

Experimental and modelling evaluation on the protective performance of bulletproof plate composites for building protection

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Abstract

Critical infrastructure such as police stations, military bases, and security checkpoints is increasingly exposed to armed threats, while most existing structures lack adequate ballistic protection. Conventional construction materials are generally ineffective against high-velocity projectile impacts, highlighting the need for practical, retrofit-compatible protective systems. This study aims to develop and optimize composite bulletproof panels that meet NIJ 0108.01 Level III requirements for resistance against 7.62×51 mm NATO M80 ammunition, with emphasis on structural feasibility and cost-effectiveness. An experimental program was conducted using three materials: standard structural steel (SS400), high-hardness steel (HS450), and asphalt cement (AC). These materials were configured as single-layer, double-layer, and sandwich panels. Ballistic tests were performed using 7.62×51 mm NATO projectiles at an average velocity of 847±9.1 m/s. Projectile velocities before and after impact were recorded to evaluate energy absorbed. Finite element simulations using ABAQUS were employed to validate experimental results and analyze stress-wave propagation and failure mechanisms. The results indicate that material hardness plays a more significant role than thickness in enhancing ballistic resistance. While 6 mm SS400 absorbed 35.81% of impact energy, a thinner 3 mm HS450 layer achieved 28.95%, demonstrating the efficiency of high-hardness materials. Layered configurations significantly improved performance, with SS400-6/AC25 and HS450-3/AC25 absorbing 62.39% and 78.35% of impact energy, respectively. Notably, sandwich configurations (SS400-6/AC25/SS400-6 and HS450-3/AC25/SS400-6) achieved complete projectile arrest. Numerical results confirm that a high-hardness strike face combined with a viscoelastic backing layer maximizes energy dissipation. The optimized HS450-3/AC25/SS400-6 panel provides full ballistic protection with reduced weight compared to conventional steel armor. Field validation demonstrates its applicability for retrofitting existing infrastructure. This study contributes practical design guidelines for developing cost-effective ballistic-resistant building systems in high-risk environments.

Keywords: Bullet protection, NIJ Standard 0108.01, Composite armor, High-hardness steel, Finite element method

1. Introduction

Over the past several decades, global security threats from terrorism, political unrest, and military operations have increased significantly. These challenges have made strategic infrastructure including police stations, military bases, and security checkpoints primary targets for armed attacks [1, 2]. However, most structures continue to use conventional construction materials such as brick and concrete, which cannot effectively resist high-velocity ballistic impacts [3-5]. This inadequacy has resulted in severe casualties and extensive property damage [6]. To address these vulnerabilities, researchers have developed ballistic protection technologies for architectural applications. Composite materials have emerged as particularly promising solutions. These materials combine reinforced layers of various constituents including ultra-high molecular weight polyethylene (UHMWPE) fibers, polymeric resins, steel plates, and natural fibers such as fique fabric [7-9]. Composites demonstrate superior performance in energy absorption, impact force distribution, and penetration resistance while maintaining favorable weight-to-protection ratios and cost-effectiveness. The National Institute of Justice (NIJ) standard provides an internationally recognized benchmark for assessing ballistic resistance in protective materials [10]. This standard classifies protection levels based on bullet type, size, and velocity. NIJ Level III specifically addresses military-grade rifle threats, particularly the 7.62×51 mm NATO M80 projectile, which possesses high kinetic energy [11-13]. Table 1 presents the six protection levels defined by the NIJ standard for body armor. Previous research has demonstrated that multilayer composite structures offer significantly enhanced ballistic resistance [14, 15]. Designs inspired by biological architectures, such as seashells that alternate between hard and soft material layers, have proven especially effective. Additional technologies have expanded protective capabilities. Shear thickening fluid (STF) coatings, which transition to solid-like behavior under high shear stress, increase impact resistance without substantial weight addition [2, 16].

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Table 1 NIJ Standard -0108.01 Ballistic Resistant Protective Material [10].

Armor Type	Test Ammunition	Nominal Bullet Mass	Required Bullett Velocity
I	22 LRHV Lead 38 Special RN Lead	2.6 g	320 ± 12 m/s
		40 gr	1050 ± 40 ft/s
		10.2 g	259 ± 15 m/s
		158 gr	850 ± 50 ft/s
II - A	357 Magnum JSP 9 mm FMJ	10.2 g	381 ± 15 m/s
		158 gr	1250 ± 50 ft/s
		8.0 g	332 ± 12 m/s
		124 gr	1090 ± 40 ft/s
II	357 Magnum JSP 9 mm FMJ	10.2 g	425 ± 15 m/s
		158 gr	1395 ± 50 ft/s
		8.0 g	358 ± 12 m/s
		124 gr	1175 ± 40 ft/s
III - A	44 Magnum Lead SWC Gas Checked 9 mm FMJ	15.55 g	426 ± 15 m/s
		240 gr	1400 ± 50 ft/s
		8.0 g	426 ± 15 m/s
		124 gr	1400 ± 50 ft/s
III	7.62 mm 308 Winchester FMJ	9.6 g	838 ± 15 m/s
		150 gr	2750 ± 50 ft/s
IV	30-06AP	10.8 g	868 ± 15 m/s
		166 gr	2850 ± 50 ft/s

Natural fiber composites incorporating fique fibers with epoxy resin have achieved ballistic performance comparable to Kevlar under specific test conditions [8]. These materials offer practical advantages in regions with limited access to advanced synthetic materials. Applications include lightweight, portable guard posts fabricated from Kevlar-polyurethane composites, which provide structural robustness and ease of deployment [17]. Recent simulation studies have investigated the ballistic performance of composite plates using various matrix materials reinforced with alumina ceramic balls [18]. These studies employed three-dimensional finite element models to evaluate design configurations, demonstrating that ceramic ball-reinforced composite armor provides suitable protective solutions. Despite these advances, most research has focused on personal protective equipment, including body armor and vehicle protection. This concentration has created a significant knowledge gap regarding ballistic protection systems designed specifically for building infrastructure in high-risk environments [19]. Building protection applications demand additional considerations including installation feasibility, retrofit compatibility with existing structures, and economic viability.

This study therefore evaluates the ballistic protection capability of materials according to NIJ Standard 0108.01 Level III for Ballistic Resistant Protective Materials. The test protocol requires materials to resist 7.62×51 mm NATO M80 ball projectiles weighing 9.6 g at 847±9.1 m/s velocity. Three materials were selected for investigation: standard steel plate (Grade SS400), high-hardness steel (HS450), and asphalt cement. Critically, this research systematically investigates the influence of material hardness versus thickness, layer sequencing effects, and the synergistic performance of metal-viscoelastic combinations—aspects that remain underexplored in building ballistic protection literature. The research employs a comprehensive three-phase methodology integrating laboratory ballistic testing, finite element method (FEM) modeling, and field validation. This integrated experimental-computational-practical approach distinguishes the study from purely theoretical investigations or laboratory-only assessments, ensuring the developed protection systems are not only effective but also practically implementable in real-world building applications. This integrated approach establishes a robust foundation for developing efficient and cost-effective ballistic protection systems suitable for buildings in threat-prone areas.

2. Materials and methods

The mechanical properties of materials used in finite element analysis are summarized in Table 2. Complete mechanical properties for HS450 steel and asphalt cement were unavailable due to proprietary restrictions and lack of manufacturer documentation. Consequently, finite element modeling of ballistic impact was conducted exclusively for SS400 steel, which has comprehensive material characterization data.

Table 2 Engineering properties of SS400 and HS450 steels.

Properties	SS400	HS450
Density (kg/m ³)	7860	7898
Young's Modulus (GPa)	188	315
Poisson's ratio	0.3	-
Yield stress (MPa)	246	450
Ultimate stress (MPa)	450	1250
Maximum equivalent plastic strain	0.329	-
Fracture strain	0.35	-
Displacement at Failure	0.4	-

Table 3 lists the mechanical properties of projectile components. The 7.62×51 mm NATO M80 bullet consists of a lead core and a brass jacket [20, 21], modelled using the respective material characteristics of each component. Three-dimensional finite element models of the bulletproof plates were developed using ABAQUS CAE software [22, 23]. Laboratory ballistic tests conformed to NIJ Standard 0108.01 Level III requirements, with specimens impacted by 7.62×51 mm NATO M80 projectiles (9.6 g) at 847±9.1 m/s. Each specimen was tested only once due to budget constraints.

Table 3 Engineering properties of lead core and brass jacket of bullet.

Properties	Lead core	Brass jacket
Density (kg/m ³)	11340	8450
Shear modulus (MPa)	8600	3000
Yield stress (MPa)	8	-
Ultimate stress (MPa)	100	-
Maximum equivalent plastic strain	1	-
C_0 (m/s)	2006	3726
S	1.429	1.434
Fracture strain	2	-
Displacement at Failure	0.5	-

Velocity measurement employed speed sensors installed 10 cm before and after the test specimen (Figure 1) to record the initial projectile velocity (v_i) and exit velocity (v_f). Energy absorption was quantified using Equation 1 to calculate the percentage of kinetic energy dissipated by the material. The laboratory ballistic testing configuration is illustrated in Figure 2.

$$\text{Percent Energy absorbed} = \frac{\left(\frac{1}{2}mv_i^2\right) - \left(\frac{1}{2}mv_f^2\right)}{\left(\frac{1}{2}mv_i^2\right)} \times 100\% \quad (1)$$

Table 4 details the materials tested for ballistic protection, including SS400 steel plates of varying thicknesses, high-hardness steel (HS450) plates, and asphalt cement layers. These materials were evaluated in single-layer, double-layer, and sandwich panel configurations as specified in Table 5.

Finite element simulations incorporated an impact velocity of 838 m/s with fully fixed boundary conditions applied to all four plate edges. The 7.62×51 mm NATO projectile geometry was modeled to scale. The target plate measured 300×300 mm, and mesh discretization utilized three-dimensional eight-node linear brick elements (C3D8) throughout the computational domain. Element density was refined at the plate center to capture localized deformation accurately. The model contained 19,724 elements per millimeter of plate thickness, totaling 16,398 elements for the baseline configuration. ABAQUS software performed all numerical calculations using the finite element method with material nonlinearity considered, as illustrated in Figure 3.

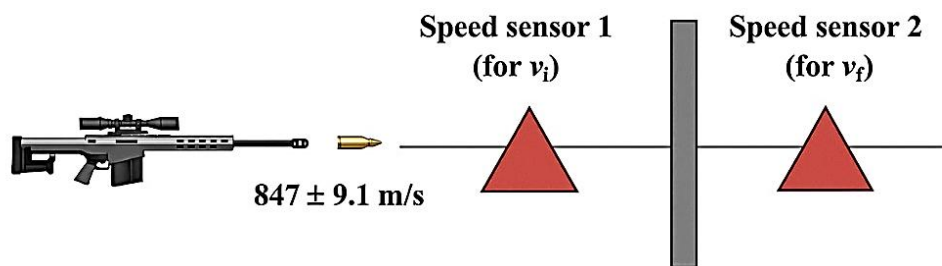
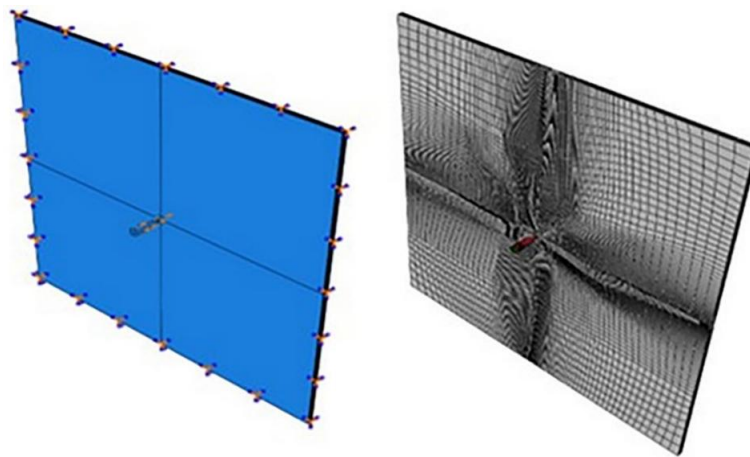
**Figure 1** Experimental setup for bullet resistance ability of materials.**Figure 2** Photograph of the bullet protection capability test in the laboratory.

Table 4 Details of the materials selected for testing bullet protection testing.

Sample code	Description
SS400-3	Steel plate grade SS400 with 3 mm thick
SS400-6	Steel plate grade SS400 with 3 mm thick
HS450-3	High hardness steel plate grade (HBW = 450) with 3.2 mm thick
AC15	Asphalt cement which was packed in a container with a thickness of 15 mm.
AC25	Asphalt cement which was packed in a container with a thickness of 25 mm.

Table 5 Configuration of materials for bullet protection testing.

Test set	Number of layers	Materials
1	1	SS400-3
2	1	SS400-6
3	1	HS450-3
4	1	AC15
5	1	AC25
6	2	SS400-6/AC25
7	2	AC25/SS400-6
8	2	HS450-3/AC25
9	3	SS400-6/AC25/ SS400-6
10	3	HS450-3/AC25/ SS400-6

**Figure 3** Developed model of steel plate for bullet resistance analysis with FEM.

3. Results

The experimental investigation evaluated ballistic resistance across single-layer, double-layer, and sandwich panel configurations using SS400 steel (3 mm and 6 mm), HS450 steel (3 mm), and asphalt cement (15 mm and 25 mm). Table 6 summarizes projectile velocities before and after impact and the corresponding percentage of kinetic energy absorbed. Figure 4 shows the test specimens after single-shot impact.

Table 6 Bullet speed before and after penetrating the single layer material and percent energy absorbed.

Sample	v_i (m/s)	v_r (m/s)	Percent Energy Absorbed
SS400-3	841	739	22.72
SS400-6	842	674	35.81
HS450-3	844	711	28.95
AC15	840	809	7.11
AC25	847	798	11.13

Finite element analysis of SS400 plates at varying thicknesses revealed distinct von Mises stress distributions and damage zones (Figures 5-7).

Finite element analysis revealed a thickness-dependent ballistic response in SS400 plates, consistent with experimental findings. The 3 mm plate (Figure 5) showed overlapping stress waves and shear plug formation, leading to full perforation matching physical test results. The 6 mm plate (Figure 6) exhibited radial stress propagation and rear bulging without penetration, in line with observed deformation zones and irregular edges. For the 12 mm plate (Figure 7), balanced wave attenuation and plastic deformation reduced stress concentration and inhibited cracking, as confirmed by smaller perforation diameters and projectile mushrooming. These trends support that increased thickness enhances energy absorption and stress distribution. The strong correlation between simulation and test results validates FEM as a reliable tool for predicting ballistic performance. Figure 8 further confirms that thicker plates reduce exit velocity, though slight overestimation occurred due to simplifications in projectile modeling.



Figure 4 Tested sample after 1 shot penetration.

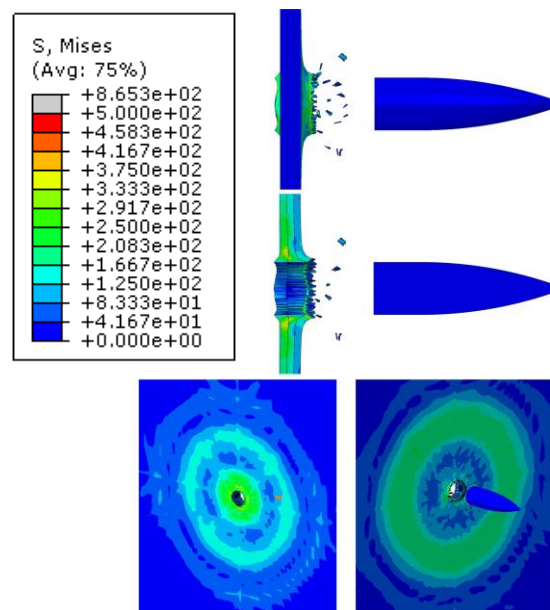


Figure 5 Stress distribution and damage of SS400-3 plate after 7.62×25 mm bullet impact from FEM analysis.

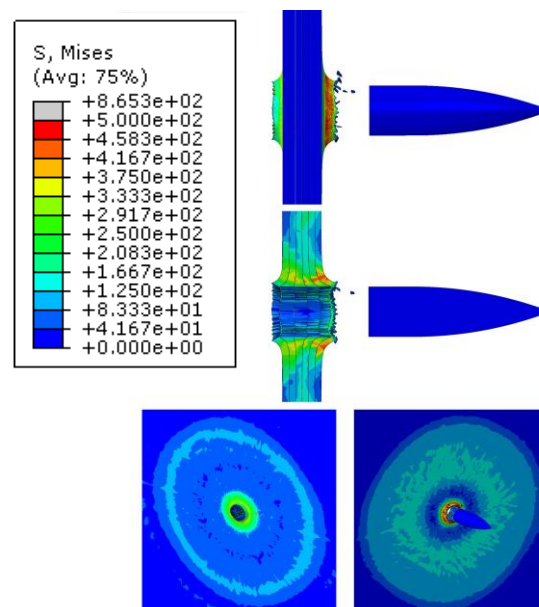


Figure 6 Stress distribution and damage of SS400-6 plate after 7.62×25 mm bullet impact from FEM analysis.

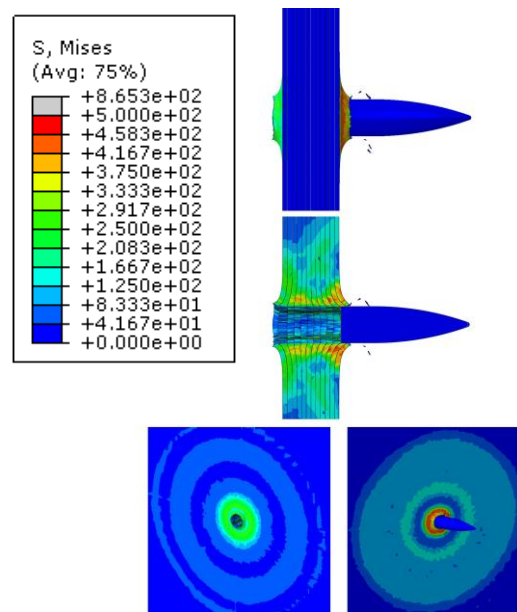


Figure 7 Stress distribution and damage of SS400-12 plate after 7.62×25 mm bullet impact from FEM analysis.

Figure 8 demonstrates that plate thickness directly influences projectile velocity reduction. The 3 mm plate exhibited minimal deceleration (~840→825 m/s), reflecting low resistance and higher energy transmission to the rear surface. The 6 mm plate showed progressive deceleration (~840→810 m/s), indicating increased energy absorption through plastic deformation. The 12 mm plate demonstrated the most significant velocity reduction (~840→780 m/s) before reaching steady state, reflecting highly efficient energy absorption through stress wave propagation and internal friction. These results confirm that thicker plates provide substantially superior ballistic resistance. Additionally, post-impact perforation dimensions and material deformation along the plate length are illustrated in Figure 9 and Figure 10.

Figure 9 reveals that although average perforation diameters showed minimal variation (11.399, 11.999, and 11.108 mm, respectively), the damage mechanisms differed significantly. The 3 mm plate exhibited pronounced shear plug formation with extensive perforation enlargement due to high shear stress and metal tearing. The 6 mm plate showed irregular perforation edges with a broader deformation zone resulting from internal energy absorption. The 12 mm plate demonstrated the smallest perforation radius with dense edge characteristics, indicating superior energy absorption and effective crack propagation inhibition. These observations confirm the trend of enhanced ballistic resistance with increased plate thickness.

Figure 10 shows that all plate thicknesses exhibited maximum deformation at the impact center (~150 mm), but peak magnitudes differed substantially. The 3 mm plate displayed maximum deflection of approximately 1.15 mm, indicating severe plastic deformation and stretching. The 6 mm plate showed reduced peak deformation of approximately 0.8 mm due to improved in-plane stress distribution. The 12 mm plate demonstrated the lowest deformation (~0.6 mm) with smooth stress gradients on both sides of the impact center, reflecting the most efficient energy absorption and dissipation mechanisms. These results indicate that thicker plates resist impact loads with minimal widespread permanent deformation.

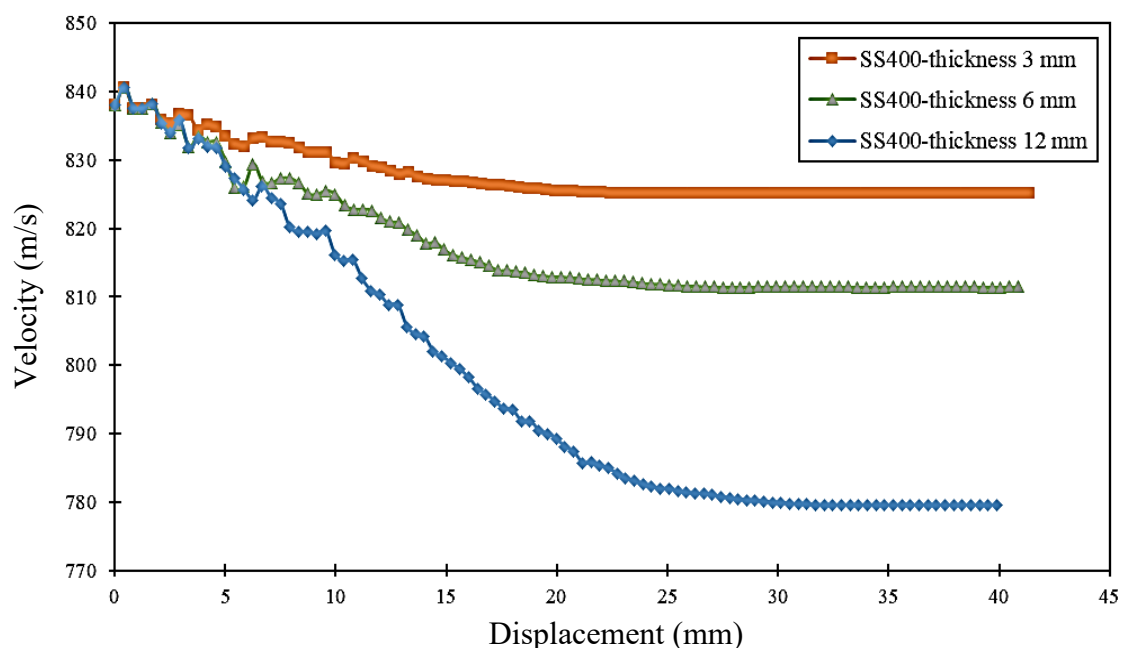


Figure 8 Bullet Speed-Displacement relation of SS400 plates with various thickness from FEM analysis.

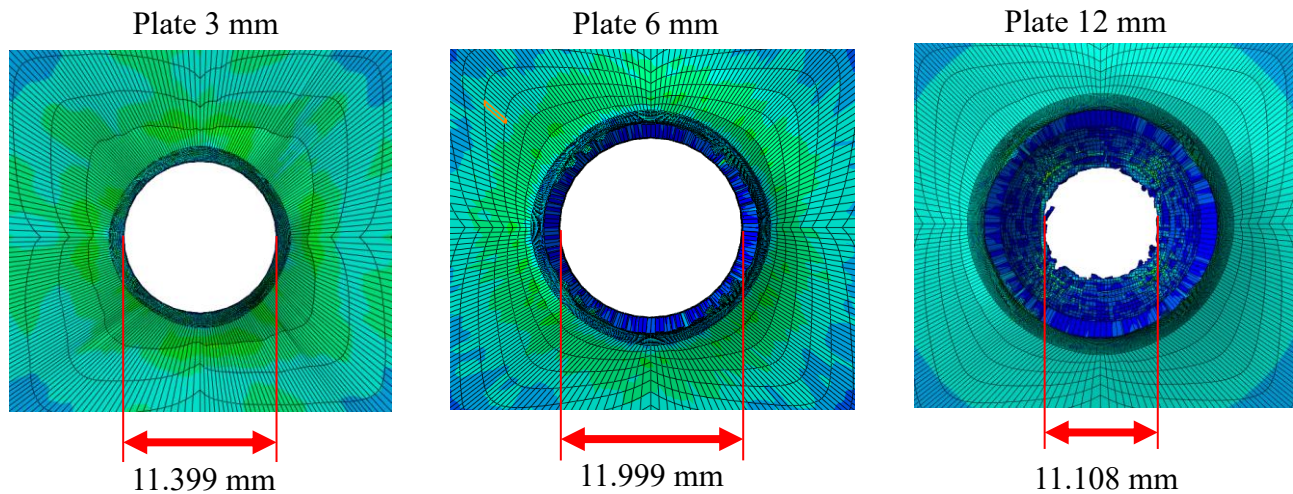


Figure 9 Post-impact perforation dimensions of SS400 plates with various thickness from FEM analysis.

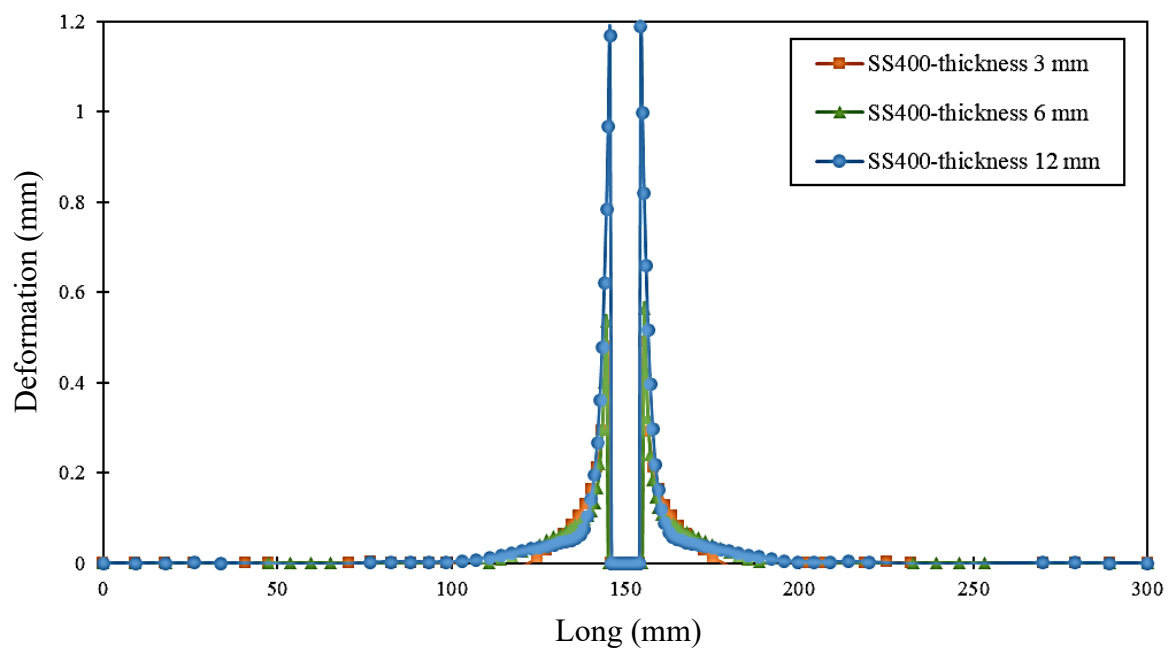


Figure 10 Deformation along the plate length of SS400 plates with various thickness from FEM analysis.

Table 7 reports the enhanced ballistic performance of layered configurations. The SS400-6/AC25 pairing improved energy absorption to 62.39%, while reversing the order (AC25/SS400-6) reduced it to 44.47%. When HS450-3 was used as the strike face, energy absorption reached 78.35%. Both sandwich panel configurations, SS400-6/AC25/SS400-6 and HS450-3/AC25/SS400-6, successfully arrested the projectile. Field trials (Figure 11) confirmed these laboratory findings. The HS450-3/AC25/SS400-6 configuration was selected for prototype deployment (Figure 12) based on its superior ballistic performance, lower mass, and compatibility with existing structures in conflict zones. At an areal density of 129.93 kg/m², this configuration provided equivalent protection to monolithic SS400 plating while achieving a 27.27 kg/m² weight reduction.

Table 7 Bullet speed before and after penetrating the double layer materials and sandwich panels with percent energy absorbed.

Sample	v_i (m/s)	v_r (m/s)	Percent Energy Absorbed
SS400-6/AC25	837	513	62.39
AC25/SS400-6	845	630	44.47
HS450-3/AC25	855	398	78.35
SS400-6/AC25/ SS400-6	851	0	100
HS450-3/AC25/ SS400-6	846	0	100



Figure 11 Field test for bullet resistance of HS450-3/AC25/ SS400-6 composite panel.



Figure 12 Buildings installed the bulletproof panels from the study.

4. Discussion

The experimental findings emphasize that material hardness plays a more critical role than thickness in ballistic performance. Although doubling the thickness of SS400 from 3 mm to 6 mm improved energy absorption from 22.72% to 35.81%, this effect was limited by SS400's low hardness a limitation previously noted by Kim et al. [24]. In contrast, HS450-3, with similar thickness but higher Brinell hardness, absorbed 28.95% of energy, effectively confirming that harder materials better dissipate kinetic energy by promoting projectile deformation. This observation is consistent with Yamada et al. [25], who found that high-stiffness materials yield superior ballistic energy absorption. The deformation and mushrooming effect induced by high-hardness surfaces documented in Ryan et al. [26] enhance the kinetic energy dissipation mechanism. Asphalt cement, while ineffective as a standalone layer due to its low hardness, showed potential in secondary layers due to its viscoelastic properties. Mansour et al. [27] similarly demonstrated that incorporating steel fibers into asphalt concrete significantly boosts energy absorption and impact resistance.

FEM simulations reinforced these findings. As seen in Figures 5–7, thicker SS400 plates exhibited elevated von Mises stress and internal energy absorption due to constrained plastic deformation. Holmen et al. [28] highlighted that case-hardened and layered plates provide superior stress distribution due to gradient material properties. Yadav et al. [29] also noted that thicker materials absorb more energy and resist deformation effectively. Sastranegara et al. [30] validated this phenomenon in multilayer armor simulations. Furthermore, Da Luz et al. [31] demonstrated that multilayered composite systems especially those with intermediate epoxy layers enhance both residual stress dissipation and structural integrity under ballistic loads. Similarly, Figure 8 shows that FEM-predicted exit velocities exceeded experimental results, a discrepancy also identified by Sastranegara et al. [30] and attributed to the absence of projectile deformation modeling. Figure 9 illustrates a clearly defined perforation with dense edges. Increasing the plate thickness

enhances bullet resistance, consistent with the findings of Mosa et al. [32]. Figure 10 demonstrates that thicker plates reduce permanent deformation by improving force distribution and energy absorption, in agreement with the research by Alonso et al. [33].

The improved performance of configurations with hard front layers supports previous findings [34], which emphasize the critical role of strike face hardness in penetration resistance. The HS450-3/AC25 configuration further enhanced energy absorption, confirming the critical role of front-layer hardness. Flores-Johnson et al. [35] also reported enhanced resistance in high-hardness multilayer metallic systems, where the front layers cause projectile fragmentation and subsequent layers dissipate residual energy.

5. Conclusions

This study demonstrates that material hardness has a greater effect on ballistic resistance than thickness. Increasing SS400 steel plate thickness from 3 mm to 6 mm resulted in a moderate 35.81% rise in energy absorption. In contrast, high-hardness HS450 steel at 3 mm thickness absorbed 48.66% of the projectile's kinetic energy, mainly due to enhanced projectile deformation. Asphalt cement (AC25) alone showed limited effectiveness (11.13%), but as a backing layer, it significantly improved energy dissipation because of its elasticity. Multilayer configurations combining complementary materials notably enhanced ballistic resistance. The SS400-6/AC25 double-layer panel absorbed 62.39% of impact energy, while the HS450-3/AC25 arrangement reached 78.35%. The sandwich panel HS450-3/AC25/SS400-6 achieved complete projectile stoppage, underscoring the critical role of layer sequencing. Finite element simulations confirmed that thicker plates induce higher residual stress due to constrained deformation, a drawback mitigated effectively by layered designs. These findings offer practical guidance for composite ballistic panel applications in building protection. The HS450-3/AC25/SS400-6 configuration stands out as a high-performance, lightweight, and retrofit-friendly solution ideally suited for reinforcing structures in conflict or high-risk areas. Future studies should evaluate multi-hit performance, assess environmental durability of material interfaces, explore advanced viscoelastic alternatives, and establish standardized installation protocols for building applications.

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