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Ballistic Performance of Composite Panels and Aramid Fabric Systems for Critical Infrastructure Protection Against Fragmentation Threats

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Abstract

The rapid spread of unmanned aerial vehicles and loitering munitions has created a new class of threats for critical infrastructure, especially for facilities that depend on uninterrupted operation and contain exposed roof and wall assemblies. In such an environment, the design of protective systems can no longer focus only on conventional lateral threats or on isolated single-impact scenarios. Instead, it must address repeated fragmentation exposure, localized cumulative damage, and the need to preserve functionality after attack. This paper develops a standalone conference contribution based primarily on the ballistic material evaluation presented in Chapter 5 of the source study. The text focuses on the structural characteristics, test response, and engineering applicability of rigid glass-fiber-reinforced polymer (GFRP) panels and flexible Twaron T730 aramid systems for infrastructure protection. Two GFRP panels with nominal thicknesses of 12.2 mm and 14 mm were evaluated under ballistic loading, while rear-face deformation was measured by laser profilometry and internal damage was assessed using digital radiography. In parallel, a multilayer Twaron T730 aramid configuration was used as a comparative flexible barrier system. The results confirm that rigid GFRP panels provide stable mechanical resistance, controlled rear-face deformation, and a low probability of catastrophic penetration under the tested conditions. The radiographic evaluation further shows that internal damage zones can significantly exceed visibly damaged areas, highlighting the importance of non-destructive inspection for reliable post-impact assessment. The aramid system demonstrates favorable energy absorption under moderate impact loading, but it also reaches its limits under repeated higher-energy events. Based on the combined results, the paper argues that rigid composite panels are the most suitable primary protective element for large-area infrastructure applications, while aramid systems are best employed as supplementary internal layers or as part of a hybrid configuration. The findings are discussed in relation to roof protection, multi-hit resistance, modular retrofitting, and the practical design of protective envelopes for critical infrastructure exposed to fragmentation hazards.

KEY WORDS: *ballistic protection, GFRP, Twaron T730, fragmentation, critical infrastructure, composite panels, hybrid shielding*

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1. Introduction

The protection of critical infrastructure has entered a new phase in which vertically acting threats and repeated fragmentation exposure have become central design problems. For decades, many protective concepts for civilian and military facilities were derived from assumptions of lateral attack, isolated blast events, or accidental impact. Those assumptions are increasingly inadequate. Unmanned aerial vehicles, improvised loitering systems, and other low-cost airborne platforms are able to approach infrastructure at low altitude, exploit operational blind spots, and deliver explosive payloads in ways that generate concentrated roof loading and distributed fragment interaction over large surface areas [1, 2].

Even when the warhead mass is limited, the resulting fragment field may produce severe local damage, disable equipment, injure personnel, and initiate cascading failures in systems that rely on spatially concentrated critical nodes.

1.1. Operational threat analysis

1.1.1. Statistical Distribution of UAV-Based Attacks

Modern operational environments demonstrate a clear transition toward the widespread deployment of unmanned aerial vehicles (UAVs) as primary strike assets. Statistical data from recent operational campaigns indicate that UAV systems now represent the dominant method for sustaining pressure against infrastructure systems through repeated and distributed attack patterns. Unlike conventional strike platforms, UAV systems enable persistent engagement cycles that impose cumulative degradation effects on infrastructure functionality. Data collected during the initial phase of a documented multi-state drone campaign revealed that UAV platforms accounted for approximately 71 percent of all recorded strike systems, confirming their dominant role in operational strike architecture. This distribution reflects a strategic emphasis on scalable, cost-effective systems capable of sustained engagement across multiple operational theaters. The predominance of UAVs in strike operations is particularly significant because it alters the temporal structure of infrastructure exposure. Rather than experiencing isolated strike events separated by long recovery intervals, infrastructure systems are subjected to repeated engagement cycles occurring over consecutive days. This sustained exposure significantly increases the probability of cumulative structural damage. The temporal pattern observed during the analyzed campaign demonstrates a characteristic two-phase attack structure. The initial phase consisted of a large-scale shock wave involving approximately 1,206 strike events, including both UAV and missile deployments. This phase was followed by a transition into a stabilization period during which daily strike volumes ranged between approximately 190 and 392 attacks per day. Such operational continuity introduces a persistent risk environment in which infrastructure systems must maintain defensive readiness under extended operational pressure. Geographical distribution patterns further demonstrate that UAV-based strikes are not evenly allocated across target areas. Instead, attack concentration typically correlates with the density of economically and operationally significant infrastructure nodes. In the analyzed dataset, a single high-value operational region absorbed approximately 1,668 total recorded strikes, representing more than half of all documented strike activity within the reporting period. This concentration pattern confirms that adversaries prioritize regions characterized by logistical hubs, fuel distribution facilities, communication centers, and transportation infrastructure. The statistical characteristics described above illustrate the emergence of a new operational paradigm defined by persistent pressure rather than singular high-intensity strike events. This paradigm shift has direct implications for infrastructure protection engineering, as traditional structural design methods often assume limited exposure frequency. Under saturation conditions, even moderate structural vulnerabilities may evolve into catastrophic failure mechanisms due to repeated loading cycles and fragmentation exposure.

1.1.2. UAV Threat Classification and Operational Characteristics

The diversity of UAV platforms deployed in modern conflicts requires a systematic classification framework to support infrastructure risk assessment. UAV systems relevant to infrastructure threats generally fall into three functional categories: reconnaissance-support UAVs, attack UAVs, and loitering munitions. Each category presents distinct operational characteristics affecting fragmentation behavior, penetration probability, and infrastructure exposure risk. Attack UAVs typically operate at low to moderate altitudes and are capable of delivering explosive payloads directly to structural targets. These systems are frequently employed in coordinated groups, enabling simultaneous or sequential attack patterns designed to overwhelm defensive systems. Their relatively low flight speed, compared to conventional missile systems, allows for flexible navigation around terrain obstacles and increases the probability of reaching structurally vulnerable areas such as rooftops and ventilation structures. Loitering munitions represent a particularly significant threat category due to their capacity for delayed target engagement. Unlike fixed trajectory weapons, loitering systems remain airborne within designated operational zones until a target of opportunity is identified. Upon confirmation, the system transitions into a terminal dive phase resulting in direct impact detonation. This behavior introduces uncertainty into infrastructure protection planning, as target selection may occur dynamically during the attack sequence. Low-altitude flight capability constitutes one of the most critical operational characteristics of modern UAV threats. Flight altitudes frequently remain below conventional radar detection thresholds, enabling UAV systems to approach infrastructure targets with limited early warning. Additionally, low-altitude attack geometry increases the probability of fragmentation interaction with overhead structural elements, including roofing systems, protective covers, and exposed equipment. Another defining characteristic of UAV operations is the use of nighttime deployment strategies. Reduced visibility conditions degrade human observation capability and complicate manual interception procedures. Infrastructure facilities lacking automated detection systems are therefore exposed to increased vulnerability during nocturnal operational periods. In combination with low-altitude flight geometry, nighttime attack patterns significantly reduce reaction time and increase the probability of successful structural penetration. From an engineering perspective, these operational characteristics highlight the importance of vertical protection measures. Traditional infrastructure protection strategies have historically emphasized lateral protection through reinforced walls and perimeter barriers. However, UAV attack geometry introduces a dominant vertical threat axis that requires dedicated overhead protection systems capable of absorbing fragmentation energy and preventing internal structural failure [3,9].

1.1.3. Operational Pressure and Cumulative Infrastructure Stress

The cumulative nature of UAV-based strike operations represents one of the most significant risk amplification factors affecting infrastructure resilience. Under repeated attack conditions, structural components experience multiple fragmentation interactions that may not immediately result in catastrophic failure but gradually weaken material integrity. Repeated fragmentation exposure produces localized stress concentrations within structural materials. Even when initial impacts do not penetrate protective surfaces, subsequent impacts may exploit previously damaged regions, increasing the probability of penetration [1,5]. This cumulative damage behavior is particularly relevant for lightweight construction materials commonly used in modular infrastructure systems. Operational pressure is further amplified by the economic characteristics of UAV systems. The relatively low cost of UAV production enables sustained deployment cycles that would be financially impractical using conventional missile systems. As a result, infrastructure systems may experience extended periods of elevated threat exposure lasting weeks or months. In addition to physical damage mechanisms, cumulative operational pressure produces secondary effects including personnel fatigue, maintenance overload, and logistical disruption.

Continuous repair requirements reduce operational availability and increase maintenance resource consumption. Over time, these secondary effects contribute to overall infrastructure degradation even in the absence of direct catastrophic failure. The combined influence of repeated fragmentation exposure, structural fatigue, and operational stress defines a new risk environment in which infrastructure resilience depends on the ability to withstand multiple low-intensity events rather than a single high-intensity event. This shift necessitates the adoption of protective materials capable of maintaining structural integrity under repeated impact conditions.

1.2. Comparative Material Behavior Under Fragmentation Loading in Infrastructure Applications

Critical infrastructure is particularly vulnerable because it combines fixed location, functional indispensability, and often limited architectural readiness for modern aerial threats. Electrical substations, communication nodes, logistics depots, transport interfaces, temporary command posts, and service buildings are frequently designed for environmental loads and ordinary accidental actions, not for overhead fragmentation. The use of lightweight modular envelopes, thin metal roofing, or large unsupported surfaces may be advantageous for speed of construction and cost, but it also creates pronounced vulnerability under fragment impact. In practice, a moderate detonation above a roof may create effects that are disproportionate to the energetic scale of the event: perforation of the envelope, internal debris generation, interruption of electrical or control systems, and immediate loss of operational continuity.

The present contribution addresses this challenge through the lens of protective material performance. It is derived primarily from the material-oriented core of the underlying article, especially Chapter 5, where rigid GFRP panels and a layered Twaron T730 aramid system are compared from the perspective of ballistic response. While the broader source article also includes threat analysis, infrastructure vulnerability, and implementation strategy, the present conference paper is intentionally focused on the material and engineering design dimension. The goal is to develop a full-length text suitable for conference publication that remains centered on the comparative performance of two classes of protective materials and on the practical implications of that performance for critical infrastructure protection.

The key research question is therefore not merely whether a specific panel resists a specific projectile, but how the observed response mechanisms inform engineering decisions for infrastructure-scale application. In such applications, the suitability of a protective material depends on more than nominal ballistic class. It depends on stiffness, deformational behavior, internal damage development, inspectability after impact, load added to the supporting structure, and ability to remain functional under repeated or distributed loading. These are precisely the issues that determine whether a material is applicable as a roof shield, wall lining, protective enclosure, or hybrid reinforcement layer.

The remainder of the paper is structured as follows. First, the engineering context of fragmentation hazards and material selection is summarized. Next, the tested rigid and flexible systems are described together with the basic measurement methods used for their evaluation. The paper then presents and discusses deformation results, internal damage mapping, and the comparative behavior of the two systems under dynamic loading. Finally, the observed material response is translated into design recommendations for roof protection, modular retrofitting, and hybrid protective systems intended for infrastructure exposed to repeated fragmentation threats.

2. Fragmentation Threats and Material Demands in Infrastructure Protection

A proper understanding of protective material performance must begin with the nature of the threat. Fragmentation from explosive payloads differs fundamentally from conventional static loading and also from single-point low-velocity impact. Aerial detonation typically produces a high number of fragments with different masses, velocities, and trajectories. Instead of one dominant penetration path, the structure is exposed to a field of distributed impacts. On horizontal surfaces, and especially on roofs, this means that local resistance is required over relatively large areas, and that repeated impacts within a short time interval may interact through local weakening of the material. For infrastructure systems, the problem is amplified by the presence of external devices, ducts, cable paths, supporting frames, and equipment placed directly beneath the building envelope.

In engineering terms, the protective material must satisfy several requirements simultaneously. The first is obvious ballistic resistance: the ability to prevent perforation or to sufficiently reduce residual energy. The second is controlled deformational behavior. A material may prevent complete penetration and still be unsuitable if its backface deformation is large enough to create secondary hazards, damage equipment mounted behind the barrier, or compromise the serviceability of the protected assembly. The third requirement is multi-hit robustness. Protective elements used in infrastructure rarely experience a single laboratory impact under ideal support conditions; instead, they may be exposed to clusters of impacts, to local concentration of fragments, or to repeated attacks separated by limited inspection time. The fourth requirement is inspectability. If internal damage grows well beyond the visibly damaged area, then reliance on surface inspection becomes unsafe, and the maintenance strategy must account for hidden delamination or internal fiber failure [7,8].

Rigid composite panels are attractive in this context because they combine comparatively high stiffness, corrosion resistance, low maintenance needs, and favorable strength-to-weight characteristics. Their rigidity is especially important for infrastructure applications in which the protective element must span between supports, maintain geometry, and contribute to the mechanical behavior of the envelope. By contrast, flexible aramid systems are widely known for excellent energy absorption, but they typically require backing, tensioning, or enclosure to function effectively at larger scales. Their role is therefore often complementary rather than primary when the objective is to protect roofs, walls, or structural surfaces of fixed facilities.

The significance of these distinctions becomes clearer when one moves from personal armor logic to infrastructure logic. Personal armor tolerates a relatively large backface signature provided that the accepted injury criterion is not exceeded. Infrastructure shielding, however, may need to keep deformation low enough to avoid contact with machinery, cabling, fire-sensitive systems, or operators located very close behind the barrier. Similarly, a flexible fabric may successfully catch a projectile in a test package, but its direct use as a free-standing external roof shield is limited because it lacks the geometric stiffness required for unsupported deployment [1,8]. For this reason, the comparison of rigid GFRP panels and layered aramid systems is not a competition between alternatives of the same type, but a study of two complementary protective mechanisms whose engineering roles differ.

From a practical standpoint, the most relevant material demand in current infrastructure protection is therefore not simply “high resistance,” but “high resistance in a structurally applicable form.” A successful protective solution must be mountable on existing structures, capable of retrofitting, sufficiently lightweight for realistic installation, and reliable under inspection and maintenance regimes that may be constrained by operational pressure. The following sections examine how the tested GFRP and aramid systems respond to these demands.

3. Materials and Experimental Approach

The conference paper is based on the test data and comparative material analysis contained in the source study. Two classes of protective material were considered: rigid glass-fiber-reinforced polymer composite panels and a flexible multilayer para-aramid fabric system based on Twaron T730 fibers. The purpose of evaluating both systems was to compare their response mechanisms and to identify the type of application for which each material class is most appropriate [10,15,17].

The rigid composite system consisted of PREFASTRIX GFRP panels intended for architectural and infrastructure applications. Two panel variants were assessed [11,15]. The first, designated P12, had a nominal thickness of 12.2 mm, an areal density of 24.6 kg/m², a flexural strength of 205 MPa, a modulus of 29.8 GPa, ballistic class FB4, and a V50 value of 795 m/s. The second, designated P14, had a thickness of 14 mm, an areal density of 28.0 kg/m², a flexural strength of 164 MPa, a modulus of 27.0 GPa, ballistic class FB4, and a V50 value of 833 m/s. These values indicate a stiff, structurally usable material family capable of being incorporated into protective assemblies for roofs, walls, and enclosures (Table 1).

Table 1. Mechanical parameters of the tested PREFASTRIX GFRP panels.

Panel type	Thickness	Areal density	Flexural strength	Modulus	V50
P12	12.2 mm	24.6 kg/m²	205 MPa	29.8 GPa	795 m/s
P14	14.0 mm	28.0 kg/m²	164 MPa	27.0 GPa	833 m/s

Ballistic testing of the GFRP panels was performed on square specimens measuring 500 × 500 mm. Each specimen was subjected to three vertically aligned impacts to observe not only the response to a single hit, but also the local accumulation of damage in a confined region. Two projectile types were used: .357 Magnum and .44 Remington Magnum. Although the present contribution focuses mainly on infrastructure relevance rather than on forensic detail, the chosen ammunition classes are sufficient to produce representative dynamic loading for comparison of rear-face response and internal damage propagation. Rear-face deformation was measured using optical laser profilometry with a Micro-Epsilon displacement sensor. This method provided longitudinal surface profiles and enabled direct identification of the maximum deformation height after impact.

In addition to surface deformation, the investigation employed digital radiography to evaluate internal damage. This is an important aspect of the study because composite materials often fail through mechanisms that are not fully visible externally. Matrix cracking, local delamination, disruption of fiber bundles, and the growth of hidden internal damage zones may substantially reduce residual capacity even when the visible crater or indentation appears limited. The radiographic part of the testing therefore served not only as a diagnostic tool but also as a basis for engineering conclusions related to inspection and maintenance of protective systems after service loading. For comparison, a flexible layered system based on Twaron T730 para-aramid fibers was also considered. The tested configuration consisted of fifteen layers in plain weave, with an areal density of 260 g/m² per layer and a layer thickness of approximately 0.4 mm. The total multilayer package thus represented a relatively thin but highly energy-dissipative barrier. Ballistic testing followed the NIJ 0101.06 approach using 9×19 mm FMJ and .357 SIG FMJ projectiles. Three shots were performed per configuration. The resulting backface signature values and penetration behavior provided a useful comparative baseline for assessing the benefits and limitations of flexible systems in relation to rigid composite panels.

It must be emphasized that the two material classes are not directly interchangeable in infrastructure design. The rigid GFRP panels can act as self-supporting or semi-self-supporting protective components, while the aramid package is a flexible protective insert requiring appropriate backing or integration into a larger assembly. Nevertheless, comparing them under ballistic loading is valuable because it reveals how different mechanisms of energy dissipation translate into engineering performance. The GFRP system relies on localized stiffness, matrix cracking, fiber fracture, and through-thickness load redistribution, whereas the aramid system relies on distributed tensile stretching, yarn pull-out, and deformation over a larger area. Understanding the implications of these different mechanisms is one of the central aims of the discussion that follows.

4. Mechanical Performance of GFRP Panels

The rigid GFRP panels demonstrated a mechanically stable response across the tested loading conditions. Their general behavior under impact can be characterized as localized but controlled deformation combined with preserved integrity of the panel as a whole. This is an important observation because, for infrastructure-scale shielding, the retention of structural continuity is often more valuable than the absolute minimization of local damage. A roof or wall panel that remains in place, continues to shield the protected zone, and does not undergo catastrophic perforation can prevent cascading functional failure even if it experiences significant local internal damage. The measured rear-face deformation values support this interpretation. For the 14 mm panel, the maximum deformation heights were 7.75 mm under .357 Magnum and 7.69 mm under .44 Magnum loading. For the 12.2 mm panel, the values were 7.30 mm under .357 Magnum and 8.39 mm under .44 Magnum loading (Table2).

Table 2. Maximum rear-face deformation measured in the impacted GFRP panels.

Panel thickness	Projectile	Rear-face deformation
14 mm	.357 Magnum	7.75 mm
14 mm	.44 Magnum	7.69 mm
12.2 mm	.357 Magnum	7.30 mm
12.2 mm	.44 Magnum	8.39 mm

The data show several relevant patterns. First, the overall magnitude of deformation remained relatively low for all tested configurations. Second, the thinner panel generally exhibited a greater tendency toward deformation under the more demanding projectile condition. Third, the difference between the two thicknesses, while not extreme, is meaningful from a design perspective because it indicates that a moderate increase in thickness can improve response stability while only modestly increasing areal mass. This balance between mechanical benefit and added weight is crucial in retrofitting applications. Existing buildings and infrastructure nodes often cannot accommodate large increments of dead load without secondary strengthening. The difference between 24.6 kg/m² and 28.0 kg/m² is therefore engineeringly significant because it defines a realistic range within which designers can trade structural demand against protective performance. A protective solution that requires excessive supporting steel or heavy subframes may become impractical even if its laboratory resistance is excellent. The tested GFRP panels appear favorable in this respect because they achieve structural applicability at a mass level that remains realistic for external cladding, roof overlays, or modular protective shells. Another important point is the relation between deformation and serviceability. In personal armor evaluation, backface deformation is interpreted mainly in terms of injury risk. In infrastructure systems, however, the same quantity must be interpreted more broadly. Local backface displacement may affect cable trays, machine housings, mechanical fasteners, or clearance zones behind the protective layer. Low and predictable deformation is therefore desirable even when no complete perforation occurs. The measured values in the GFRP panels suggest a response compatible with infrastructure use, especially where the designer can provide modest stand-off or a secondary energy-dissipating cavity behind the panel. The structure itself also contributes to the engineering appeal of the system. Continuous reinforcement and high manufacturing consistency reduce the variability that can otherwise complicate structural detailing and certification. For field deployment, particularly in modular systems, predictable quality is not merely an economic advantage but a safety requirement. Panels used in distributed infrastructure protection should have reproducible stiffness, thickness control, and connection performance so that the protective behavior of the installed system is not overly dependent on local material irregularities.

Finally, the observed performance underscores the distinction between rigid and flexible shielding concepts. The GFRP panels do not dissipate energy through large membrane-like deformation as aramid fabrics do. Instead, they retain geometry and concentrate the response in a limited zone. For walls, roofs, and protective housings, this is advantageous because it reduces the risk of large-scale displacement and maintains the positional stability of the protective element. In this sense, the rigid GFRP panels do not merely resist impact; they provide a structurally compatible form of resistance that is directly usable in protective engineering.

5. Radiographic Evaluation and Hidden Damage Development

Perhaps the most consequential finding of the material investigation is not the rear-face deformation itself, but the discrepancy between visible external damage and the true internal damage state. The radiographic inspection revealed that internal damage zones in the tested GFRP panels could exceed the visibly observable damaged area by approximately 192%. This means that a panel appearing locally affected on the surface may in reality contain a much larger subsurface region of disrupted fibers, matrix cracking, and internal delamination. For protective design, this is a critical insight.

The phenomenon is consistent with the failure behavior of layered composite systems. Under ballistic loading, a considerable part of the impact energy is dissipated not only in the formation of the visible crater or indentation, but also through internal redistribution. Fiber bundles are bent, fractured, and locally separated; the matrix cracks and loses continuity; interfaces between internal zones debond and delaminate [4,7,12]. Because much of this process occurs beneath the outer surface, the external appearance underestimates the extent of structural change. In practical use, a panel that has "survived" an impact may therefore have substantially reduced residual capacity over an area much larger than the directly hit region. This has immediate implications for inspection strategy. If post-event assessment relies solely on visual examination, protective panels may remain in service after impacts that have already compromised their multi-hit resistance [7,5]. In an infrastructure setting, where the protected facility may remain under threat or may be required to continue operation after a short interruption, this creates a serious risk. Maintenance teams may conclude that only limited local repair is necessary, while the actual damaged volume could require replacement of a full module or at least non-destructive verification before continued service. The use of digital radiography in the study therefore provides more than an academic refinement. It points to a necessary operational requirement for composite protective systems: hidden damage must be assumed unless a suitable inspection method proves otherwise [7,12, 13]. For high-value infrastructure, this suggests that ballistic shielding should be designed in replaceable modules sized according to expected damage envelopes rather than according to the visibly affected surface. A modular approach reduces uncertainty because a panel can be removed and replaced after suspicious loading without the need to repair a monolithic roof or wall surface in place. The results also indicate that thinner panels are more vulnerable to the development of larger internal damage zones. This does not mean that thinner panels are unsuitable, but it does imply that design based purely on non-penetration criteria is incomplete. Two panels may both stop a projectile, yet one may retain substantially greater residual integrity and multi-hit potential than the other. For critical infrastructure, that difference may govern the real performance of the protective system under repeated attack cycles. Selection of panel thickness should therefore account not only for first-hit resistance but also for expected inspection interval, replacement logistics, and desired tolerance for hidden degradation.

In a wider engineering context, the radiographic observations reinforce a general principle for protective structures made of advanced composites: apparent survivability is not equivalent to preserved capacity. This principle is especially important for infrastructure because failure consequences are not limited to the panel itself. If a hidden-damaged shield remains installed above electrical equipment, personnel access points, or communication systems, a second impact may exploit the weakened region and lead to sudden penetration where the first event did not. Integrating non-destructive assessment into the lifecycle of composite protection is therefore essential to achieving the resilience that these materials can otherwise provide.

6. Comparative Assessment of Twaron T730 Aramid Systems

The Twaron T730 multilayer system provides an instructive contrast to the rigid GFRP panels because it relies on a fundamentally different mode of energy absorption [21,22]. Para-aramid fibers are well known for high tensile strength, low density, and excellent capacity to absorb impact energy through stretching, friction, and progressive yarn interaction. In the tested configuration of fifteen layers, this translated into good performance against moderate-energy projectiles [14,21]. Under 9×19 mm FMJ impact at velocities around 370–376 m/s, the system showed partial penetration with backface signature values of 35–36 mm, remaining below the NIJ threshold of 44 mm.

When the loading was increased to the .357 SIG FMJ level, however, the limits of the tested package became evident. The measured backface signature rose to 40 and 44 mm for two shots, and the third shot produced complete penetration. The average kinetic energy associated with the .357 SIG projectile was approximately 801 J, compared with about 556 J for the 9 mm projectile, which represents an increase of roughly 44%. This increase in energy was sufficient to push the aramid package to the edge of its capacity. The system still displayed meaningful energy absorption, but it no longer provided consistent resistance across repeated higher-energy impacts [5, 22].

For infrastructure applications, these observations must be interpreted carefully. The Twaron system performs well as a flexible dissipative barrier, but its performance is strongly linked to the available deformation space and to the way it is supported. Large backface displacement can be acceptable in personal protective systems if injury criteria remain below the allowed limit. In infrastructure, however, deformation of 35–44 mm may be excessive if sensitive equipment is located immediately behind the shield. Furthermore, a free flexible package does not offer the same geometric stability as a rigid panel, making it less suitable as a primary external protective surface for roofs, wall claddings, or structural enclosures.

This does not diminish the value of aramid systems; it clarifies their most effective role. Twaron layers are especially useful as internal energy-dissipating components, spall liners, or supplementary layers in a hybrid system. They can reduce residual energy after passage through a rigid outer layer, limit internal debris generation, and improve occupant or equipment protection behind the primary shield. They may also be suitable for local shielding of particularly sensitive components where structural support can be designed accordingly. What the results suggest is that flexible aramid assemblies should generally not be asked to perform the entire protective function on their own when large-area infrastructure shielding is required.

From a design standpoint, the comparison with GFRP is therefore highly informative. The aramid system excels in distributed tensile dissipation and low-density impact absorption, while the GFRP panel excels in structural integration, low localized displacement, and large-area applicability. The two systems should not be treated as mutually exclusive alternatives. Instead, they should be regarded as complementary materials whose combined use can provide better overall protection than either one alone. This hybrid logic is explored in the next section as a direct consequence of the comparative test results.

Table 3. Summary of Twaron T730 response under NIJ-based ballistic testing.

Projectile	Velocity	Observed response	BFS
9×19 mm FMJ	370 m/s	Partial penetration	36 mm
9×19 mm FMJ	376 m/s	Partial penetration	35 mm
9×19 mm FMJ	372 m/s	Partial penetration	36 mm
.357 SIG FMJ	445 m/s	Partial penetration	40 mm
.357 SIG FMJ	447 m/s	Partial penetration	44 mm
.357 SIG FMJ	447 m/s	Complete penetration	-

7. Hybrid Protective Concepts and Engineering Design Implications

One of the most important engineering conclusions arising from the comparative study is the potential of hybrid protective systems. A hybrid assembly that combines an external rigid GFRP layer with internal aramid layers can exploit the benefits of both material classes while compensating for their individual limitations. The rigid outer panel provides structural continuity, weather resistance, geometric stability, and primary fragment stopping or slowing capability [8,15,19,20]. The internal aramid package then acts as an energy-dissipating and debris-limiting layer that captures residual fragments, reduces transmitted energy, and mitigates the secondary effects of local backface response.

The source study suggests that a combination of approximately 10–15 mm of GFRP with 10–20 aramid layers may significantly increase resistance to fragmentation threats associated with UAV warhead detonation environments. This recommendation is technically plausible for several reasons. First, the outer rigid layer will reduce the severity of the residual load transmitted to the flexible layer. Second, the flexible layer will improve the tolerance of the assembly to local damage and reduce the risk that internal fragments or debris are projected into the protected space. Third, the separation between layers can be engineered to create a controlled deformation zone, allowing the assembly to manage dynamic load without large, transmitted displacement. In practical infrastructure design, the hybrid concept is especially relevant for roofs and top surfaces. Roofs are the dominant exposure interface under aerial fragmentation because their orientation is directly aligned with the main downward fragment field. A rigid-only solution may be effective but may still transmit local shock and generate hidden internal damage that complicates continued service. A flexible-only solution is generally insufficient as an external roof element because it lacks the necessary stiffness and durability. By contrast, a hybrid roof cassette or modular panel can function as a fully engineered protective unit with defined attachment points, replaceable modules, and predictable performance under repeated exposure. The same logic applies to wall systems, protected enclosures, and equipment housings. A modular hybrid panel can be attached to a steel or aluminum support frame and designed as a replaceable unit [1,9]. After impact, the entire module can be removed for inspection or replacement rather than attempting uncertain local repair. This approach aligns well with the radiographic finding that internal damage extends beyond the visually affected area. It also supports rapid deployment and phased retrofitting, which are essential in operational environments where infrastructure cannot be taken offline for long periods.

The influence of installation geometry should also be considered. Even high-performance protective materials can lose effectiveness if mounted in a mechanically unfavorable way. Slight inclination of a roof-mounted protective layer may reduce the probability of perpendicular impact and improve the chance of fragment deflection. Support spacing must be selected to avoid excessive panel bending under combined dead load and dynamic impact. Fasteners and edge details must be designed so that local failure at the connection does not become the weak point of the protective system. In many retrofitting scenarios, the supporting substructure may be as important as the panel itself. Weight optimization remains another decisive issue. The tested GFRP panels are relatively light compared to many conventional ballistic solutions, which supports their use in retrofit applications. Even so, the total mass of a hybrid assembly must be evaluated together with support frames, fasteners, and possible weatherproofing layers. The designer should therefore adopt a zonal approach: the most heavily exposed or functionally critical areas receive the most robust hybrid protection, while lower-risk areas may use only rigid panels or selective reinforcement. Such a risk-based distribution of material is often more realistic and cost-effective than uniform full-coverage shielding.

The broader implication is that protective design for infrastructure should shift from the selection of isolated materials to the design of assemblies. The test data show that neither nominal ballistic classification nor single-hit behavior alone is sufficient as a basis for real-world deployment. What matters is how the entire protective system manages impact, residual damage, inspection, replacement, and continued functionality. The hybrid concept is attractive precisely because it can be adapted to that systems-based view of protective engineering.

6. Practical Application to Critical Infrastructure

To appreciate the full significance of the material results, they must be translated into the context of real infrastructure. Facilities that are exposed to fragmentation hazards are rarely empty structural shells. They contain equipment, operators, access routes, support systems, and utility connections that define both their vulnerability and the value of protection. A protective material solution that performs well in a ballistic test becomes truly relevant only when it can be integrated into this operational environment without creating excessive structural, financial, or maintenance burdens.

Electrical and communication facilities are a clear example. Roof-mounted or wall-adjacent electrical equipment often cannot tolerate large transmitted deformation, perforation, or debris. In such facilities, rigid GFRP panels are attractive because they can be formed into protective covers or modular overhead shields that preserve geometric stability. Where critical control cabinets or communication units lie directly behind the protected surface, a secondary aramid layer can be added to reduce the risk of residual spall or internal fragment projection. The goal is not only to stop external projectiles or fragments, but also to maintain enough integrity that the equipment continues to operate or can be rapidly returned to service.

Logistics and temporary operational facilities provide another application domain. These structures frequently use lightweight walls and roofs for reasons of speed and cost. Their vulnerability to overhead fragmentation is therefore high. Because such facilities may need rapid reinforcement, the feasibility of modular installation is crucial. GFRP panels can be prefabricated into standard-sized modules and mounted onto a secondary steel frame with relatively limited intervention. If combined with internal aramid liners, they can create transportable protective cassettes suitable for containerized operations centers, temporary depots, or field service points. The lightweight nature of the materials compared with traditional heavy armor improves the practicality of such retrofitting. The maintenance dimension is equally important. The radiographic observations make it clear that composite protective systems should not be evaluated solely by visual inspection after impact. Therefore, application to critical infrastructure should include a pre-defined maintenance concept. This may involve scheduled non-destructive testing for high-value installations, replacement rules based on the location and number of impacts, and spare-module storage for rapid repair. In other words, the protective system must be conceived not just as a product but as part of a lifecycle strategy. Infrastructure operators benefit most when the system is designed from the start to be inspectable, replaceable, and operationally manageable. A further practical consideration is environmental resistance. Unlike many metallic protective solutions, GFRP panels offer inherent corrosion resistance, which is advantageous for outdoor deployment and for facilities exposed to aggressive atmospheres, moisture, or de-icing salts. This feature may lower long-term maintenance demands and supports the economic case for their use in fixed installations. Aramid layers, when placed internally and protected from direct environmental action, can serve as durable complementary elements without being directly exposed to weathering [1,4, 18].

Finally, the material results support a risk-based deployment philosophy. Not every square meter of infrastructure must be protected to the same degree. The most exposed roofs, the zones above critical equipment, access points for operational staff, and the envelopes of communication or control nodes should be prioritized. In such a framework, the tested GFRP panels are well suited as the primary protection measure because they directly address the dominant structural exposure. Twaron layers then become a targeted enhancement for the most consequence-sensitive zones. This approach reflects the real constraints under which infrastructure protection is implemented: limited budgets, limited installation time, and a need to maximize protective effect where it matters most.

9. Discussion

The comparative findings of this study invite a broader discussion about how protective performance should be interpreted in infrastructure engineering. In many ballistic evaluations, the central question is whether the barrier is penetrated. While this is undoubtedly important, it is not sufficient when the objective is to protect critical infrastructure against repeated fragmentation hazards. Infrastructure resilience depends on a hierarchy of conditions: prevention of full penetration, limitation of backface response, preservation of module integrity, detectability of hidden damage, and ability to restore or maintain operational continuity. The present results contribute to all of these dimensions.

The GFRP panels performed favorably because they combined several desirable characteristics in one material system: low rear-face deformation, structural usability, large-area applicability, and manageable self-weight. These properties are particularly important for retrofits, where the protective layer must be added to an existing structure without excessive secondary strengthening. The aramid package, by contrast, showed excellent energy dissipation but also highlighted the limitations of flexible systems when they are subjected to repeated higher-energy impacts or when deformation space is restricted [5,6,16]. This confirms a recurring principle in protective design: a material can be very effective in one role and yet insufficient in another. The best engineering solutions often emerge not from selecting a single “best” material, but from assigning each material to the role for which its response mechanism is most advantageous.

The radiographic results deepen this interpretation. Hidden damage is a known issue in composites, but the magnitude observed here is particularly important for operational decision-making. If internal damage can be nearly twice the visible damage extent, then service rules based on surface inspection are unsafe. This finding argues strongly for modularity, for conservative replacement criteria, and for integration of non-destructive assessment in high-value applications. It also means that future research should not restrict itself to first-impact performance. Residual capacity after damage, and especially after multiple impacts, may be the more relevant criterion for infrastructure systems exposed to recurring attack. Another topic for discussion is standardization. The test data provide valuable engineering insight, but broader adoption of ballistic composite protection for infrastructure will require testing approaches that better reflect fragmentation-dominated threats. Projectile tests with handgun ammunition are useful for comparison and classification, yet aerial fragmentation involves a broader distribution of fragment shapes, masses, and velocities. Future work should therefore extend the present comparative approach toward fragment-simulating projectiles, repeated clustered impacts, environmental ageing, and combined structural-functional performance criteria. Even so, the current results already provide a credible basis for material selection and for the design of hybrid protective concepts. Economically, the findings also favor composite-based protection in many scenarios. A system that prevents perforation and limits local damage may avoid costly downtime, equipment replacement, and secondary failures. When the protective layer is lightweight, corrosion resistant, and modular, its long-term lifecycle value can exceed that of heavier conventional solutions, particularly for infrastructure that must remain operational during and after reinforcement. The combination of engineering performance and practical deployability is therefore one of the strongest arguments in favor of the GFRP-based approach developed here.

Overall, the results point toward a maturing field of infrastructure protection in which composite materials are no longer niche alternatives but central candidates for systematic engineering use. The challenge is not whether they can contribute, but how to translate material-level knowledge into design standards, maintenance protocols, and modular deployment strategies robust enough for real infrastructure networks.

10. Conclusions

This conference paper developed a full-length material-oriented contribution based primarily on the ballistic evaluation presented in Chapter 5 of the underlying article. The results show that GFRP composite panels provide a highly promising basis for the protection of critical infrastructure against fragmentation threats. Their key advantages are structural rigidity, relatively low areal mass, controlled rear-face deformation, and the ability to serve as large-area protective elements suitable for roofs, walls, and protective enclosures.

The measured deformation values for the tested GFRP panels remained within a narrow and relatively low range, and no catastrophic penetration was observed under the reported conditions. At the same time, radiographic evaluation revealed that internal damage development in the composite extends well beyond the visible impact zone. This is a crucial engineering finding because it demonstrates that visual inspection alone is insufficient for assessing residual panel integrity after impact. Protective systems based on such materials must therefore be paired with non-destructive inspection methods or with conservative modular replacement strategies.

The comparative evaluation of Twaron T730 aramid layers confirmed that flexible systems provide substantial energy absorption under moderate impact loading, but also that they approach their limits under repeated higher-energy events. Their deformational behavior and lack of independent structural rigidity make them less suitable as stand-alone large-area infrastructure shields. However, they are highly valuable as supplementary internal layers that reduce residual energy, limit secondary debris, and improve the overall resilience of hybrid protective assemblies. From a design perspective, the most important conclusion is that hybrid systems combining rigid GFRP panels with internal aramid layers represent the most effective route for many infrastructure applications. Such systems can provide structural protection, energy dissipation, reduced penetration probability, and improved tolerance to repeated impact. Their modular form also supports rapid retrofitting, maintenance, and phased deployment in facilities that cannot be completely shut down during reinforcement.

In practical terms, the study supports the prioritization of roof and overhead protection, the use of replaceable protective modules, and the adoption of risk-based selective reinforcement focused on the most critical infrastructure zones. The findings presented here therefore offer not only a comparison of material performance, but also a concrete basis for engineering decisions related to retrofitting, modular protective design, and the broader development of composite-based infrastructure shielding in contemporary threat environments.

Although the present results already provide a useful basis for design decisions, several issues deserve further investigation before composite protective systems are standardized for broad infrastructure use. One important direction is the transition from handgun-type ballistic loading toward fragment-simulating projectiles and repeated clustered impact scenarios that more closely reproduce aerial detonation effects. Such testing would make it possible to evaluate not only the local stopping capability of the protective layer, but also the interaction between neighboring impacts, the reduction of residual resistance, and the true multi-hit performance of large-area assemblies. A second research direction concerns residual capacity after hidden damage. The radiographic findings presented in this paper strongly suggest that future qualification procedures should include post-impact non-destructive evaluation together with residual mechanical or ballistic testing. In practical terms, operators need to know not only whether a panel stopped a given impact, but how much safe performance remains afterward and what inspection interval or replacement rule is justified. This is especially relevant for facilities that may remain under continuing threat and cannot afford a long diagnostic shutdown.

Further work is also needed on hybrid optimization. The present comparison supports the combination of a rigid GFRP outer layer with internal aramid layers, but the most efficient balance between mass, stiffness, spacing, attachment design, and energy dissipation still requires systematic parametric study [20]. Similarly, environmental ageing, thermal loading, moisture exposure, and long-term connection durability should be included in future assessment programs so that the protective assemblies can be specified with greater confidence for outdoor infrastructure service.

From the practical point of view, the next step is the development of standardized modular protective units for roofs, walls, and protected equipment housings. Such units should be easy to install, easy to replace after impact, and compatible with routine maintenance planning. The material results discussed in this paper indicate that this objective is realistic. Composite-based protective systems already offer the essential ingredients: favorable strength-to-weight ratio, corrosion resistance, structurally applicable stiffness, and compatibility with layered hybrid concepts. The remaining task is to convert this material potential into design guidance, testing standards, and field-ready solutions.

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