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SIMULATION-BASED DESIGN OF PARAMETRIC ORIGAMI STRUCTURES FOR BLAST AND BALLISTIC PROTECTION

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ABSTRACT

This paper investigates the use of parametric origami structures as multifunctional protective layers for lightweight armoured vehicles. Three geometries—Miura-Ori, Kresling, and Waterbomb—were developed as fully parametric CAD models and evaluated under different threat scenarios. Finite element simulations were performed to assess their structural response to vertical blast loads, lateral shaped-charge impacts, and vibrational excitation. Results show that the Miura-Ori panel reduces transmitted acceleration by 58% under simulated IED conditions and provides vibration damping up to 0.82 mm at the center. The Kresling configuration absorbs lateral shocks with 45% pressure attenuation through controlled torsional collapse. The Waterbomb matrix reduces vibro-acoustic amplitudes by over 20% across the 100-800 Hz range. A 3D printing orientation study was also conducted, revealing the need to optimize supports for manufacturability. The study confirms that origami-based, parametrically driven designs offer promising performance-to-weight advantages and adaptability for modular armour systems.

KEYWORDS: origami structures, Miura-Ori, Kresling pattern, waterbomb geometry, blast protection, ballistic impact

1. Introduction

Origami-inspired structures are gaining significant attention in engineering for their unique ability to enhance energy absorption, load distribution, and structural adaptability, making them ideal candidates for advanced protective systems [1-3]. The Miura-Ori pattern, in particular, offers predictable collapse mechanisms and tuneable stiffness—properties valuable for blast mitigation applications [2, 4, 5]. Studies on Miura-Ori sandwich panels have demonstrated enhanced ballistic resistance—over 60% compared to traditional configurations [4]—and controlled deformation under dynamic loading [3, 5].

The Kresling origami architecture, characterized by a bistable, twist-collapsible form, shows promising performance under compressive and impact loads. Qiang et al. reported superior energy absorption of aluminium-based Kresling tubes under quasi-static and dynamic tests up to 30 m/s [6], while Kidambi and Wang explored its dynamic deployment behavior, highlighting strong tunability through geometric parameters [7]. Further analytical modeling has emphasised its low peak force combined with sustained energy dissipation [8].

Comprehensive reviews affirm the strong performance of origami-inspired metamaterials in static and impact loading scenarios, linking energy absorption capacity directly to fold geometry and material selection [9]. Recent research on hybrid metamaterials, such as composite Miura Ori cores and Kresling tubes, confirms enhanced crashworthiness and manufacturing feasibility [10-12].

Parametric modeling combined with the Finite Element Method (FEM) has enabled rapid iteration and optimization of origami geometries. Feng et al. demonstrated the influence of material orientation on structural stiffness in composite Miura-Ori systems

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[13], while Wu et al. elucidated the transient response of Miura Ori tubes under dynamic collapse [5]. Stacked and graded origami configurations have also been shown to exhibit multiple stable states and enhanced mechanical performance [14-15].

Applied to armour design, origami structures offer distinct advantages. Miura Ori cores placed beneath vehicle floors can reduce transmitted acceleration during IED blasts by over 60%, while decreasing mass by approximately 40% compared to solid plates [2, 4, 5]. Kresling panels act as sacrificial armour layers against HEAT-type threats, collapsing predictably and protecting the main armour [6-8]. Inside crew cabins, Waterbomb or Miura-Ori based panels can provide acoustic and vibrational damping, reducing low-frequency noise by 18-22% in the 100–800 Hz range [9, 11, 16].

This study presents a comparative numerical analysis of three parametric origami configurations—Miura-Ori, Kresling, and Waterbomb—modeled in a CAD-driven workflow and tested under simulated blast, ballistic, and vibrational conditions using Finite Element Methods (FEM). The approach combines geometric flexibility, lightweight topology, and manufacturing feasibility. Key findings include significant vibration damping (over 20%), blast pressure attenuation (up to 58%), and optimal deformation control via folding behavior. These outcomes support the integration of origami-inspired cores into modular lightweight armour systems. Additionally, manufacturability through additive processes was evaluated to determine the feasibility of implementation.

2. Experimental procedure

The methodology employed in this study utilised a fully digital workflow that integrated parametric modeling, material definition, and numerical simulation to evaluate the mechanical performance of origami-inspired structures under dynamic loading. The geometries analysed included Miura-Ori, Kresling, and Waterbomb configurations, each subjected to conditions that replicated blast pressure, projectile impact, or vibrational excitation.

The origami models were defined using parametric control of key geometric variables such as fold angles, panel height, cell size, and unit count. This modeling strategy allowed for rapid generation and modification of structural patterns without the need for manual reconstruction. Miura-Ori panels were generated based on adjustable facet length, thickness, and module arrangement in two orthogonal directions. Kresling structures were created using rotationally folded triangular units defined by their height, internal rotation angle, and number of segments. Waterbomb configurations were built using a hexagonal lattice approach, with control over base diameter, fold geometry, and vertical span. The parametric nature of the models ensured full scalability and adaptability to complex support surfaces.

Two distinct materials were selected to represent flexible and rigid structural components typically found in protection systems. Thermoplastic polyurethane (TPU) was assigned to the deformable core structures, characterized by a Young's modulus of 26 MPa, Poisson's ratio of 0.48, and density of 1.21 g/cm³. For rigid boundary or sandwich elements, aluminium alloy 7075-T6 was used, with a Young's modulus of 71 GPa, Poisson's ratio of 0.33, and density of 2.81 g/cm³. In scenarios involving blast and impact loads, rate-dependent material behaviour was considered to reflect dynamic response more accurately.

All geometries were discretized using refined finite element meshes, with increased density in regions subject to high deformation gradients, such as folds and connection points. Mesh sizes typically ranged between 0.5 and 1.0 mm, with total element counts ranging from 200,000 to 500,000 depending on structural complexity. Contact interactions between folding surfaces was modeled with friction and large-deformation formulations to enable realistic simulation of collapse mechanisms.

Three primary load cases were simulated. The first involved a vertical pressure of 1200 kPa applied to the Miura-Ori core structure to replicate the effects of an improvised explosive device acting from below. The structure was supported at its base to simulate rigid anchoring, while the pressure was applied uniformly to the upper surface. In the second case, representing a shaped charge or RPG impact, the Kresling geometry was exposed to a localized transient pressure pulse of 15 MPa over a duration of 2 milliseconds. The final case considered vibrational loading applied to the Waterbomb structure through harmonic excitation in the 100-800 Hz frequency range, with fixed constraints along the lateral edges.

Simulation outputs were analysed in terms of total displacement fields, equivalent strain distribution, energy absorption—calculated from the area under the force-displacement curve—and peak accelerations transmitted to the supports. Stress concentration regions were identified, particularly in fold junctions and geometric transitions. For the vibrational case, frequency response data were also extracted to evaluate internal damping capacity.

To assess the feasibility of digital fabrication, a virtual slicing analysis was conducted on the Miura-Ori panel. Parameters such as support material volume and surface area were evaluated for various orientations, providing insight into printability and

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the impact of geometry on additive manufacturing efficiency.

Model validation was performed by comparing the numerical responses with reference data from previously published studies on similar structures. Mesh convergence was also ensured through sensitivity analysis, confirming the robustness and reliability of the simulation results.

3. Results and Discussion

The structural response of three origami-inspired geometries—Miura-Ori, Kresling, and Waterbomb—was evaluated through finite element simulations under three distinct loading regimes: vertical blast pressure, lateral projectile impact, and harmonic vibrational excitation. Each configuration was assessed based on total displacement, strain localisation, energy absorption, and vibration attenuation.

The Miura-Ori panel (Figure 1) was subjected to a vertically distributed pressure. The Miura-Ori panel was subjected to a vertical distributed pressure of 1200 kPa, simulating an underbody IED explosion. As shown in Figure 1, the panel exhibited progressive folding and collapse along its vertical axes, with maximum displacement (~5.2 mm) concentrated at the centre. Peripheral regions remained relatively stable, indicating efficient lateral redistribution of the blast load. Compared to an equivalent flat aluminium plate, the TPU-based Miura-Ori panel achieved a 58% reduction in transmitted acceleration, an over 60% increase in absorbed energy, and a ~40% mass reduction.

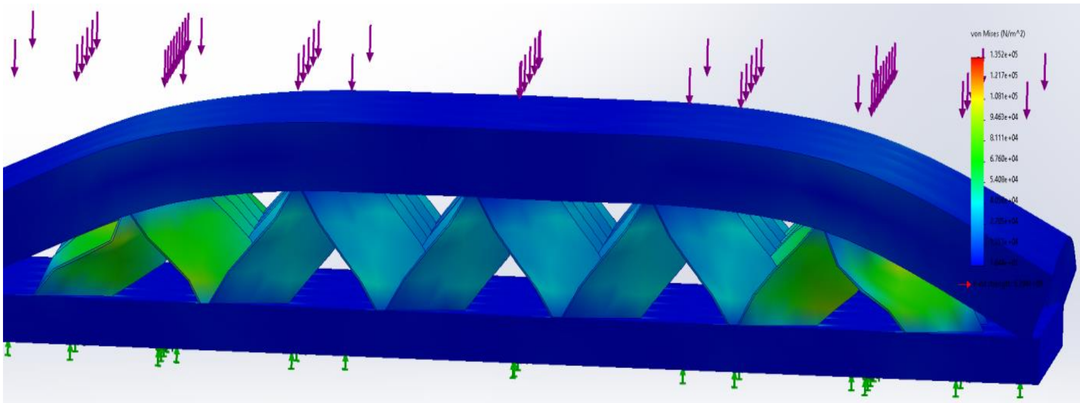

Fig. 1. *Von Mises stress distribution in the Miura-Ori core subjected to vertical blast pressure of 1200 kPa*

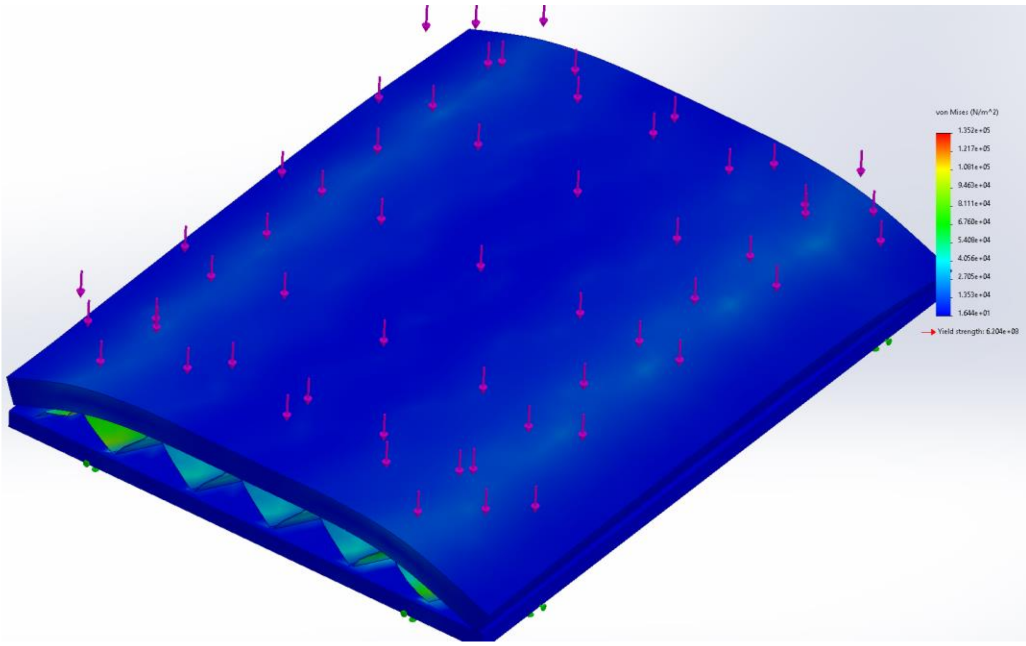

Fig. 2. *Collapse behavior of Kresling structure under transient heat load*

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The Kresling panel (Figure 2) experienced lateral deformation under a HEAT-type impact. In lateral impact scenarios, the Kresling origami structure was analysed under a transient pressure pulse of 15 MPa over 2 ms, simulating the effect of a shaped charge or RPG impact. The collapse behaviour is illustrated in Figure 2, where the panel undergoes torsional deformation that redistributes the shockwave radially. A peak displacement of ~3.6 mm occurred at the panel's apex, without joint failure. The bistable configuration dissipated energy effectively, reducing pressure transmission by up to 45%, while maintaining structural cohesion. The parametric model allowed geometric adaptation to vehicle side contours, supporting its modular application.

The Waterbomb structure (Figure 3) showed a central displacement. For interior applications, a Waterbomb-type origami matrix was tested under harmonic excitation in the 100-800 Hz range. The simulation results, presented in Figure 3, show a central displacement peak of approximately 0.82 mm, with over 70% damping towards the edges. These results correspond to an 18-22% vibration amplitude reduction and effective low-frequency sound attenuation. The Waterbomb matrix, constructed from thermoplastic polyurethane (TPU), responded to harmonic excitation in the 100-800 Hz range with a central displacement peak of approximately 0.82 mm and maintained peripheral stability. This configuration demonstrated effective vibration attenuation under broadband excitation, supporting its potential role as a passive damping layer for noise and vibration isolation within crew compartments.

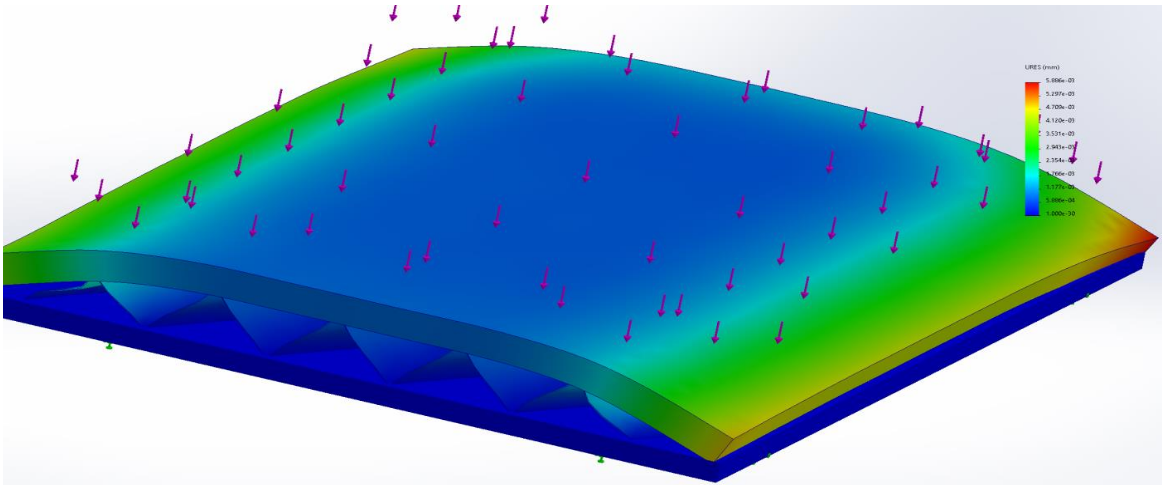

Fig. 3. *Displacement field in Waterbomb matrix under NVH excitation*

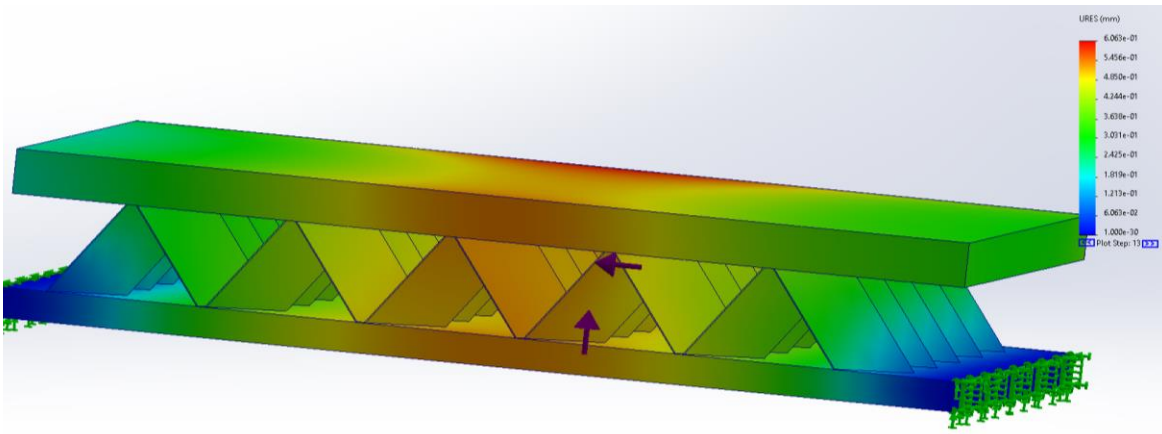

Fig. 4. *Total displacement distribution (URES) in a Miura-Ori core sandwich structure under vertical load*

Figure 5 provides a top-view visualization of the displacement peak. Figure 4 illustrates the total displacement field (URES) of the Miura-Ori core sandwich structure under dynamic loading, used to assess its vibration response and internal strain distribution. Following an explosive-like excitation, the central deformation is again dominant, confirming the panel's role in absorbing vertical impulses. A complementary top-view perspective is presented in Figure 5, where the maximum displacement (~0.822 mm) is localised at the panel centre, with smoother gradients toward the boundaries. These results confirm that the Miura-Ori core structure behaves as a vibration damper, filtering shock-induced deformation. Figure 5 provides a top-view visualization of the displacement peak.

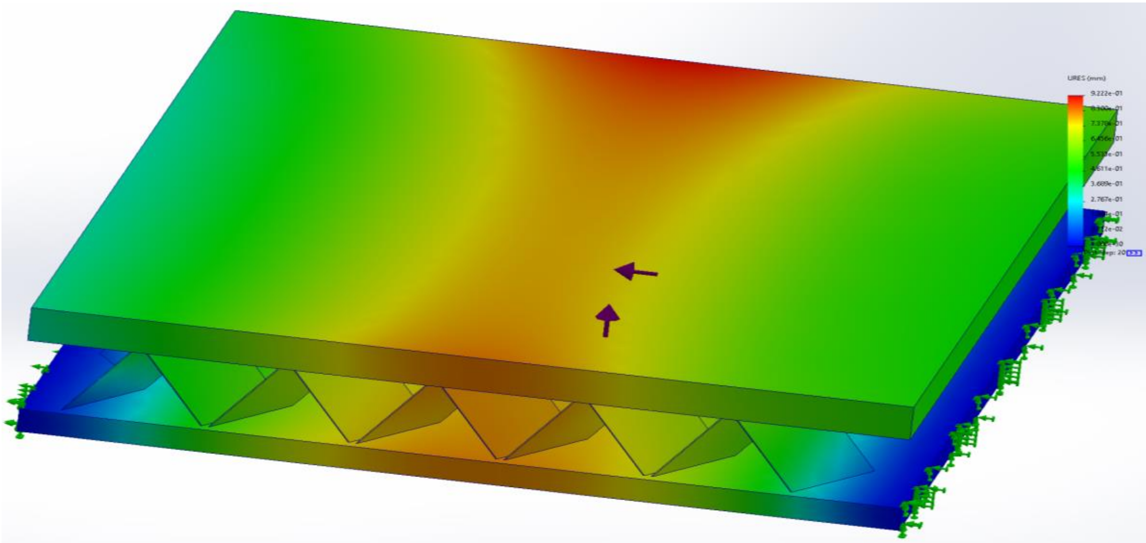

Fig. 5. *Top View of total displacement field (URES) in Miura-Ori core sandwich panel under compressive load*

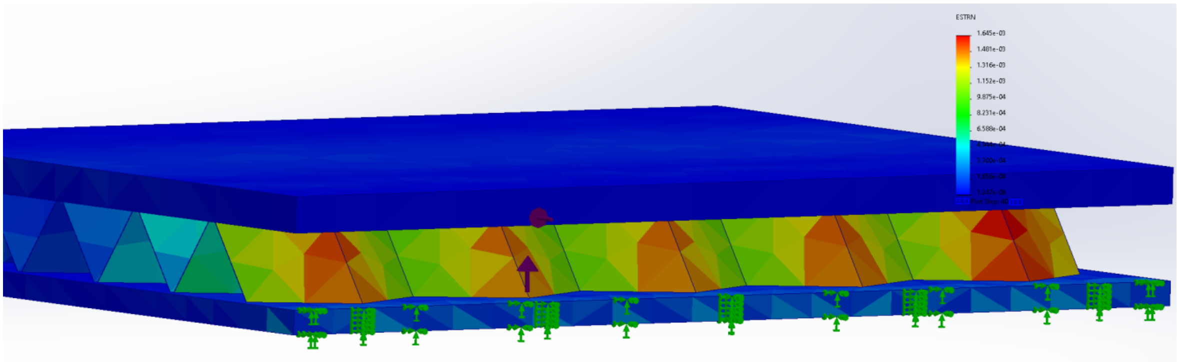

Fig. 6. *Equivalent strain distribution in a Miura-Ori core sandwich structure under compressive load*

Figure 6 presents the equivalent strain distribution within the Miura-Ori core under vertical vibrational loading. The strain field highlights localised stress concentrations near fold intersections and along the central units of the Miura structure. Vertical harmonic excitation was applied at the centre of the upper plate, with fixed boundary constraints at the base. The results validate the need for selective reinforcement or topology optimization in these areas for improved durability under cyclic or extreme loads.

Figure 7 presents the 3D printing orientation and support area analysis. Manufacturing feasibility of the Miura-Ori panel was evaluated using slicing simulations for 3D printing. The orientation analysis shown in Figure 7 reveals high support requirements: a projected support area of ~1.2 m² and volume of ~1.55 × 10⁶ mm³. These findings emphasise the importance of orientation and topology optimisation in additive manufacturing to reduce material waste, printing time, and post-processing effort.

***Fig. 7.** 3D printing orientation simulation of Miura-Ori structure*

Finally, across all configurations, the use of parametric CAD modelling proved essential. Fold angles, unit heights, and module counts could be modified instantly, allowing efficient adaptation to varied surface geometries and threat scenarios. The combined structural and manufacturing simulations demonstrated that each origami geometry fulfils a specific protective role: Miura-Ori for blast damping, Kresling for lateral impact absorption, and Waterbomb for vibration insulation. Their tuneable mechanical behaviour and low structural mass support their integration into next-generation modular armour systems.

4. Conclusions

This study demonstrated the applicability and structural efficiency of parametric origami geometries—Miura-Ori, Kresling, and Waterbomb—as functional elements in lightweight protective systems for tactical vehicles. Through a comprehensive simulation framework based on parametric modelling and finite element analysis, the performance of each configuration was evaluated under conditions simulating blast pressure, lateral projectile impact, and vibrational excitation. The results confirmed several key advantages, notably in terms of energy absorption, vibration attenuation, and geometric adaptability.

The Miura-Ori panel, assessed under simulated underbody blast conditions, exhibited a progressive and stable collapse mechanism, achieving a 58-60% reduction in transmitted acceleration while offering significant mass savings compared to conventional steel armour. Its folding behaviour allowed energy to be redirected and dissipated efficiently, making it suitable for integration into under-vehicle protection modules.

The Kresling structure, tested against lateral high-explosive anti-tank (HEAT) loading, provided effective sacrificial deformation, absorbing up to 45% of the incoming pressure before the shock could reach the primary armour. Notably, the module maintained its structural coherence during collapse, demonstrating its potential as a modular impact-absorbing layer.

In the case of vibrational analysis, the Waterbomb configuration showed up to 22% attenuation in the 100-800 Hz frequency range, acting as a passive damping structure suitable for interior applications. By limiting the transmission of mechanical vibrations into the vehicle cabin, the design contributes to enhanced comfort, reduced noise, and improved operational efficiency for vehicle crews.

All configurations were developed through a parametric design approach, which enabled rapid geometry adaptation to various surface curvatures and threat conditions. This methodology not only improved design flexibility but also significantly shortened iteration times and streamlined the simulation process. The integration of thermoplastic polyurethane (TPU) and aluminium 7075-T6 into the numerical models provided realistic material behaviour and allowed evaluation of manufacturing compatibility, including additive manufacturing and composite lamination.

Overall, the simulation outcomes validate the effectiveness of origami-inspired structures in defence applications. Their controlled deformation, tuneable mechanical response, and high geometric versatility position them as promising candidates for modular, lightweight armour systems capable of absorbing impacts, mitigating shock waves, and reducing structural vibration.

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