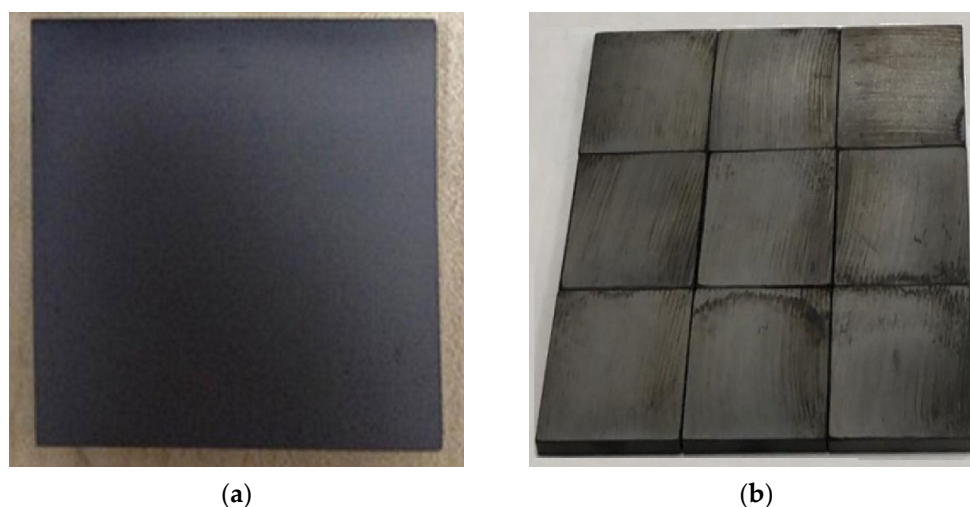


Figure 1. Cont.

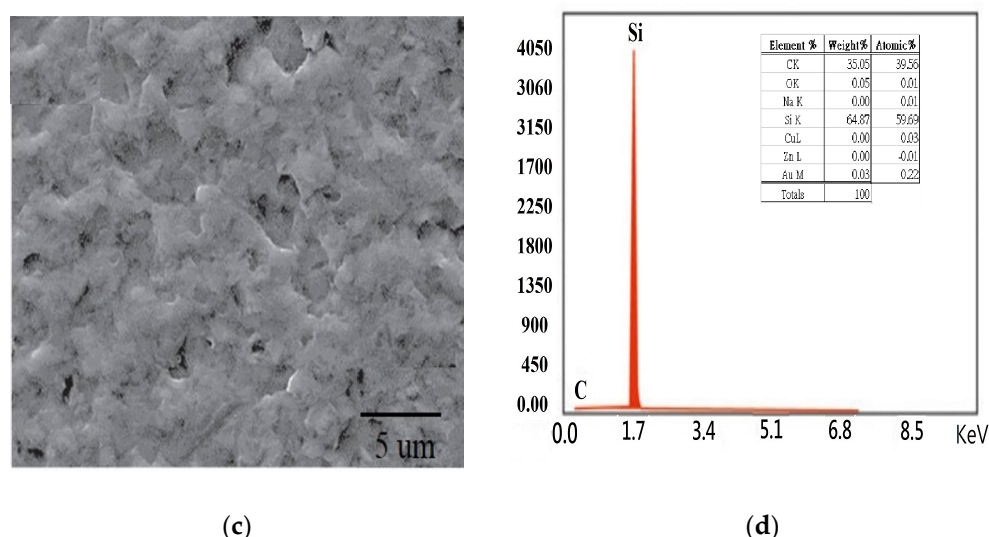


Figure 1. SiC Ceramic plate, be listed as: (a) SiC ceramic; (b) 3×3 SiC Ceramic plate. (c) SEM (d) XRD.

Figure 2a Composite metal foam (CMF) finished product made of 316 L stainless steel powder with uniform pore distribution. (b) UHMWPE laminated fiberplate after hot pressing, showing a densely bonded and aligned fiber structure for energy absorption and backing support.

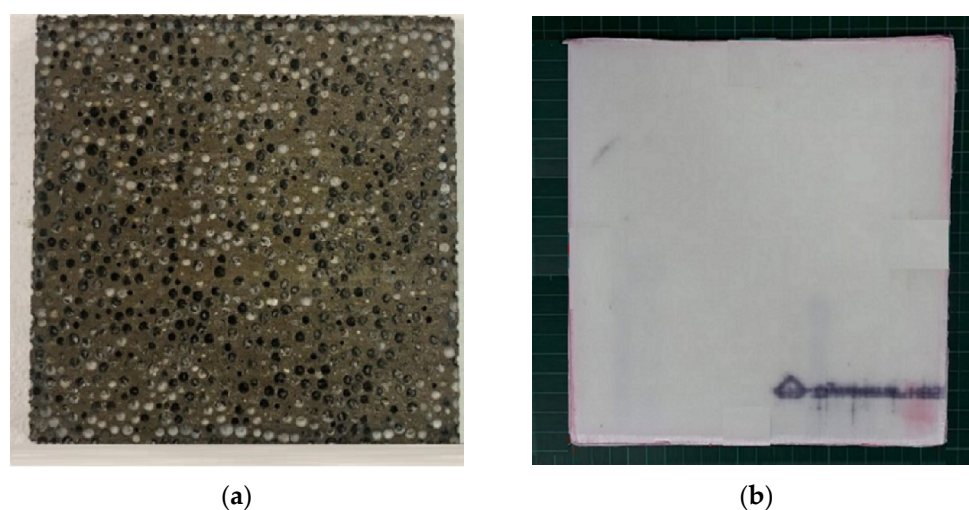


Figure 2. (a) CMF finished product (b) UHMWPE fiberplate.

(a) The composite metal foam (CMF) used in this study was provided by the well-known powder metallurgy manufacturer Taiwan Porite Co., Ltd. The CMF was fabricated from a mixture of 316 L stainless steel powder and binder using a pressureless slurry sintering molding process based on powder metallurgy technology. During production, 316 L stainless steel powder was combined with a poreforming agent in the required proportion and mixed into a homogeneous slurry. The slurry was poured into a mold, dried in a constant temperature oven to form green bodies, and subsequently sintered in a nitrogen-protected atmosphere furnace. The sintered semi-finished products were processed by precision wire cutting to obtain the final foam steel specimens. As shown in Figure 2a, the CMF exhibits an open cell structure with uniformly distributed spherical pores formed by the burnout of the poreforming agents during sintering, resulting in a low-density, energy-absorbing metallic matrix.

(b) The UHMWPE backplate was fabricated from Ultra-High-Molecular-Weight Polyethylene (UHMWPE) fiber prepreg HB50 (areal density = 235 g/m^2) supplied by DSM (Netherlands). The prepreg rolls were cut into $150 \text{ mm} \times 150 \text{ mm}$ sheets using a precision fabric cutter. These sheets were laminated through hot pressing under controlled conditions—pressure: 100 kg/cm^2 , temperature: 130°C , and duration: 25 min. Stacking 12 and 20 layers yielded fiberplates with thicknesses of 3 mm and 5 mm, respectively. As shown in Figure 2b, the resulting UHMWPE laminate exhibits a compact, well-aligned layered structure, offering high tensile strength and impact resistance, making it ideal as a ballistic backing layer for the test specimens [14].

2.2. Specimens Design

The ballistic specimen design aimed to evaluate how layer arrangement and thickness affect impact resistance. Each specimen had an overall dimension of $150 \text{ mm} \times 150 \text{ mm}$ and was composed of nine $50 \text{ mm} \times 50 \text{ mm}$ SiC tiles (7 mm thick) bonded to a composite metal foam (CMF) layer of either 7 or 10 mm thickness. A backing layer of ultra-high-molecular-weight polyethylene (UHMWPE) with 3 or 5 mm thickness was applied to complete the stack. All layers were bonded using a high-strength epoxy adhesive to ensure reliable interfacial integrity and efficient load transfer. The front surface of each specimen was reinforced with a 0.5 mm rolled homogeneous armor (RHA) steel sheet, and, where applicable, a 1 mm EPDM rubber interlayer was inserted between the CMF and ceramic layers to evaluate its effect on stress-wave attenuation.

The detailed specimen configurations and corresponding areal densities are summarized in Table 1. Each specimen is denoted by a code identifying the material layers and their thicknesses: S denotes the SiC ceramic, C denotes the CMF, A denotes the aluminum plate, X denotes the UHMWPE fiberplate, R denotes the RHA steel sheet, and E denotes the EPDM rubber interlayer. The numerical values following each letter indicate the layer thickness in millimeters (e.g., R0.5S7E1C7X5 represents a specimen with a 0.5 mm RHA layer, 7 mm SiC, 1 mm rubber, 7 mm CMF, and 5 mm UHMWPE). Areal density values are mean results obtained from measured samples. The schematic arrangement of these configurations is presented in Figure 3, while the corresponding layer dimensions and areal densities are summarized in Table 1.

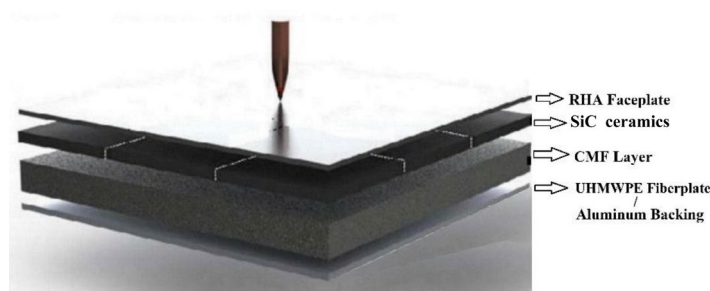


Figure 3. Specimens Sample.

The ceramic, steel foam and backplate are combined with RHA, rubber layer, and bonded with strong adhesive to form an anti-ballistic plate to perform ballistic test. The experimental configuration is shown in Table 1.

Figure 3 Structural configuration and layer sequence of the composite ballistic specimens. Each configuration consists of silicon carbide (S), composite metal foam (C), aluminum plate (A), or UHMWPE fiberplate (X), with optional rolled homogeneous armor (R) and rubber (E) interlayers. The numerical values in the specimen codes correspond to the layer thicknesses listed in Table 1. This figure also clarifies the relationship between

the coded configurations and their corresponding experimental assemblies, ensuring consistency between schematic and tabulated data.

In order to consider the lightweight design, the areal density of the specimens was included. The equation for calculating the areal density A of the ceramic composite material is as shown in Equation (1):

$$A = \rho_c h_c + \sum \rho_f h_f \quad (1)$$

among them, A is the areal density of the composite material (kg/m^2), ρ_c is the bulk density of the ceramics (kg/m^3), h_c is the thickness of the ceramics (m), ρ_f is the bulk density of each layer (kg/m^3), h_f is the thickness of each layer.

2.3. Ballistic Testing Procedure

The bullet-resistant plate analyzed in this investigation, detailed in Table 1, is primarily composed of a composite material that integrates RHA, silicon carbide ceramics, foam steel, a backing layer, and an aluminum plate. These components are arranged in a tiled structure to produce a test specimen with dimensions of 15×15 cm. Ballistic evaluations of the composite armor system were performed in compliance with the National Institute of Justice Standard 0101.06 [2], promulgated by the U.S. Department of Justice in 2008. These tests were executed using specialized ballistic testing equipment in the facilities of the Ballistics Laboratory at the National Defense University, as depicted in Figure 4. The experimental procedure employed .30" armor-piercing rounds (7.62×63 mm), designed to fulfill the criteria established for NIJ 0101.06 Level IV certification. The armor plate was subjected to projectile impacts at a predetermined velocity, with velocity measurements captured by two high-precision speed sensors positioned one meter before and one meter behind the armor. Projectile velocities were measured using a Model-57 optical chronograph (Oehler Research, TX, USA) with a measurement resolution of 0.1 m/s. The system was calibrated before testing, and the statistical error of the recorded velocities was within ± 0.3 m/s. The pre-impact velocity was recorded prior to the projectile's collision with the sample, while its residual velocity post penetration was measured by the second sensor. By applying the principles of energy conservation, the kinetic energy absorbed by the composite material was quantified, offering a comprehensive evaluation of the material's ballistic resistance and defensive capability [15].

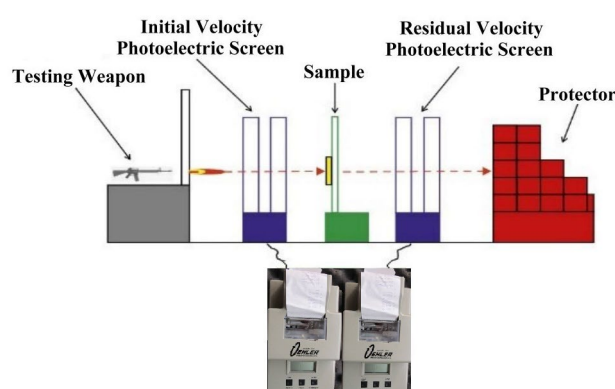


Figure 4. Schematic diagram of ballistic test.

The ballistic evaluation of all specimens followed NIJ Standard 0101.06 Level IV, which specifies the projectile type and impact velocity requirements. Since the NIJ testing procedure references MIL-STD-662F for velocity measurement and impact setup, the laboratory experiments were conducted under MIL-STD-662F-compliant conditions to ensure hardware accuracy and procedural consistency. This dual standard approach guar-

antees reproducibility and aligns the experimental procedure with both NIJ performance validation and military grade ballistic testing methodologies.

2.4. Energy Absorption Analysis Methods

In this research, ballistic test was used to evaluate the energy absorption of the specimens. According to the ballistic tests, the initial velocity of the projectile and the residual velocity after penetrating the target were obtained, and the kinetic energy consumed by the target was calculated based on the Law of Conservation of Energy [15]. The ballistic resistance of the whole specimen is evaluated by the amount of energy absorbed, and the energy absorbed by the target is shown in Equation (2).

$$E_A = \frac{1}{2}mv_i^2 - \frac{1}{2}mv_r^2 - E_{bullet} \quad (2)$$

Among them, E_A is the energy absorbed by the target plate (J), E_{bullet} is the energy absorbed by the fragmentation of the projectile (J), m is the mass of the projectile (kg), V_i is the initial velocity of the projectile hitting the target (m/s), and V_r is the residual velocity of the projectile after penetrating the target (m/s) [11].

Through the layered energy absorption approach pointed out in the literature, the energy absorption of each layer of the target was investigated [16]. Since the local temperature at the impact point cannot be measured during ballistic test, the heat generated is negligible, and the energy absorbed by each layer of the composite structure can be approximately estimated. When the target is hit, the initial kinetic energy (E_{KEi}) of the projectile is fully converted into the residual kinetic energy after the projectile penetrates the target (E_{KEr}), the energy absorbed by the fragmentation of the projectile (E_{bullet}), the energy absorbed by the front plate (E_{front}), the energy absorbed by the ceramic ($E_{ceramic}$), energy absorbed by the rubber layer (E_{rubber}), energy absorbed by the foam steel (E_{CMF}), energy absorbed by the backing plate ($E_{backing}$), and the residual energy (E_{res}) generated by the flying debris ejected from the target when penetrating the target. In the study, the debris scattered after the projectile hits the target cannot be collected and calculated, and from the perspective of the energy absorption ratio in the literature [13], the energy absorbed by the debris is almost negligible, so it is also assumed to be ignored here. Therefore, according to the principle of the law of conservation of energy, the initial kinetic energy of the projectile is fully converted into the residual kinetic energy of the projectile and the absorption energy of the target can be expressed as Equation (3)

$$E_{KEi} = E_{KEr} + E_{bullet} + E_{front} + E_{ceramic} + E_{rubber} + E_{CMF} + E_{backing} \quad (3)$$

In addition, the literature on the energy absorption of armored systems showed that the absorbed energy of the front plate and the rubber layer can be calculated by Equations (4) and (5) [17]. The absorbed energy of ceramics, foam steel and backplate can be calculated through the area under the stress–strain curve (as shown in Equation (3)) to obtain the strain energy per unit volume W_p as shown in Equation (6) [18]. Multiplying W_p by the plastic deformation volume generated when the projectile hits the target can estimate the absorption energy of the ceramic and the backplate, and then indirectly obtain the projectile fracture absorption energy (E_{bullet}).

$$E_{front} = \pi d P_e (h_f)^2 S P_f \quad (4)$$

$$E_{rubber} = \pi d_{cone} (h_r)^2 S P_r \quad (5)$$

$$W_p = \int_0^\varepsilon \sigma d\varepsilon \quad (6)$$

where dP_e is the deformed diameter of the projectile, d_{cone} is the diameter of the cone, h is the thickness of the specific layer, SP_f is the shear strength of the front plate, SP_r is the shear strength of the rubber layer, and W_p is the strain energy per unit volume [4].

To improve the quantitative accuracy of the energy distribution analysis, an uncertainty estimation was performed. The diameters D_p , D_c and H_c of the ceramic cones were each measured three times using digital calipers (accuracy ± 0.01 mm), and the mean values were used for subsequent calculations. The potential systematic error arising from the assumption of a perfect conical frustum was assessed by comparing manually calculated volumes with scanning results of representative specimens, showing deviations within $\pm 5\%$. The energy distribution data are therefore presented as mean $\pm$ standard deviation to account for experimental variability. This procedure enhances the reliability and reproducibility of the calculated energy absorption values.

3. Experimental Results and Discussion

3.1. Material and Ballistic

The ballistic tests have been carried out on the laminated ballistic resistant structure, and the impact velocity of the projectile is between 784~844 m/s. The test results show that all layers of the bullet-resistant structure are deformed or even cracked. The perforation of the ceramic panel produces a ceramic cone and generates a local crack. Under the action of the subsequent reflected stretching wave, the crack expands and even breaks. The foam steel is gradually densified by the extrusion of the projectile and the ceramic fragments, and even fractures, perforations and damages occur. The deformation degree of the backplate also increases with the increase in the impact velocity of the projectile, forming a tensile fracture of the fiberplate. Ballistic test results of specimen 「S7C10A3」 are shown in Figure 5.

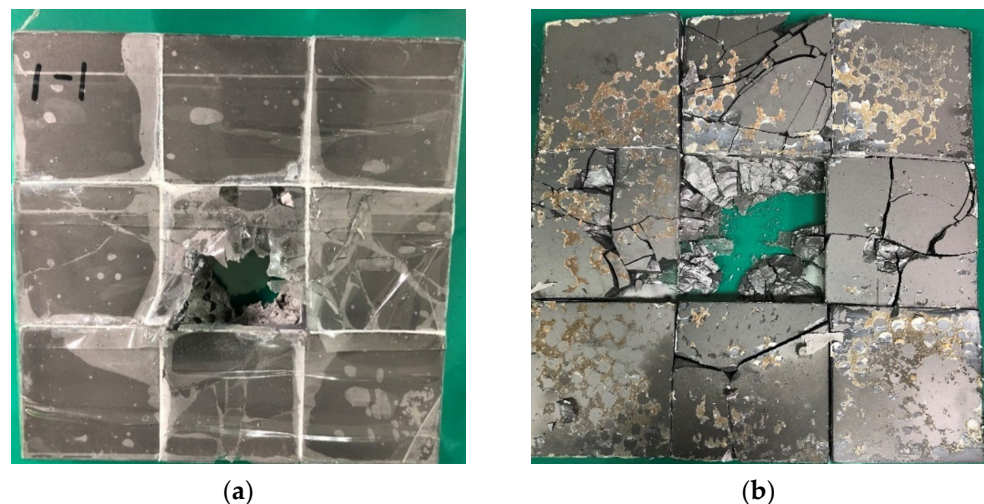


Figure 5. S7C10A3 specimen after impact: (a) front side, (b) back side.

In the ballistic test, most of the kinetic energy of the projectile during the impact process is converted into the brittle fracture energy of ceramics, the collapse energy of foam steel, the plastic deformation energy of the aluminum backplate or the fiber stretching energy of the fiberplate and the projectile deformation energy. In this study, since the temperature at the impact point cannot be measured, the generation of heat energy is neglected, and the absorbed energy is calculated using Equations (1) and (2).

Each group of test specimens is performed according to the above-mentioned experimental method. The initial velocity, residual velocity of the projectile measured by each test sample and the calculated energy absorbed by the target are arranged as shown in Table 2, and the relationship diagram is shown in Figure 6 [1,19].

Table 2. Energy absorption of each group of specimens.

Specimens	Initial Velocity (m/s)	Residual Velocity (m/s)	Initial K.E. (J)	Residual K.E. (J)	Energy Absorption (J)
S7C10A3-1	831	386	3660	790	2870
S7C10A3-2	832	435	3669	1003	2666
S7C10A3-3	798	378	3375	757	2618
S7C10X3-1	841	230	3749	280	3468
S7C10X3-2	843	293	3766	455	3311
S7C10X3-3	829	352	3642	657	2986
R0.5S7C7A3-1	842	457	3758	1107	2651
R0.5S7C7A3-2	836	490	3704	1273	2432
R0.5S7C7A3-3	829	546	3642	1580	2062
R0.5S7C7X5-1	827	0	3625	0	3625
R0.5S7C7X5-2	842	0	3758	0	3758
R0.5S7C7X5-3	843	0	3766	0	3766
R0.5S7E1C7A3-1	838	381	3722	769	2953
R0.5S7E1C7A3-2	840	434	3740	998	2741
R0.5S7E1C7A3-3	784	362	3258	695	2563
R0.5S7E1C7X5-1	844	57	3775	17	3758
R0.5S7E1C7X5-2	826	427	3616	966	2650
R0.5S7E1C7X5-3	842	69	3758	25	3732

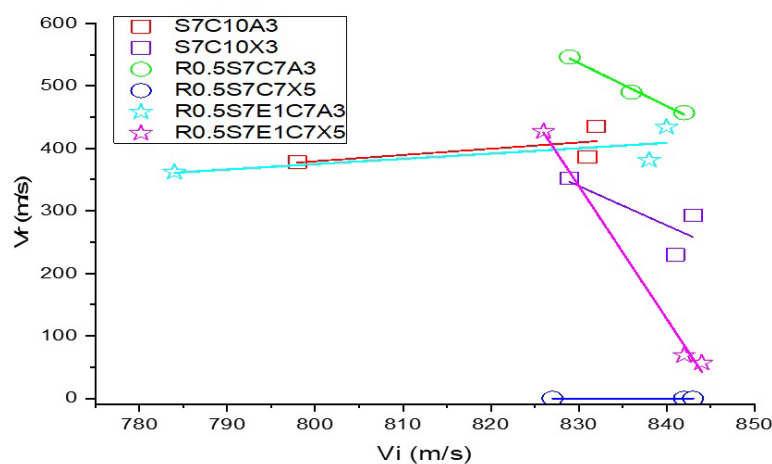


Figure 6. Comparison between initial and residual velocities for each group of specimens.

In order to analyze the energy absorption of target, Equation (5) was used to calculate the strain energy per unit volume (W_p) for the ceramic, foam steel, aluminum, and UHMWPE backing plate, as illustrated in Figure 7a–d. The stress–strain curves in these subfigures represent the material deformation behavior under quasi static compression or tension, from which the area under each curve corresponds to W_p . By multiplying W_p with the measured deformation or fracture volume of each material layer after impact, the absorbed strain energy of each material was obtained [1,20].

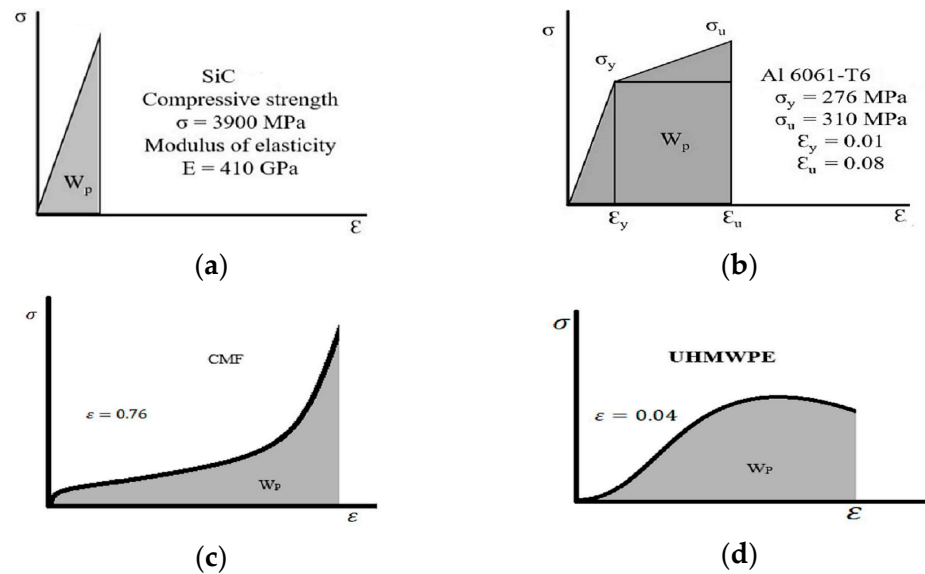


Figure 7. Comparison of energy absorption among specimen groups., be listed as: (a) Ceramic; (b) Aluminum plate; (c) CMF; (d) UHMWPE fiberplate.

Figure 8 Idealized schematic of the ceramic conical fracture geometry used to estimate the fracture volume in Equation (7). Peripheral cracks and irregular fragments observed in Figure 5 were excluded from the volume calculation to ensure consistent comparison between specimens.

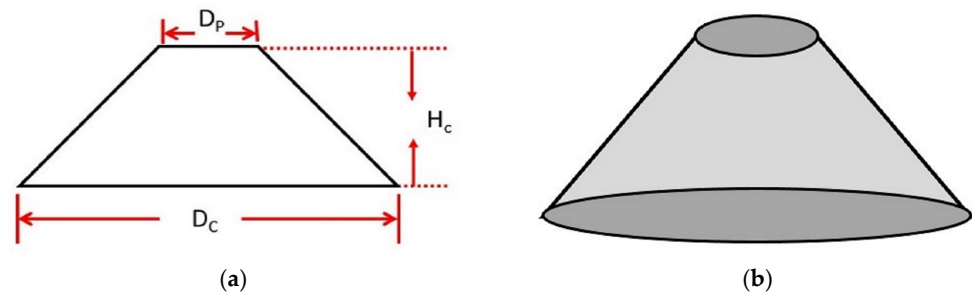


Figure 8. Ceramic cone volume calculation: (a) Schematic of the calculation procedure; (b) Illustration of the cone volume.

Figure 5 presents the post impact morphology of the ceramic surface and the fractured pattern observed in the experiment, while Figure 8 illustrates the idealized schematic representing the theoretical conical fracture geometry of the ceramic layer used to estimate the fracture volume. The difference between the actual shape (Figure 5) and the idealized cone (Figure 8) arises because numerous fragmented pieces could not be completely reconstructed, and the peripheral cracks caused by stress wave propagation were intentionally excluded from the volume calculation to maintain consistency.

The equation for calculating the volume of the ceramic cone is shown in Equation (7), and the schematic representation of the cone geometry is provided in Figure 8a,b. This idealized frustum model was verified against scanned specimens, showing a maximum volume deviation within $\pm 5\%$, confirming that the simplified geometric assumption does not affect the comparative analysis.

$$V_{ceramic} = \frac{1}{12} \pi H_c (D_p^2 + D_c^2 + D_p D_c) \quad (7)$$

where H_c is the thickness of the ceramic cone (mm), D_p is the upper diameter of the ceramic cone (mm), and D_c is the lower diameter of the ceramic cone (mm).

$$V_{backing} = \pi H_b^2 \left(D_b - \frac{H_b}{3} \right) \quad (8)$$

The equation for calculating the plastic deformation volume of foam steel and aluminum disk plate is shown in Equation (8), and the schematic diagram of the plastic deformation volume is shown in Figure 9a [21,22].

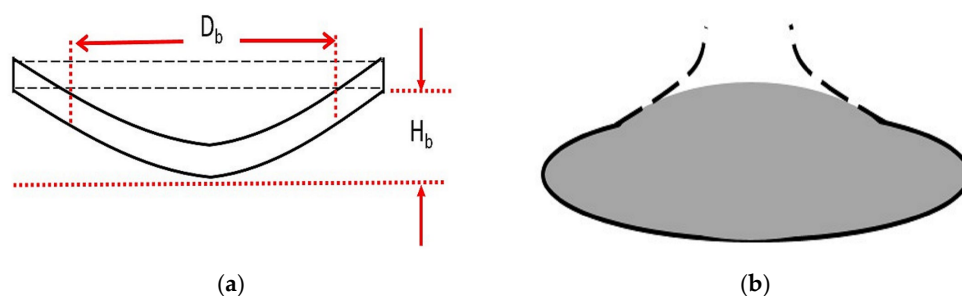


Figure 9. Schematic diagram of backing plate volume calculation (a) Diagram of disk deformation volume calculation; (b) Diagram of disk plastic deformation volume.

The stretched volume of the fiber is obtained by using clay and drainage method, based on Equation (9) [22]. The measurement process is shown in Figure 10a,b.

$$V_{UHMWPE} = V_{WATER} = W_{WATER} / \eta_{WATER} \quad (9)$$

where V_{UHMWPE} is the fiber stretch volume (cm^3), V_{WATER} is the drainage volume (cm^3), W_{WATER} is the weight of the drainage volume (mg), η_{water} is the specific weight of water (mg/cm^3).

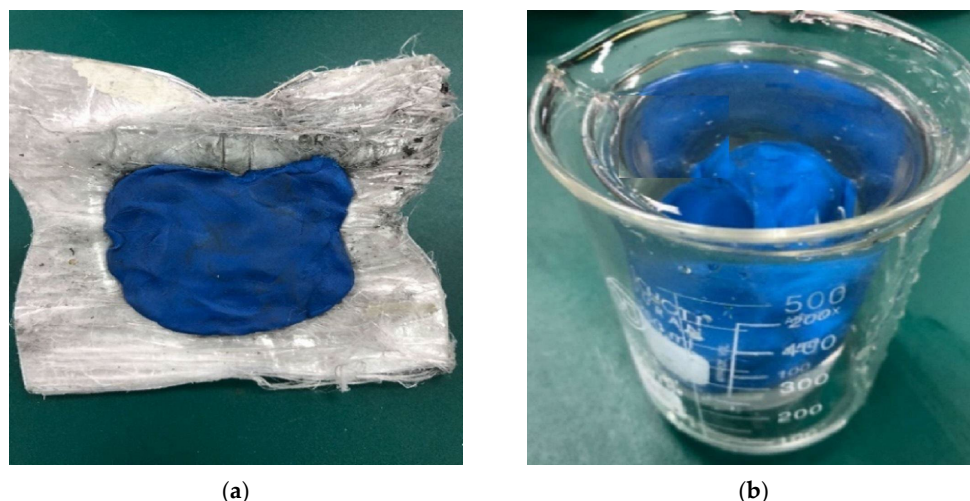


Figure 10. Archimedeian principle for non-uniform volume density calculation: (a) Clay filling in the stretched volume; (b) Drainage measurement method.

3.2. Energy Absorption of Impact

3.2.1. Impact Depth and Absorbed Energy

After calculation, energy absorption ratio of each layer of the target is shown in Table 3. Calculating energy based on depth of penetration (DOP) has been explored in numerous studies, which highlight that varying application scenarios cannot be effectively addressed

using a single method. In research focusing on bullet impacts, the depth of the rear depression is commonly used for assessment [21,22]. However, relying solely on depth of penetration fails to capture the complete energy value accurately. To address this limitation, this study incorporates both the depressed area and the weight of the sludge to determine the percentage of energy reduction. Detailed results are presented in Table 3.

Table 3. Energy absorption ratio of each layer of the target.

Specimens	(1) RHA	(2) Ceramics	(3) Rubber	(4) CMF	(5) Backplate (Al/Fiber)	Bullet Fracture (Residual Energy) 100% – (1 + 2 + 3 + 4 + 5)%
S7C10A3-1		148.39 (5%)		1349.6 (47%)	<u>519.78</u> (18%)	30%
S7C10A3-2		141.74 (5%)		1085.4 (41%)	<u>488.66</u> (18%)	36%
S7C10A3-3		139.8 (5%)		1369.2 (52%)	<u>477.65</u> (18%)	25%
S7C10X3-1		115.71 (3%)		1496.1 (43%)	<u>1093.9</u> (42%)	12%
S7C10X3-2		143.05 (4%)		1754.1 (53%)	<u>893.83</u> (26%)	17%
S7C10X3-3		143.7 (5%)		1485.4 (50%)	<u>602.36</u> (18%)	27%
R0.5S7C7A3-1	13.419 (0.51%)	254.96 (10%)		1390 (52%)	<u>421.18</u> (16%)	22%
R0.5S7C7A3-2	20.148 (0.83%)	168.83 (7%)		1350 (56%)	<u>501.07</u> (21%)	16%
R0.5S7C7A3-3	5.768 (0.28%)	228.89 (11%)		1083 (53%)	<u>528.53</u> (26%)	10%
R0.5S7C7X5-1	3.845 (0.11%)	254.96 (7%)		1835.8 (51%)	<u>1023</u> (28%)	14%
R0.5S7C7X5-2	24.834 (0.66%)	254.96 (7%)		1908.7 (51%)	<u>820.67</u> (22%)	20%
R0.5S7C7X5-3	23.232 (0.62%)	254.96 (7%)		1848.3 (49%)	<u>869.82</u> (23%)	21%
R0.5S7E1C7A3-1	28.72 (0.97%)	254.96 (9%)	0.552 (0.01%)	1505 (51%)	<u>468.54</u> (16%)	24%
R0.5S7E1C7A3-2	16.503 (0.60%)	254.96 (9%)	0.24 (0.01%)	1437.2 (52%)	<u>500.83</u> (18%)	21%
R0.5S7E1C7A3-3	11.776 (0.46%)	254.96 (10%)	0.431 (0.02%)	1297 (51%)	<u>360.14</u> (14%)	25%
R0.5S7E1C7X5-1	17.985 (0.48%)	254.96 (7%)	0.539 (0.01%)	1940.4 (52%)	<u>548.64</u> (15%)	26%
R0.5S7E1C7X5-2	18.626 (0.70%)	254.96 (10%)	0.594 (0.02%)	1336.3 (50%)	<u>516.64</u> (19%)	21%
R0.5S7E1C7X5-3	15.061 (0.40%)	254.96 (7%)	0.693 (0.02%)	1851.8 (50%)	<u>966.98</u> (26%)	17%

Shows: 1. Aluminum plate—Numbers are underlined to indicate. 2. Fiber-reinforced plate—No Line. 3. Bullet fracture (residual energy of projectile (%): 100% – (1 + 2 + 3 + 4 + 5)%; The protection system reducing its penetration capability.

3.2.2. Projectile Impact Energy Absorption

This study evaluates the efficiency of different materials and multilayer armor systems in dissipating impact energy and mitigating projectile penetration. The ceramic layer, owing to its high hardness, fragments the projectile core and disperses kinetic energy, though its brittleness limits continuous absorption [23]. The CMF layer absorbs energy

through progressive compaction and controlled collapse, extending crack paths and enhancing dissipation efficiency [24]. The UHMWPE backplate dissipates energy via fiber stretching and friction between yarns, distributing the impact load and reducing rear-face deformation. Although the rubber interlayer contributes little direct absorption, it reflects and attenuates stress waves, helping to confine cracks and improve ceramic integrity.

As summarized in Table 3 and Figure 11, the absorbed energies are: RHA (0.5 mm), 5–25 J; ceramic (7 mm), 100–260 J; CMF (7 mm), 1000–2000 J; UHMWPE (5 mm), 510–1100 J; and aluminum (0.5 mm), 360–530 J. The uncertainty associated with the calculated energy absorption values was estimated to be within $\pm 5\%$, indicating that measurement errors had a negligible influence on the comparative analysis of the specimens.

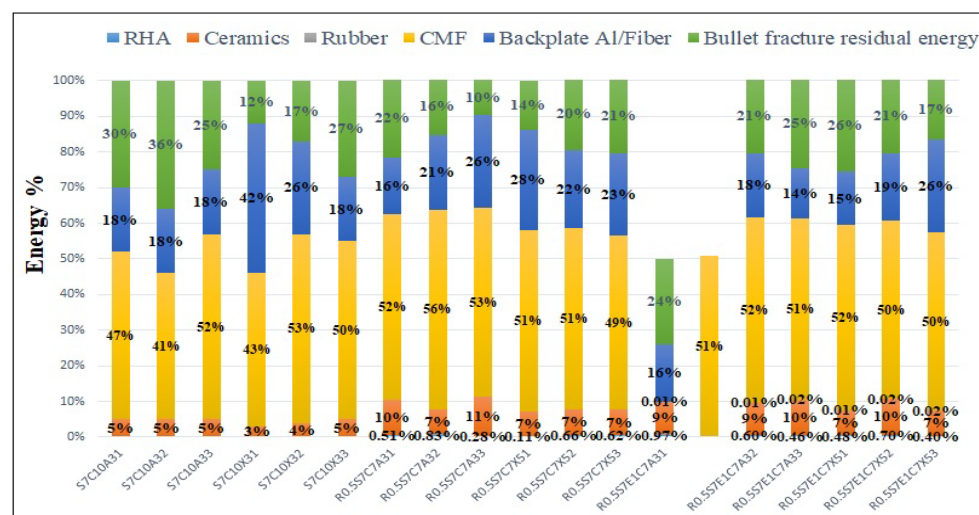


Figure 11. Energy absorption ratio of each layer.

To further quantify these observations, a comparative assessment revealed a strong positive correlation between layer thickness and absorbed energy, particularly for CMF and UHMWPE layers. The 10 mm CMF layer demonstrated approximately 35–45% higher energy absorption than the 7 mm CMF configuration, while increasing UHMWPE thickness from 3 mm to 5 mm improved energy absorption by nearly 40%. These results confirm that both material type and thickness substantially affect total ballistic energy dissipation efficiency.

3.2.3. Energy Absorbed After Impact

Table 3 also highlights that the superior performance of CMF fiber reinforced combinations derives not only from their intrinsic absorption capacities but also from complementary mechanisms such as progressive compaction and fiber stretching. The high hardness of projectiles promotes fragmentation upon impact, while their brittleness enables efficient energy transfer through disintegration. When CMF is integrated with high density fiber layers, this distributed destruction process facilitates greater energy absorption. Figure 11 illustrates that, compared with fiber alone, CMF absorbs substantially more energy during fragmentation and collapse.

The BF% clearly illustrates the energy absorption ratio of each target. By subtracting the consumed energy, it becomes evident that higher values correspond to superior protective performance. The results emphasize that CMF and fiberplate are the most effective at reducing the bullet's kinetic energy. Among these, foam steel exhibits the highest energy absorption rate, followed by fiberplate. These materials excel in energy dissipation, playing a critical role in minimizing the bullet's impact. Additionally, they efficiently dissipate

the applied force, significantly reducing the recoil energy generated by the bullet [23,24]. This pattern aligns with the observations reported in previous studies.

Table 3 and Figure 11 highlight the substantial influence of backing materials in mitigating the energy impact of low armor-piercing warheads. Among the evaluated materials, rubber exhibits an almost negligible energy reduction rate of less than 1%, demonstrating its minimal protective capability as a front layer. In stark contrast, CMF materials show exceptional performance, achieving energy reduction rates surpassing 40%, with a maximum of 50%, as corroborated by Wang's research [13]. The study further underscores the enhanced mechanical properties achieved by incorporating CMF into a sandwich structure, where it is positioned between two rigid outer plates. These outer layers significantly improve the composite material's bending strength. The data presented in Table 3 reveal that materials incorporating CMF can absorb over 50% more energy compared to those without, which have an absorption rate below 50%. This starkly highlights CMF's superior ability to absorb energy effectively.

3.3. Comparison of Areal Density and Absorbed Energy

RHA and ceramic materials offer unique properties and benefits. When impacted by a bullet, the front ceramic layer and steel plate provide hardness, effectively preventing the bullet from deforming and advancing. Subsequently, the rear protective material absorbs the remaining energy through mechanisms such as deformation, denting, or energy transfer, thereby mitigating the collision's force. These protective systems are often designed in multiple layers. Within this structure, fiber materials primarily absorb energy through stretching, while the rear layer plays a critical role in managing residual energy and dispersing the impact [25,26].

When the .30" caliber Armor-Piercing (AP) M2 armor-piercing projectiles impact is successfully resisted without penetration, the total absorbed energy by the target plate is calculated using Equation (4) for various material combinations, including silicon carbide ceramics, foam steel, and others. The internal pore structure of the CMF, along with its gradual reduction in energy transfer, significantly enhances its overall protective performance [20]. Experimental findings assessing the energy absorption mechanism indicate that aluminum plates achieve an energy dispersion capacity of just 18%, whereas fiber materials generally exceed 20%, with some instances reaching up to 42%. This highlights the superior energy dispersion and absorption characteristics of fiber materials. Furthermore, studies on the energy absorption properties of bulletproof panels consistently show that fiber composites significantly outperform single homogeneous metal materials in this regard [27].

This total energy is then converted into two key metrics: absorbed energy per unit thickness and absorbed energy per unit areal density. The results are organized and analyzed, with a summary provided in Table 4 and Figure 12 [26,27]. Notably, the "R0.5S7C7X5" combination exhibits the highest performance, with an average absorbed energy per unit areal density of 77.248 ($\text{J}\cdot\text{m}^2/\text{kg}$), the maximum value across all combinations, and an average absorbed energy per unit thickness of 190.58 (J/mm), which is also the highest among the tested materials [28,29].

Table 4. Absorbed energy per unit thickness and per unit areal density.

Specimens	Thickness (mm)	Areal Density (kg/m^2)	Absorbed Energy (J)	Absorbed Energy per Unit Thickness (J/mm)	Absorbed Energy per Unit Areal Density ($\text{J}\cdot\text{m}^2/\text{kg}$)
S7C10A3-1	20	57.11	2618	135.900	49.951
S7C10A3-2	20	55.62	2666		
S7C10A3-3	20	51.18	2870		

Table 4. Cont.

Specimens	Thickness (mm)	Areal Density (kg/m ²)	Absorbed Energy (J)	Absorbed Energy per Unit Thickness (J/mm)	Absorbed Energy per Unit Areal Density (J·m ² /kg)
R0.5S7C7A3-1	17.5	47.72	2062		
R0.5S7C7A3-2	17.5	48.48	2432	136.087	48.666
R0.5S7C7A3-3	17.5	50.37	2651		
R0.5S7E1C7A3-1	18.5	54.60	2563		
R0.5S7E1C7A3-2	18.5	60.51	2741	148.776	47.456
R0.5S7E1C7A3-3	18.5	58.92	2953		
S7C10X3-1	20	50.35	2986		
S7C10X3-2	20	45.18	3311	162.756	66.708
S7C10X3-3	20	51.36	3468		
R0.5S7C7X5-1	19.5	52.30	3766		
R0.5S7C7X5-2	19.5	45.02	3758	190.577	77.248
R0.5S7C7X5-3	19.5	47.52	3625		
R0.5S7E1C7X5-1	20.5	52.56	3732		
R0.5S7E1C7X5-2	20.5	55.90	2650	164.881	63.407
R0.5S7E1C7X5-3	20.5	52.33	3758		

Note: Areal density is the measured value.

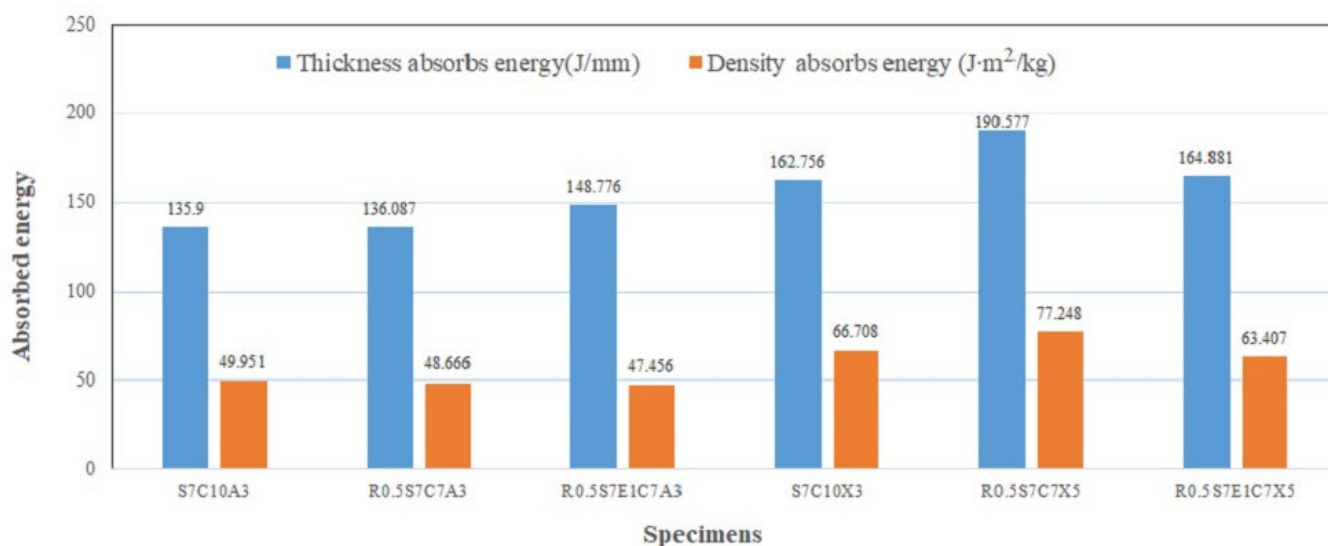


Figure 12. Total energy conversion of individual units of energy.

3.4. Effect of Rubber Interlayer on Stress Wave Behavior

To further understand the role of the rubber interlayer, this section provides an extended analysis based on the same ballistic experiments described previously. Owing to its excellent elasticity and deformability, rubber is widely used in impact protection systems for its capability to absorb and dissipate energy, thereby reducing localized damage [30,31]. By comparing the specimens with and without rubber layers, it was observed that the ceramic panel containing a rubber interlayer exhibited damage primarily concentrated in the central ceramic block, whereas the peripheral tiles remained mostly intact. In contrast, the specimen without rubber showed a broader damaged area and more extensive cracking. The indentation on the rear surface was also more localized in the rubber coated specimen, indicating that the rubber layer redistributed stress and reduced backface deformation, as shown in Figure 13a (without rubber) and Figure 13b (with rubber).

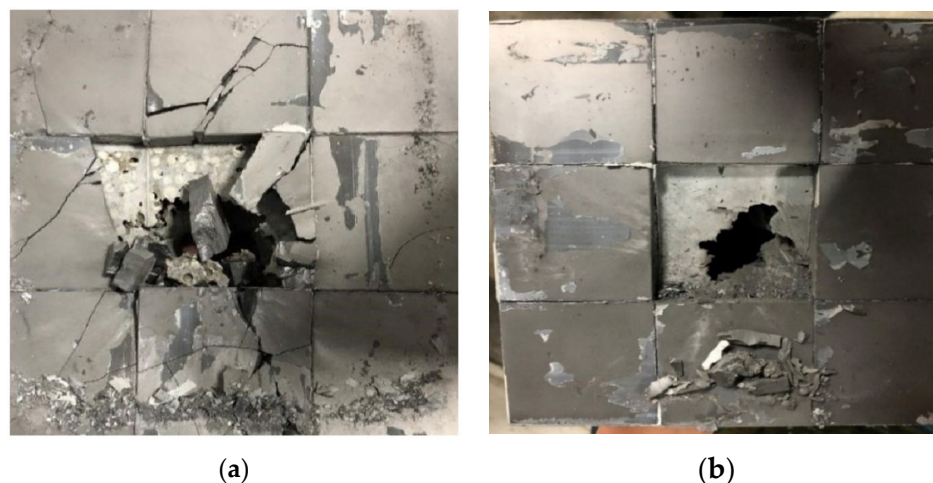


Figure 13. Ceramic fracture, (a) without rubber layer (b) with rubber layer.

These findings are consistent with the stress wave reflection theory proposed by Tasdemirci et al. [32], who demonstrated that compliant interlayers transform compressive waves into tensile reflections, mitigating crack propagation in brittle ceramics. Compared with the rigid interface structures reported by Garcia-Avila et al. [1] and Marx et al. [8], the current SiC/CMF/UHMWPE system incorporating a rubber interlayer exhibited a smaller damage area and improved integrity of surrounding tiles. This difference can be attributed to the viscoelastic impedance mismatch at the SiC–EPDM interface, which promotes partial wave attenuation rather than direct transmission.

Mechanistically, the rubber interlayer acts as a phase delay buffer, altering stress wave propagation timing across layers and thereby enhancing multi-hit durability—a feature not observed in conventional rigid laminates.

Using the calculation formulas of stress wave reflection and transmission coefficients [20], the reflection coefficient (R) and transmission coefficient (T) are calculated from silicon carbide into EPDM rubber (Equations (10) and (11)), and the obtained results are shown in Table 5.

$$R = (\rho_E * C_E - \rho_c * C_C) / (\rho_E * C_E + \rho_c * C_C) \quad (10)$$

$$T = 2(\rho_E * C_E) / (\rho_E * C_E + \rho_c * C_C) \quad (11)$$

where ρ_E is density of EPDM, C_E is wave speed of EPDM, ρ_c is density of SiC, C_C is wave speed of SiC. The calculated results are shown in Table 5, where ρ_C is wave impedance [31].

Table 5. Reflection coefficient (R) and transmission coefficient (T) from SiC to EPDM.

SiC			EPDM			Reflection Coefficient	Transmission Coefficient
ρ (g/cm ³)	C (cm/μs)	ρ_C (g/cm ³)	ρ (g/cm ³)	C (cm/μs)	ρ_C (g/cm ³)	R	T
3.098	1.1706	3.626	1.34	0.1821	0.244	−0.874	0.126

When the projectile impacts the target, a compression wave is generated instantaneously at the point of contact. As presented in Table 5, the reflection coefficient ($R < 0$) and the transmission coefficient ($T < 1$) demonstrate that the stress wave reflecting from the EPDM rubber back into the SiC transforms into a tensile wave, which plays a critical role in inducing damage to the ceramic material. Conversely, when the stress wave propagates from the ceramic layer toward the rubber layer, the rubber acts as an effective buffer. As noted by Dr. Tasdemirci A, the rapid hardening of the rubber interlayer upon receiving the transmitted impact results in concentrated damage localized within the impact region

of the projectile [20,32]. This phenomenon facilitates the absorption of a portion of the impact energy and mitigates the propagation of cracks from the primary impact zone to the adjacent ceramic blocks [33].

Beyond numerical comparisons, the superior performance of multilayer ceramic armor arises from the distinct yet complementary mechanisms of its constituents. The ceramic front layer fractures the penetrator core but provides limited sustained dissipation due to brittleness. CMF enhances efficiency through progressive compaction of its porous structure, while UHMWPE backings absorb energy via fiber stretching and redistribution of impact loads. Aluminum plates offer lower specific absorption due to limited ductility, whereas rubber layers, though minor in direct absorption, modulate stress waves and suppress ceramic cracking. [34] Together, these mechanisms optimize overall energy dissipation and enhance protective effectiveness.

4. Conclusions

This study systematically investigated the ballistic performance and energy absorption behavior of multilayer ceramic composite armor systems composed of silicon carbide (SiC) ceramics, composite metal foam (CMF), rolled homogeneous armor (RHA), ultra-high-molecular-weight polyethylene (UHMWPE), aluminum, and rubber interlayers. The integration of these materials aimed to optimize structural integrity, impact resistance, and energy dissipation efficiency against armor-piercing (AP) projectiles.

1. Ballistic and Energy Absorption Behavior

NIJ Level IV ballistic tests with .30" caliber AP M2 rounds (784–844 m/s) demonstrated that the SiC front layer effectively fragmented the projectile and dispersed its kinetic energy, though part of the impact stress was transmitted to subsequent layers. Within the thickness ranges tested in this study (CMF: 7–10 mm, UHMWPE: 5 mm), the CMF and UHMWPE layers demonstrated the highest energy absorption capacity, with absorbed energies of 1000–2000 J and 510–1100 J, respectively, outperforming aluminum (360–530 J) and ceramics (100–260 J). Although the rubber layer contributed less than 1% to direct absorption, it significantly influenced stress wave reflection and the confinement of cracks within localized ceramic zones.

2. Optimal Configuration and Structural Efficiency

The optimized armor configuration—0.5 mm RHA + 7 mm SiC + 7 mm EPDM + 7 mm CMF + 5 mm UHMWPE achieved the highest ballistic efficiency, yielding a unit areal density energy absorption of 77.2 J·m²/kg and a unit-thickness energy absorption of 190.6 J/mm. Incorporating CMF and UHMWPE layers increased suppression performance by 21–36%, far exceeding the <20% effectiveness of conventional metal backings.

3. Mechanistic Insights and Design Principles

The results highlight a hierarchical protection mechanism within the multilayer composite system:

- (1) The ceramic front layer induces brittle fracture and projectile disruption.
- (2) The CMF and UHMWPE middle layers' function as primary energy absorbers through compaction, collapse, and fiber stretching.
- (3) The rear layers (aluminum or UHMWPE) dissipate residual stress and mitigate back-face deformation.
- (4) The rubber interlayer serves as a stress wave modulator, reflecting tensile waves that confine cracks and improve ceramic durability.

4. Design Implications

These findings establish a material configuration principle for next-generation lightweight protective systems: combining brittle, porous, and ductile media in a graded sequence enhances overall ballistic resistance. The synergistic energy absorption and stress wave management mechanisms demonstrated here provide a scientific foundation for the design and optimization of high-efficiency, lightweight ceramic composite armors applicable to military, aerospace, and personal protection systems.

Finally, the study acknowledges several limitations and proposes directions for further improvement, as outlined below.

5. Limitations and Future Work

The present study was limited to single-impact ballistic tests conducted under controlled laboratory conditions in accordance with NIJ 0101.06 specifications. Although the results clearly demonstrate consistent trends in energy absorption and layer interaction, the restricted number of test repetitions and the absence of dynamic modeling introduce potential uncertainties.

Despite these encouraging findings, certain limitations remain to be addressed in future research. Expanded statistical sampling, dynamic finite element simulations, and multiple impact testing under varied environmental conditions will be essential to further validate the results and enhance model robustness.

Future work will therefore focus on overcoming these limitations through comprehensive statistical analysis, finite element dynamic simulations, and repeated-impact evaluations to verify long-term performance. In addition, hybrid layup architectures combining multiple polymer backings or functionally graded ceramic-foam interfaces will be explored to further improve ballistic efficiency and structural resilience.

Author Contributions: Conceptualization, Y.L.C.; Methodology, C.K.C. and Y.C.C.; Validation, Y.L.C., C.K.C. and Y.C.C.; Formal analysis, Y.L.C., C.K.C. and Y.C.C.; Investigation, C.K.C. and Y.C.C.; Writing—original draft preparation, Y.L.C. and Y.C.C.; Writing—review and editing, Y.L.C. and C.K.C.; Supervision, Y.L.C. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding, and all materials were purchased by the authors.

Data Availability Statement: All data are contained within the article.

Acknowledgments: The authors sincerely thank HCG Co., Ltd. and Taiwan Porite Co., Ltd. for providing ceramic materials and machining support.

Conflicts of Interest: HCG Co., Ltd. and Taiwan Porite Co., Ltd. provide ceramic materials and machining support for this research. The all authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript:

Al	Aluminum
A	Areal density
A	Intact normalized strength parameter
AP	Armour Piercing
B	Fractured normalized strength parameter
BF%	Bullet Fracture (%)

CAI:	Compression After Impact
CMF	Composite Metal Foam (316 L stainless-steel foam.)
Cs	Strength parameter (for strain rate dependence)
DOP	Depth of Penetration
E_{rubber}	EPDM rubber
E	Energy
FML	Fiber Metal Laminate
FRP	Fiber-reinforced polymer
G	Shear modulus
L/D	Length-to-diameter
M	Fractured strength parameter (pressure exponent)
NIJ:	National Institute of Justice
R	Reflection coefficient
RHA	Rolled homogeneous armour
S	Silicon carbide
T	Transmission coefficient
UHMWPE	Ultrahigh molecular weight polyethylene
W	Weight
X	UHMWPE plane thickness
ρ	Density

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