

Simulation-Guided Design of Shear-Thickening-Fluid-Filled 3D-Printed Sandwich Composite Panels for Ballistic Protection

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Abstract

Sandwich composite panels are widely used in lightweight protective structures, but improving ballistic resistance while maintaining manufacturability and structural compliance remains challenging. In this study, shear-thickening fluid (STF)-filled 3D-printed sandwich composite panels were developed by integrating Kevlar reinforcement with additively manufactured ethylene-vinyl acetate (EVA) cellular cores. Finite-element simulations were first performed to evaluate the localized deformation and strain-energy distribution of simplified Kevlar/STF laminate configurations under high-rate impact. A characteristic localization radius of approximately 10 mm was identified and used as a physically motivated basis for selecting cellular-core pitches of 10 and 20 mm. Honeycomb and fish-scale-inspired cores were subsequently fabricated using a print–fill–seal process, filled with nanosilica/polyethylene glycol STF, and assembled with Kevlar layers to form STF-filled sandwich composite panels. Flexural testing was used to assess configuration-dependent structural compliance, while ballistic tests were conducted using 9×19 mm full-metal-jacket projectiles under NIJ 0101.06-referenced conditions. The Kevlar-only reference exhibited a back-face signature (BFS) of 34.01 mm, whereas the STF-filled sandwich assemblies exhibited BFS values of 7.53–11.43 mm. The lowest BFS was obtained for the 20 mm fish-scale-inspired STF-filled configuration, which exhibited a BFS of 7.53 mm and an estimated absorbed energy of 718.66 J. The results indicate that ballistic mitigation was governed by the coupled effects of Kevlar load spreading, configuration-dependent cellular deformation, geometry-controlled STF confinement, and localized energy dissipation. This study demonstrates a simulation-guided and manufacturable strategy for designing STF-filled sandwich composites with enhanced back-face deformation mitigation and tunable structural compliance for ballistic protection.

1. Introduction

Body armor for military and law-enforcement applications must provide sufficient ballistic protection while maintaining low weight, flexibility, and wearer mobility. High-performance aramid fabrics such as Kevlar remain among the most widely used materials for soft ballistic protection because of their high specific strength, tensile energy absorption, and ability to dissipate impact energy through yarn stretching, pull-out, friction, and progressive fabric deformation [1]. However, achieving higher protection levels generally requires an increased number of fabric plies. Such multilayer configurations inevitably increase thickness, areal density, and bending stiffness, thereby reducing comfort and conformability [2–4]. Consequently, a persistent challenge in personal armor design is to improve impact-energy dissipation and reduce back-face deformation without simply increasing the amount of structural material.

Shear-thickening fluids (STFs) have attracted considerable attention as a means of addressing this challenge. STFs are concentrated non-Newtonian suspensions that exhibit a pronounced and reversible increase in apparent viscosity when subjected to sufficiently high shear rates [5, 6]. When incorporated into high-performance fabrics, STFs can increase inter-yarn friction, restrict yarn mobility, promote load transfer to neighboring yarns, and contribute additional energy dissipation during impact [5–8]. Ballistic

experiments on nanosilica/PEG-impregnated Kevlar have demonstrated that appropriately formulated STF's can significantly improve impact resistance and specific energy absorption [7]. Low-velocity impact measurements have further shown that STF treatment modifies the deformation basin and energy-absorption behavior of Kevlar fabrics [8]. More recently, fluid–structure interaction models have been developed for STF-impregnated UHMWPE and Kevlar systems, enabling numerical interpretation and prediction of their impact responses [9, 10]. In particular, Xie et al. demonstrated that a fluid–structure interaction model could reproduce the ballistic limit of STF/Kevlar fabrics with good agreement with experiments, highlighting the potential of numerical simulation for STF-assisted armor design [10].

An alternative to direct fabric impregnation is to confine STF within a discrete structural layer. This approach can separate the fluid from the textile reinforcement and provide greater control over its spatial distribution. In our previous work, STF-filled paper honeycomb panels were integrated with Kevlar laminates, and the effects of STF rheology and layer sequence on ballistic performance were investigated [11]. The results showed that ballistic response depended not only on the rheological properties of the STF but also on the position of the STF-containing layer within the armor system. Subsequent work combining STF-filled honeycomb structures with Kevlar/polyurea composites further demonstrated that suitable structural integration could reduce the thickness and weight required for a given protection level [12]. Related studies have since examined STF-filled sandwich and honeycomb structures under impact loading. Astaraki et al. investigated the low-velocity impact response of STF-filled sandwich panels [13], while Yi et al. recently showed that STF filling in aluminum honeycomb sandwich panels can redistribute a concentrated impact load over a wider region of the back face sheet, with the cell geometry influencing the effectiveness of the fluid–structure interaction [14]. These findings suggest that the protective contribution of STF is strongly coupled to the geometry of the surrounding confinement structure.

Recent studies have extended this concept from conventional honeycomb cores toward architected and additively manufactured STF-filled structures. Hu et al. investigated the dynamic response of STF-filled lattice structures and demonstrated that the interaction between the lattice architecture and the rate-dependent STF response can substantially alter structural stiffness and energy absorption [15]. Corvi and Collini subsequently introduced a 3D-printed flexible metamaterial filled with STF and showed, through experiments and finite-element simulations, that the non-Newtonian filler can significantly improve low-velocity impact mitigation compared with air- or Newtonian-fluid-filled configurations [16]. At higher impact velocities, Gu et al. employed fluid–structure interaction simulations to study STF-filled sandwich lattice-truss panels and reported substantially enhanced energy dissipation compared with unfilled lattice structures [17]. Fila et al. further investigated additively manufactured STF-filled sandwich panels over intermediate- and high-strain-rate penetration regimes, using high-speed X-ray radiography to reveal rate-dependent changes in fluid distribution, structural collapse, and penetration mechanisms [18]. These studies demonstrate that combining STF with cellular or additively manufactured structures is now an established and rapidly developing approach for impact mitigation.

Meanwhile, recent work has also clarified STF behavior in the ballistic regime. Long et al. combined experiments, finite-element analysis, and analytical modeling to examine the response of bulk STF under high-velocity ballistic impact [19]. Chen et al. investigated STF-impregnated Kevlar fabrics using ballistic experiments, finite-element simulations, and an analytical energy-absorption model, showing that the relative contributions of deformation and localized failure mechanisms evolve with impact velocity [20]. Most recently, Pedram et al. reported an experimental and theoretical investigation of nano-STF-filled aluminum honeycomb sandwich panels under high-velocity impact, demonstrating that STF rheology, projectile geometry, and honeycomb interaction jointly influence ballistic limit velocity and damage evolution [21]. Collectively, these recent results show that STF-enhanced protection cannot be understood solely in terms of bulk rheological properties; spatial confinement, structural geometry, strain-rate-dependent fluid–structure interaction, and load-transfer pathways must also be considered.

Bio-inspired architectures provide a promising route for controlling these structural interactions. Natural protective systems frequently achieve combinations of local stiffness, impact resistance, and global flexibility through segmented or hierarchical geometries rather than through uniformly rigid structures. For example, the overlapping scale architecture of chitons has inspired artificial protective systems capable of maintaining flexibility while providing localized mechanical resistance [22]. More broadly, bio-inspired porous and cellular structures produced by additive manufacturing have demonstrated considerable potential for tailoring deformation modes and impact-energy absorption [23]. Numerical optimization of elastomeric honeycomb structures has similarly shown that cellular geometry can be systematically adjusted to modify impact response [24]. These concepts are particularly relevant to wearable protection, where excessive structural stiffness can undermine the practical benefit of improved ballistic resistance.

Despite these advances, an important design gap remains. Previous studies have successfully demonstrated STF-impregnated fabrics [7–10], STF-filled conventional honeycombs [11–14, 21], STF-filled lattices and metamaterials [15–17], and additively manufactured STF-filled sandwich structures [18]. However, these approaches generally evaluate a predefined structure or fluid configuration rather than using the spatial distribution of impact-induced energy within the STF as a physically derived design parameter for the confinement architecture. In particular, a systematic framework that extracts a characteristic STF energy-localization length scale from impact simulation and then translates that length scale into the unit dimensions of an architected confinement layer has received comparatively little attention. Furthermore, linking such simulation-guided confinement design with a flexible Kevlar armor system, controlled STF encapsulation, configuration-dependent flexural behavior, and experimentally measured backface signature remains insufficiently explored.

Accordingly, the present study develops a simulation-guided, bio-inspired STF confinement strategy for Kevlar-based ballistic composites. Finite-element simulations of Kevlar/STF laminates under hemispherical impact are first used to quantify the spatial localization of strain energy in the STF and to define a characteristic localization radius, R_{80} , representing the radius containing 80% of the accumulated STF strain energy. The resulting length scale is then used to guide the selection of 10 and

20 mm unit pitches for honeycomb and fish-scale confinement architectures. To achieve controlled fluid placement and reduce post-processing variability, a customized print–fill–seal 3D-printing process is employed to integrate EVA structural fabrication, in situ STF filling, and encapsulation within a single manufacturing workflow. The resulting STF-filled architectures are incorporated into Kevlar laminates and evaluated by three-point bending and NIJ 0101.06-referenced 9 mm ballistic testing. Through this simulation-to-architecture-to-experiment framework, the study aims to establish how confinement length scale, configuration-dependent load transfer, structural compliance, and layer sequencing collectively govern the stiffness–protection balance of STF-enhanced hybrid protective composites.

2. Materials and methods

Figure 2.1 Materials

Commercial Kevlar fabric was used as the primary ballistic reinforcement, and ethylene-vinyl acetate (EVA) filament was used to fabricate the flexible cellular confinement structures by 3D printing. The proposed composite concept combines Kevlar reinforcement, a 3D-printed EVA cellular core, and confined shear-thickening fluid (STF), as illustrated in Fig. 1.

The STF was prepared following the nanosilica/polyethylene glycol (PEG) formulation used in our previous studies [11, 12]. Fumed nanosilica particles with a nominal particle size of 10–30 nm (Kingmaker Chemical, ECHO, Miaoli, Taiwan) were dispersed in PEG 200, with Disperbyk-111 used as a wetting and dispersing agent. A nanosilica concentration of 40 wt% was adopted based on the rheological and ballistic performance reported previously [11, 12].

For STF preparation, PEG 200, nanosilica, and Disperbyk-111 were mixed in a planetary mixer at 2000 rpm for 10 min, followed by defoaming at 2500 rpm for 5 min. The mixing–defoaming sequence was repeated until the target silica concentration was reached. The suspension was then processed using a three-roll mill with sequential gap settings of 150, 100, 50, 10, and 5 μm to reduce particle agglomeration and improve dispersion homogeneity [12]. The prepared STF was stored in sealed containers prior to filling the 3D-printed cellular cores.

2.2 Design of STF-filled sandwich composite panels

Two cellular-core architectures were investigated in this study: conventional honeycomb geometry and a fish-scale-inspired geometry, as shown in Fig. 2. The honeycomb architecture consisted of continuously interconnected hexagonal walls and was selected to provide a relatively rigid load-transfer network. In contrast, the fish-scale-inspired architecture was composed of periodically arranged segmented units, providing greater freedom for local deformation and structural compliance. These two core configurations were therefore used to examine how differences in structural configuration influence STF confinement, deformation behavior, and impact-load transfer.

The characteristic pitches of 10 and 20 mm were selected based on the finite-element localization analysis described in Section 2.3. The same two pitches were applied to both architectures to systematically evaluate the effects of confinement length scale within each core configuration.

The final honeycomb cores were fabricated with a wall thickness of 1.0 mm, a supporting base-layer thickness of 1.0 mm, and an overall core height of 10 mm. The fish-scale-inspired cores were fabricated with a wall thickness of 0.6 mm, the same 1.0 mm supporting base layer, and an overall core height of 10 mm. All specimens used for ballistic testing had an in-plane dimension of 130 mm × 130 mm. The corresponding CAD schematics and representative fabricated specimens are shown in Fig. 2(a)–(d). The cellular compartments served simultaneously as structural elements and geometry-defined STF confinement regions.

Because the final manufacturable designs employed different wall thicknesses for the two core types, direct comparisons between the honeycomb and fish-scale-inspired configurations reflect the combined effects of cellular architecture and wall thickness rather than architecture alone. Accordingly, the two designs were treated as distinct manufacturable configurations in the subsequent flexural and ballistic comparisons.

2.3 Finite-element-guided core pitch selection

Finite-element simulations were performed using COMSOL Multiphysics 6.3 to establish a physically motivated characteristic length scale for the design of the STF confinement architecture. The Solid Mechanics interface was employed with geometric nonlinearity enabled. The numerical analysis was not intended to reproduce the complete fluid–structure interaction or the full ballistic response of the final STF-filled sandwich composite panel. Instead, a simplified comparative model was developed to evaluate the localized deformation and energy distribution of Kevlar/STF laminate configurations under transient high-rate impact and to provide a numerical basis for cellular-core pitch selection.

The target had an in-plane dimension of 50 mm × 50 mm. The reference Kevlar laminate had a total thickness of 4.5 mm and consisted of 16 plies. Kevlar was represented using equivalent in-plane orthotropic elastic properties of $E_1 = 70$ GPa, $E_2 = 5$ GPa, $\nu_{12} = 0.25$, and $G_{12} = 2$ GPa, with a density of 1440 kg m^{-3} . The impactor was modeled as a steel striker consisting of a hemispherical nose with a radius of 4.5 mm and a short cylindrical shank. An initial striker velocity of 436 m s^{-1} was adopted as the nominal high-rate condition used in the numerical model.

The perimeter of the laminate was constrained through a bonded rigid frame, with the outer surfaces of the frame fixed during the transient analysis. Striker–target interaction was modeled using contact with Coulomb friction. A nominal friction coefficient of 0.25 was adopted. The initial clearance between the striker and target was maintained within 0–0.05 mm.

For computational efficiency, the STF-containing layer was represented as an equivalent linear viscoelastic solid using a Kelvin–Voigt formulation within the Solid Mechanics interface. The viscous

parameter was determined from the high-shear thickened regime of the shear-rate-dependent viscosity response previously reported for the nanosilica/PEG STF formulation [11, 12]. Based on the published rheological curve, the viscosity in this regime was approximately 50–60 Pa·s; a representative value of approximately 50 Pa·s was therefore adopted to characterize the equivalent viscous response of the STF domain. The STF density was taken as 1100 kg m^{-3} . This equivalent-material representation was used to approximate the enhanced rate-dependent resistance of the STF under high-rate loading without explicitly resolving non-Newtonian fluid flow, particle interactions, or the continuous evolution of viscosity with local shear rate. Accordingly, the numerical model was used as a comparative design model rather than as a complete constitutive or fluid–structure interaction representation of the physical STF.

The mesh was locally refined around the impact region, with an in-plane element size of approximately 0.15–0.25 mm and at least eight elements through the thickness of the deformable laminate region. Nonlinear transient simulations were conducted over 0–200 μs , with a maximum time step of 0.05–0.10 μs . The principal numerical outputs included out-of-plane displacement, maximum central dent depth, and the radial strain-energy distribution within the STF-equivalent domain.

Four laminate configurations were investigated: (i) a 4.5 mm Kevlar-only laminate; (ii) a 4.5 mm Kevlar laminate backed by a 2.25 mm STF-equivalent layer; (iii) an equal-total-thickness laminate consisting of 2.25 mm Kevlar on the impact side and 2.25 mm STF-equivalent material on the rear side; and (iv) the reversed equal-total-thickness configuration consisting of a 2.25 mm STF-equivalent front layer and a 2.25 mm Kevlar backing layer. These configurations were used to evaluate the effects of STF placement and relative layer thickness on the early-stage localized impact response.

To quantify the spatial extent of the STF-assisted response, the strain-energy distribution within the equivalent STF domain was evaluated as a function of radial distance from the impact center. A characteristic localization radius, R_{80} , was defined as the radial distance enclosing 80% of the accumulated strain-energy measure within the modeled STF region:

$$\frac{E(R_{80})}{E_{STF}} = 0.8$$

where $E(R_{80})$ represents the accumulated strain-energy measure within a radial distance from the impact center and E_{STF} represents the total strain-energy measure within the equivalent STF domain. Because the STF was represented by an equivalent Kelvin–Voigt solid, R_{80} **was treated** as a comparative numerical localization metric rather than as a direct measure of energy storage or dissipation in the physical STF suspension.

The resulting characteristic localization radius was subsequently used as the primary design reference for cellular-core pitch selection. The numerical results and their implications for core-pitch selection are discussed in Section 3.1.

2.4 Additive manufacturing and print–fill–seal fabrication

The STF-filled cellular cores were fabricated using a sequential print–fill–seal workflow. The process consisted of four main steps: fabrication of the EVA cellular core, STF filling, sealing of the filled compartments, and integration with the Kevlar reinforcement layer.

First, the honeycomb and fish-scale-inspired cellular cores were fabricated from EVA filament using fused-filament fabrication according to the geometries described in Section 2.2. The cellular structures were printed with open upper compartments to allow subsequent STF filling, while an integrated bottom supporting layer was retained to prevent fluid leakage during the filling step. After printing, the cellular cores were visually inspected for wall continuity, compartment integrity, and obvious defects that could compromise fluid containment.

The prepared STF described in Section 2.1 was then introduced into the open cellular compartments. Filling was performed individually for each compartment until the designed cavity volume was occupied while avoiding excessive overflow. After filling, residual STF on the upper surface of the cellular walls was removed prior to sealing.

The filled cellular core was subsequently sealed with a thin EVA top layer to encapsulate the STF within the geometry-defined compartments. The sealing step was performed immediately after filling to minimize fluid displacement during specimen handling. The resulting sealed core therefore maintained the STF within the prescribed honeycomb or fish-scale-inspired cellular regions.

Finally, the sealed STF-filled cellular core was assembled with the Kevlar reinforcement layer to form the final sandwich composite panel. The Kevlar layer was positioned on the impact-facing side, whereas the STF-filled cellular core served as the backing layer. A schematic overview of the complete print–fill–seal fabrication sequence is shown in Fig. 3.

2.5 Specimen configurations

Eight cellular-core configurations were prepared to evaluate the effects of core configuration, characteristic pitch, and STF filling condition. Two core architectures were investigated: honeycomb (H) and fish-scale-inspired (F), each with characteristic pitches of 10 and 20 mm. The corresponding unfilled specimens were denoted as H10, H20, F10, and F20, whereas the suffix “-STF” was added to designate the STF-filled configurations (H10-STF, H20-STF, F10-STF, and F20-STF).

For flexural testing, the unfilled and STF-filled cellular-core specimens were evaluated directly to characterize the bending resistance and structural compliance of the two architectures. For ballistic testing, each cellular-core specimen was incorporated into a multilayer Kevlar assembly. The cellular core was positioned between 29 layers of Kevlar fabric on the impact-facing side and 5 layers of Kevlar fabric on the rear side. The 29-layer front Kevlar laminate had a measured thickness of approximately 14.5 mm. A separate 29-layer Kevlar laminate without a cellular core was tested as the ballistic baseline. This configuration allowed the contributions of the cellular architecture and STF filling to be evaluated

relative to the Kevlar-only reference. The specimen configurations used in the present study are summarized in Table 1.

Table 1
Summary of specimen configurations used in this study.

Code	Core architecture	Pitch	STF	Flexural specimen	Ballistic assembly
Kevlar-only	None	—	No	—	29-layer Kevlar
H10	Honeycomb	10 mm	No	Cellular core only	29-layer Kevlar / H10 / 5-layer Kevlar
H20	Honeycomb	20 mm	No	Cellular core only	29-layer Kevlar / H20 / 5-layer Kevlar
F10	Fish-scale-inspired	10 mm	No	Cellular core only	29-layer Kevlar / F10 / 5-layer Kevlar
F20	Fish-scale-inspired	20 mm	No	Cellular core only	29-layer Kevlar / F20 / 5-layer Kevlar
H10-STF	Honeycomb	10 mm	Yes	STF-filled cellular core	29-layer Kevlar / H10-STF / 5-layer Kevlar
H20-STF	Honeycomb	20 mm	Yes	STF-filled cellular core	29-layer Kevlar / H20-STF / 5-layer Kevlar
F10-STF	Fish-scale-inspired	10 mm	Yes	STF-filled cellular core	29-layer Kevlar / F10-STF / 5-layer Kevlar
F20-STF	Fish-scale-inspired	20 mm	Yes	STF-filled cellular core	29-layer Kevlar / F20-STF / 5-layer Kevlar

2.6 Flexural testing

Flexural tests were conducted to evaluate the bending resistance and structural compliance of the unfilled and STF-filled cellular-core specimens. Because the proposed protective structures are intended for conformable applications, the flexural response was used to compare the deformation adaptability of the honeycomb and fish-scale-inspired configurations.

The specimens were tested under a three-point bending configuration using a universal testing machine. The support span was set to 160 mm, and the crosshead speed was 3 mm min^{-1} . Loading was continued until a displacement of 3 mm was reached. During testing, the applied load and crosshead displacement were continuously recorded to obtain the load–displacement response of each specimen. These testing conditions were consistent with those used in the original experimental program.

Because of the asymmetric geometry of the fish-scale-inspired structure, its flexural response depended on specimen orientation. The fish-scale-inspired specimens were therefore positioned in the same orientation for all tests, with the supporting base layer facing upward, as adopted in the original

experimental procedure. In contrast, the honeycomb specimens were tested using a consistent orientation throughout the test series.

The maximum load measured within the 3 mm displacement range was used as a comparative indicator of bending resistance. Lower load values were interpreted as greater structural compliance, whereas higher load values indicated greater resistance to bending. Comparisons were made according to core configuration, characteristic pitch, and STF filling condition. A single specimen was tested for each configuration, and the flexural results were therefore used for comparative evaluation rather than statistical analysis. The corresponding flexural results are presented in Section 3.3.

2.7 Ballistic impact testing and post-impact observation

Ballistic impact tests were conducted to evaluate the back-face deformation and protective response of the Kevlar-only reference and the unfilled and STF-filled cellular-core configurations. The test arrangement was referenced to NIJ Standard 0101.06 using 9 × 19 mm full-metal-jacket (FMJ) handgun projectiles. Each projectile had a mass of approximately 8.0 g. The muzzle-to-target distance was 5 m, and a photogate positioned between the firearm and the target was used to measure the incident velocity of each projectile. Because the impact velocity varied among individual shots, the measured velocity of each specimen was used in the subsequent analysis. The recorded incident velocities ranged from approximately 334 to 430 m s⁻¹.

The ballistic assemblies followed the configurations summarized in Table 1. A single specimen was tested for each configuration, and the ballistic results were therefore interpreted as comparative performance indicators rather than statistically representative values. Each specimen was positioned directly in front of the backing clay to quantify the deformation transmitted through the protective system.

After impact, the maximum indentation depth in the backing clay was measured using a depth gauge and recorded as the back-face signature (BFS), as illustrated in Fig. 4. Lower BFS values indicate reduced deformation transmitted through the protective assembly. A BFS depth of 44 mm was adopted as the NIJ-referenced upper-limit criterion for comparison. Because the incident velocities were not identical among specimens, BFS was used as the primary experimental indicator of back-face deformation.

No complete projectile perforation occurred in the ballistic tests considered in this study. As a complementary performance indicator, the energy transmitted to the backing clay was estimated using the empirical indentation–energy relationship reported by Shih [25]:

$$E_{BM} = 1.3023 d_{BFS} - 5.9652$$

where E_{BM} is the estimated energy associated with deformation of the backing material and d_{BFS} is the measured indentation depth in millimeters. The target-absorbed energy was subsequently estimated from the measured incident projectile kinetic energy after accounting for the energy transmitted to the

backing clay. Because this value was derived from an empirical indentation relationship rather than direct residual-velocity measurement, it was used only as a complementary indicator of ballistic performance.

Following ballistic testing, the impacted specimens were visually examined for Kevlar damage, cellular-core deformation or collapse, STF retention or leakage, sealing integrity, and rear-surface deformation. These observations were considered together with the measured BFS and estimated absorbed energy to interpret the effects of cellular configuration and STF filling on the ballistic response.

3. Results and Discussion

3.1 Finite-element response and characteristic length-scale identification

Finite-element simulations were first used to examine the early-stage localized response of the simplified Kevlar/STF laminate configurations described in Section 2.3. Figure 5 compares the out-of-plane displacement fields of the four configurations. The results reveal that both the presence and through-thickness position of the STF-equivalent layer modified the deformation field beneath the impactor.

The Kevlar-only configuration exhibited a relatively broad out-of-plane deformation region around the impact point. In contrast, the configurations containing an STF-equivalent layer showed a more localized deformation pattern and a reduced displacement transmitted toward the rear surface. The difference between the two equal-thickness STF/Kevlar configurations, Fig. 5(a) and (d), further indicates that the stacking sequence affected the spatial development of the deformation field. For the protective configuration used in the subsequent sandwich-panel design, positioning Kevlar on the impact-facing side and the STF-containing region behind it was considered more representative of the intended load-transfer sequence, in which the Kevlar layer first distributes the projectile load before the backing region undergoes rate-dependent deformation.

The calculated central dent depths further illustrate the influence of the STF-equivalent backing layer. At $t = 50 \mu\text{s}$, the 4.5 mm Kevlar-only laminate exhibited a maximum dent depth of 21.789 mm. When a 2.25 mm STF-equivalent layer was added behind the 4.5 mm Kevlar laminate, the dent depth decreased to 12.374 mm, corresponding to a reduction of approximately 43% relative to the Kevlar-only configuration. For the equal-total-thickness configuration consisting of 2.25 mm Kevlar and 2.25 mm STF-equivalent backing, the calculated dent depth was 13.333 mm, approximately 39% lower than that of the 4.5 mm Kevlar-only reference. These numerical values are consistent with the original simulation dataset.

The reduction obtained for the 4.5 mm Kevlar + 2.25 mm STF configuration should, however, not be attributed exclusively to the STF-equivalent material response because the total laminate thickness increased from 4.5 to 6.75 mm. This configuration therefore represents the combined influence of an

additional backing layer and its rate-sensitive viscoelastic response. In comparison, the equal-total-thickness Kevlar/STF configurations provide a more direct indication that the location and constitutive response of the STF-equivalent layer can modify the localized deformation field without increasing the overall laminate thickness. Accordingly, the numerical analysis was used primarily as a comparative design tool rather than as a direct prediction of the complete ballistic performance of the experimental panels.

To convert the simulated response into a characteristic geometric parameter, the radial strain-energy distribution within the STF-equivalent domain was analyzed using the criterion defined in Section 2.3. The calculated characteristic localization radius was $R_{80} \approx 10$ mm, indicating that approximately 80% of the accumulated strain-energy measure in the equivalent STF domain was concentrated within about 10 mm of the impact center. Because the STF was represented by an equivalent Kelvin–Voigt solid, R_{80} should be regarded as a comparative simulation-derived localization length scale rather than a direct measure of energy storage or dissipation in the physical nanosilica/PEG suspension. This characteristic length scale provided the basis for the subsequent core-pitch design: a 10 mm pitch was selected as a confinement scale comparable to R_{80} , whereas a 20 mm pitch was selected to investigate a larger confinement scale approximately corresponding to $2 R_{80}$, thereby providing greater local deformation space. These simulation-guided pitches were subsequently applied to both the honeycomb and fish-scale-inspired architectures for experimental evaluation.

3.2 Fabrication feasibility and STF encapsulation

Both honeycomb and fish-scale-inspired EVA cores were successfully fabricated using the print–fill–seal procedure described in Section 2.4. After process optimization, both architectures exhibited sufficient wall continuity and sealing integrity to retain the STF within the prescribed cellular compartments.

During fabrication development, incomplete extrusion and insufficient top-surface closure were identified as the main causes of STF leakage in the honeycomb structures. The printing parameters were therefore adjusted to improve wall continuity and sealing around the upper perimeter. Excessive internal supporting features were also found to reduce structural flexibility and interfere with STF filling. Consequently, the final honeycomb design adopted a simplified regular hexagonal configuration that provided reliable fluid containment while maintaining the intended cellular structure.

The fish-scale-inspired architecture required additional geometric refinement because its curved and inclined units were more sensitive to printing defects when fabricated using flexible EVA filament. Earlier configurations with greater unit height and steeper inclination exhibited incomplete interlayer bonding and localized leakage. The geometry was therefore progressively modified, with the unit inclination adjusted to approximately 52.5° . A wall thickness of 0.6 mm was ultimately selected because thinner 0.4 mm walls could not be reproduced continuously, whereas the 0.6 mm configuration provided sufficient print continuity for STF encapsulation while preserving structural compliance.

Following these modifications, both architectures could be repeatedly filled and sealed without relying on direct fabric impregnation for STF retention. The printed cellular compartments therefore enabled controlled spatial confinement of the STF and provided mechanically distinct platforms for evaluating the effects of core configuration and confinement scale on the subsequent flexural and ballistic responses.

3.3 Flexural response of cellular-core specimens

The flexural responses of the unfilled and STF-filled cellular-core specimens were evaluated to compare the bending resistance and structural compliance of the honeycomb and fish-scale-inspired configurations. Figure 6 summarizes the maximum loads measured at a displacement of 3 mm. A clear configuration-dependent difference was observed, with the honeycomb cores exhibiting substantially higher bending resistance than the fish-scale-inspired structures.

For the unfilled honeycomb specimens, the maximum load decreased from 40.86 N for H10 to 30.77 N for H20. The higher resistance of H10 is attributed to its smaller pitch and denser interconnected wall network, which restricted relative deformation between adjacent cells. Increasing the pitch to 20 mm reduced the number of load-bearing walls across the specimen and consequently increased bending compliance.

In contrast, the unfilled fish-scale-inspired specimens required much lower loads, with maximum values of 0.313 N for F10 and 1.266 N for F20. This greater compliance is associated with the combined effects of the segmented cellular geometry and the thinner 0.6 mm walls used in the final manufacturable design. The raised units were mechanically coupled mainly through the thin supporting base layer, allowing greater local rotation and deformation under bending. Accordingly, the observed difference between the honeycomb and fish-scale-inspired specimens should be interpreted as a configuration-level response rather than as an isolated effect of cellular architecture.

STF filling increased the maximum load in all four configurations. The load increased from 40.86 to 42.05 N for H10 and from 30.77 to 34.99 N for H20, corresponding to increases of approximately 3% and 14%, respectively. Larger relative changes were observed for the fish-scale-inspired specimens: F20 increased from 1.266 to 1.779 N, whereas F10 increased from 0.313 to 1.223 N. Despite these increases, the overall compliance ranking remained unchanged, with F10 being the most compliant, followed by F20, H20, and H10.

The influence of STF filling was more pronounced in the highly compliant fish-scale-inspired configurations. In the honeycomb cores, flexural behavior was dominated by the continuous EVA wall network, whereas deformation of the segmented fish-scale-inspired compartments involved both structural deformation and displacement of the confined fluid. Nevertheless, because the tests were conducted at a low crosshead speed of 3 mm min⁻¹, the increased flexural resistance should not be interpreted as direct evidence of shear-thickening activation. Under these quasi-static conditions, the

additional resistance is more appropriately attributed to confined-fluid displacement and fluid–structure interaction within the cellular compartments.

3.4 Ballistic impact response

Ballistic impact tests were conducted to evaluate the influence of cellular-core configuration and STF filling on back-face deformation. The measured incident velocities, back-face signature (BFS) depths, and estimated absorbed energies are summarized in Table 2. Because the incident velocities varied among specimens, ranging from 334 to 430 m s⁻¹, the results were interpreted primarily through comparisons between corresponding unfilled and STF-filled configurations tested at relatively similar velocities.

The 29-layer Kevlar-only reference exhibited a BFS depth of 34.01 mm at an incident velocity of 334 m s⁻¹. All cellular-core assemblies produced smaller BFS values, ranging from 7.53 to 18.88 mm, despite being tested at higher incident velocities of approximately 407–430 m s⁻¹. However, because the cellular-core assemblies also contained five additional rear Kevlar layers, the Kevlar-only specimen was treated as a practical baseline rather than as a strictly equivalent structural control.

More direct evidence of the STF contribution was obtained from paired comparisons between unfilled and STF-filled cellular-core configurations. For the honeycomb configuration, STF filling reduced the BFS from 17.93 to 11.23 mm for H20 and from 18.88 to 11.43 mm for H10, corresponding to reductions of approximately 37% and 39%, respectively. For the fish-scale-inspired configuration, the BFS decreased from 14.73 to 10.23 mm for F10 and from 14.43 to 7.53 mm for F20, corresponding to reductions of approximately 31% and 48%, respectively. Among all tested configurations, F20-STF exhibited the lowest BFS of 7.53 mm.

The estimated absorbed-energy results provided a complementary measure of ballistic performance. The Kevlar-only reference exhibited an estimated absorbed energy of 407.89 J, whereas the cellular-core assemblies showed values ranging from approximately 648 to 731 J. Among the STF-filled configurations, H20-STF, F20-STF, H10-STF, and F10-STF exhibited estimated absorbed energies of 663.75, 718.66, 730.68, and 674.92 J, respectively. H10-STF exhibited the highest estimated absorbed energy, whereas F20-STF exhibited the lowest BFS, indicating that the configuration with the greatest estimated energy absorption did not necessarily correspond to the minimum back-face deformation. Because the absorbed-energy values were derived from the empirical backing-clay indentation relationship and the incident velocities were not identical, these values were used as complementary rather than absolute ranking indicators.

Comparison with the flexural results further showed that greater quasi-static bending resistance did not necessarily correspond to lower BFS. Although the honeycomb configurations exhibited substantially higher flexural resistance, the more compliant fish-scale-inspired configurations produced lower BFS values than their corresponding honeycomb counterparts. **Because the two core types differed in both cellular geometry and wall thickness, these differences should be interpreted as configuration-level**

responses rather than as isolated effects of cellular architecture. The mechanisms associated with these contrasting deformation responses are discussed in Section 3.5.

Table 2
Ballistic impact results of the Kevlar reference and cellular-core assemblies.

Specimen	Incident velocity (m $\varvec{S}^{-1}$)	BFS (mm)	Estimated absorbed energy (J)
Kevlar-only	334	34.01	407.89
H20	408	17.93	648.47
F20	407	14.43	649.77
H10	427	18.88	710.69
F10	411	14.73	662.47
H20-STF	410	11.23	663.75
F20-STF	425	7.53	718.66
H10-STF	430	11.43	730.68
F10-STF	413	10.23	674.92

3.5 Failure and energy absorption mechanisms

Post-impact observations revealed distinct deformation modes for the two cellular architectures, as shown in Fig. 8. The honeycomb structure exhibited broader global bending, whereas the fish-scale-inspired architecture produced multiple localized indentation regions in the rear Kevlar layer and a more distributed deformation pattern in the backing clay. These observations are consistent with the different deformation characteristics identified in the flexural tests.

The protective response of the STF-filled panels can therefore be interpreted as a sequential load-transfer process, as illustrated schematically in Fig. 9. Upon impact, the front Kevlar layers initially intercept the projectile and spread the concentrated load laterally. Deformation of the EVA cellular core subsequently mobilizes the STF confined within the geometry-defined compartments, while the surrounding cell walls restrict fluid motion and provide local structural support. The residual load is then redistributed through the rear Kevlar layers before being transmitted to the backing material.

The experimental observations suggest that cellular configuration and STF confinement act cooperatively rather than independently. In the honeycomb configuration, the continuous wall network favors collective load transfer and higher structural resistance. In contrast, the fish-scale-inspired configuration, combining segmented geometry with relatively thin walls, provides greater local deformation space while maintaining compartmentalized STF confinement.

Because the internal STF flow field and local shear-rate distribution were not directly measured, the mechanism proposed in Fig. 9 should be regarded as a physically supported interpretation rather than a direct observation of shear-thickening behavior. Nevertheless, the combined numerical, flexural, ballistic, and post-impact results consistently indicate that effective back-face deformation mitigation arises from the coupled effects of Kevlar load spreading, configuration-dependent cellular deformation, and geometry-controlled STF confinement.

4. Conclusions

This study developed a simulation-guided STF-filled 3D-printed sandwich composite concept integrating Kevlar reinforcement, flexible EVA cellular architectures, and confined nanosilica/PEG shear-thickening fluid. Honeycomb and fish-scale-inspired cores with characteristic pitches of 10 and 20 mm were fabricated using a print–fill–seal process and evaluated through finite-element analysis, flexural testing, ballistic impact testing, and post-impact observations.

The simplified finite-element model showed that both the presence and through-thickness position of the STF-equivalent layer affected the early-stage deformation field of the Kevlar/STF laminate. A characteristic energy-localization radius of approximately 10 mm was identified and subsequently used as a physically motivated reference for selecting the 10 and 20 mm cellular pitches.

Flexural testing revealed a clear configuration-dependent stiffness–compliance trade-off. The honeycomb cores exhibited substantially greater bending resistance, whereas the segmented fish-scale-inspired structures retained much greater structural compliance. Because the two core types employed different wall thicknesses, these differences reflect the combined influence of architecture and structural dimensions rather than geometry alone. STF filling increased flexural resistance in all configurations; however, under the low-rate bending conditions used here, this increase is more appropriately attributed to confined-fluid displacement and fluid–structure interaction rather than direct shear-thickening activation.

Ballistic testing demonstrated that STF filling reduced the back-face signature of all investigated cellular configurations. The F20-STF configuration exhibited the lowest BFS of 7.53 mm, representing an approximately 48% reduction relative to its unfilled counterpart. In contrast, H10-STF exhibited the highest estimated absorbed energy of approximately 730.68 J, indicating that maximum estimated energy absorption and minimum back-face deformation were not necessarily achieved by the same configuration. Together with the post-impact observations, these results indicate that ballistic protection was governed by the coupled effects of Kevlar load spreading, configuration-dependent cellular deformation, and geometry-controlled STF confinement rather than by core stiffness alone.

Overall, the results demonstrate that confinement geometry and structural compliance are important design variables for STF-enhanced protective composites. Among the investigated configurations, the 20 mm fish-scale-inspired STF-filled structure provided the most favorable back-face deformation response while retaining comparatively high structural compliance. The present numerical model

employed an equivalent Kelvin–Voigt representation of the STF and did not explicitly resolve non-Newtonian fluid flow or particle-scale shear-thickening behavior. Future work should therefore incorporate experimentally calibrated rate-dependent STF constitutive models, fluid–structure interaction simulations, repeated ballistic testing with tighter velocity control, and systematic optimization of cellular geometry, STF filling fraction, and Kevlar layer arrangement.

Declarations

Ethical Considerations

Not applicable. This study did not involve human participants, human data, human tissue, or animals.

Consent to Participate

Not applicable.

Consent for Publication

Not applicable.

Competing Interests

The authors have no relevant financial or non-financial interests to disclose.

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Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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Figures

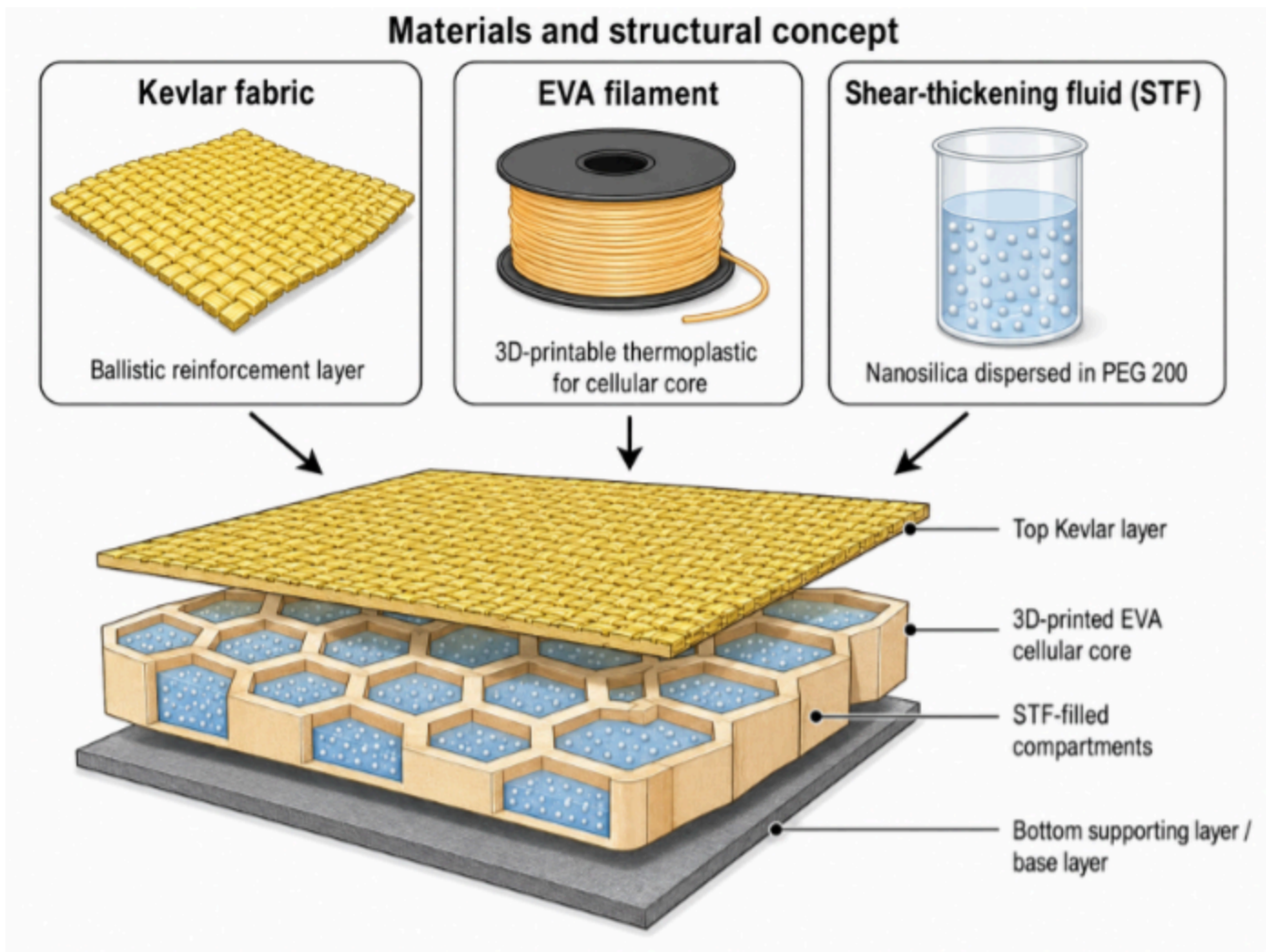


Figure 1

Constituent materials and structural concept of the STF-filled 3D-printed sandwich composite panel. Kevlar fabric serves as the primary ballistic reinforcement and load-spreading layer, the 3D-printed EVA cellular core provides geometry-defined structural support and STF confinement, and the nanosilica/PEG 200 STF acts as the rate-sensitive energy-dissipating medium within the cellular compartments.

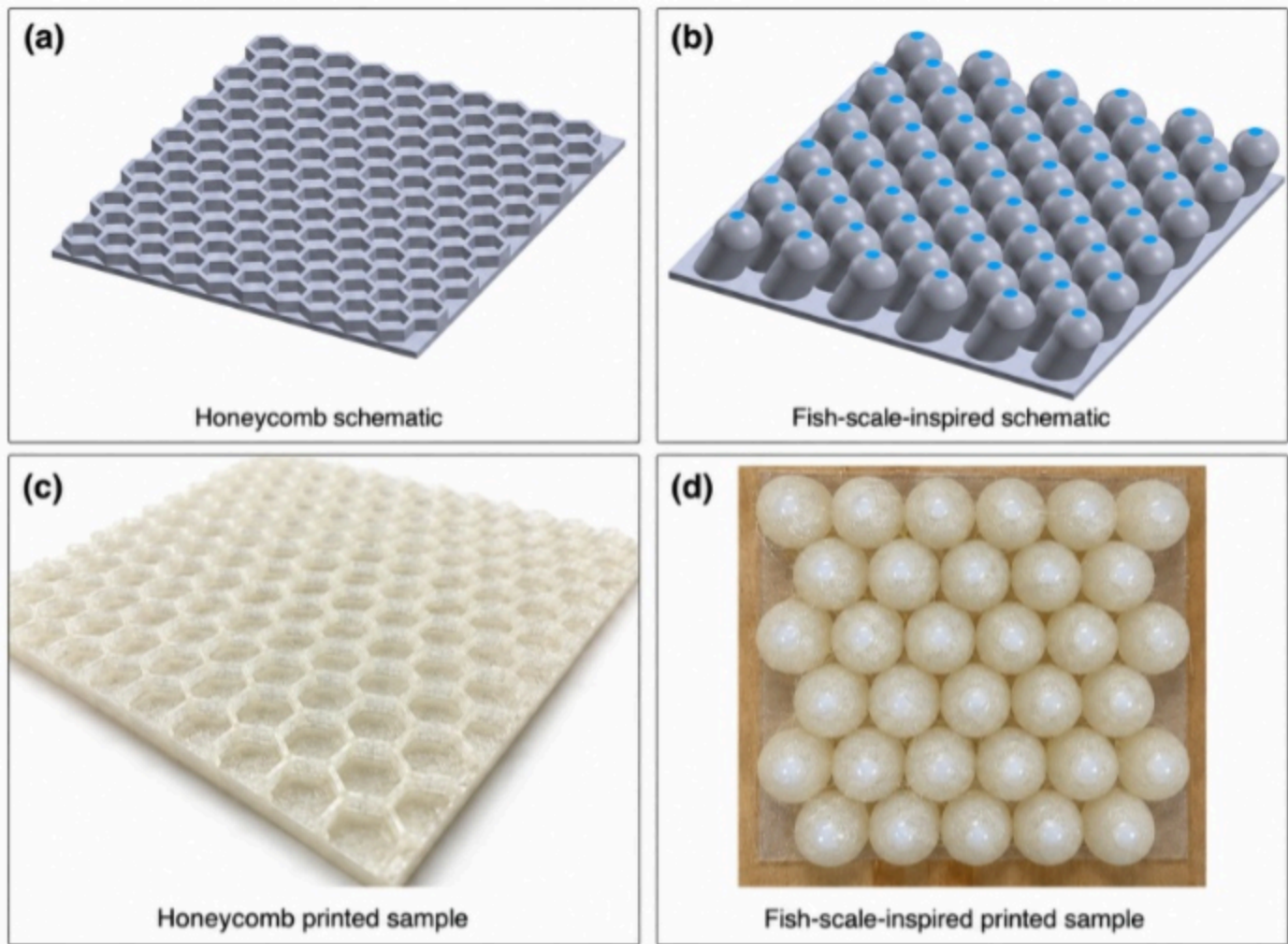


Figure 2

Cellular-core architectures and representative fabricated specimens investigated in this study. (a) CAD schematic of the honeycomb architecture; (b) CAD schematic of the fish-scale-inspired segmented architecture; (c) representative 3D-printed honeycomb core; and (d) representative 3D-printed fish-scale-inspired core. Honeycomb specimens were fabricated with a wall thickness of 1.0 mm, whereas fish-scale-inspired specimens used a wall thickness of 0.6 mm. Both architectures had a 1.0 mm supporting base layer, an overall core height of 10 mm, and simulation-guided characteristic pitches of 10 and 20 mm.

Print–fill–seal fabrication workflow

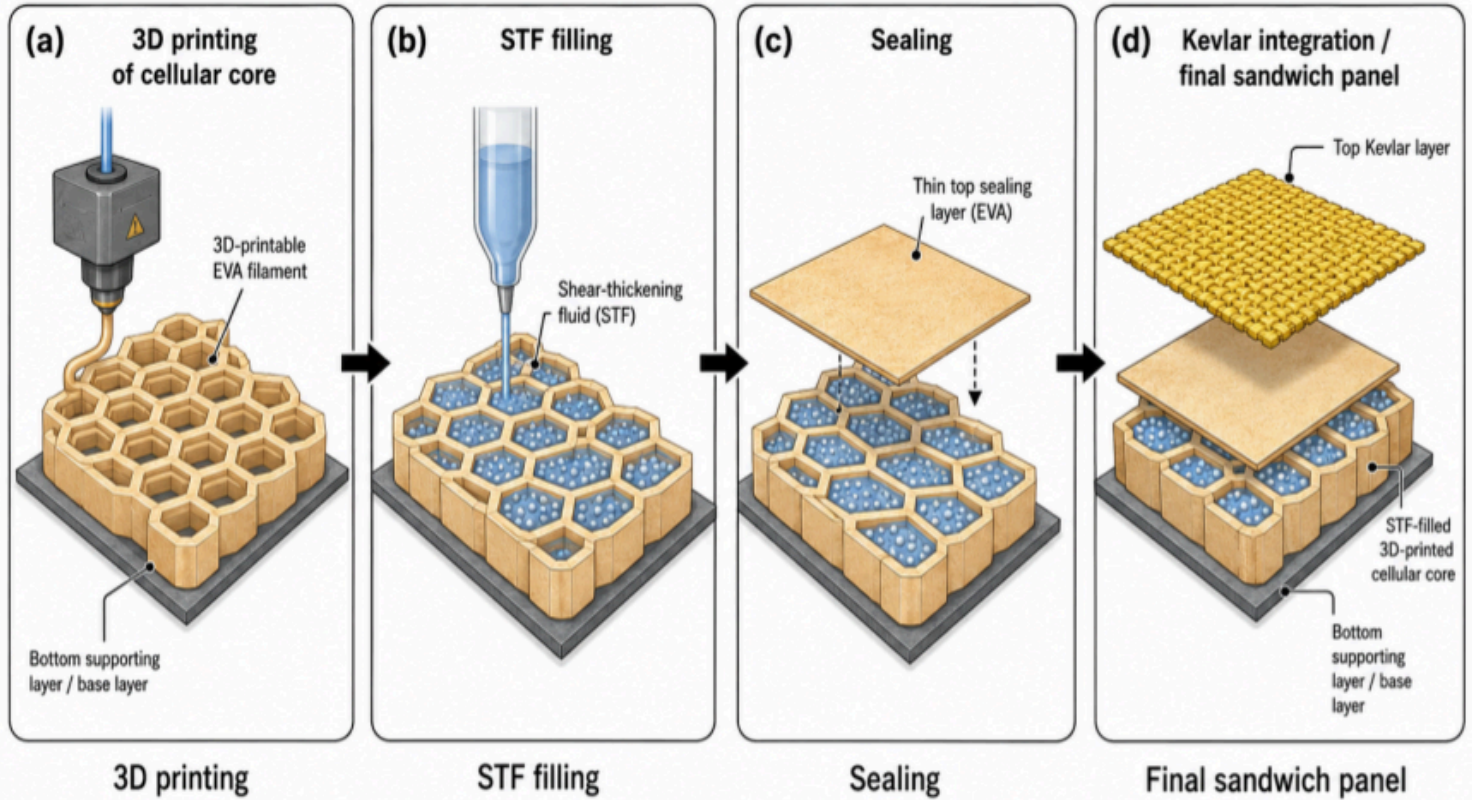


Figure 3

The honeycomb geometry is shown schematically as a representative example; the same print–fill–seal procedure was applied to both honeycomb and fish-scale-inspired cellular cores.

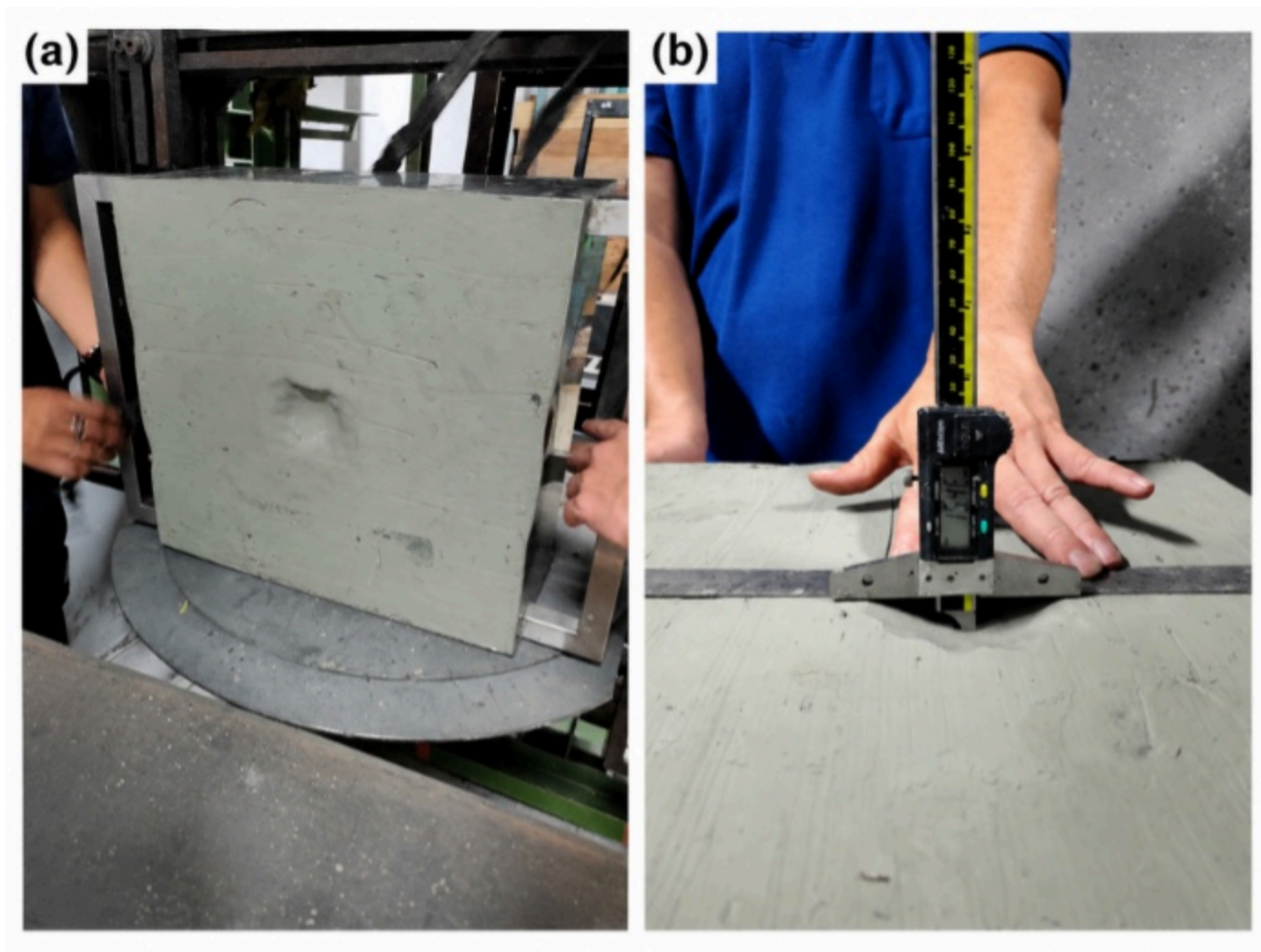


Figure 4

Back-face signature measurement after ballistic impact testing. (a) Representative indentation formed in the backing clay after projectile impact; (b) measurement of the maximum indentation depth using a depth gauge. The maximum measured depth was recorded as the back-face signature (BFS).

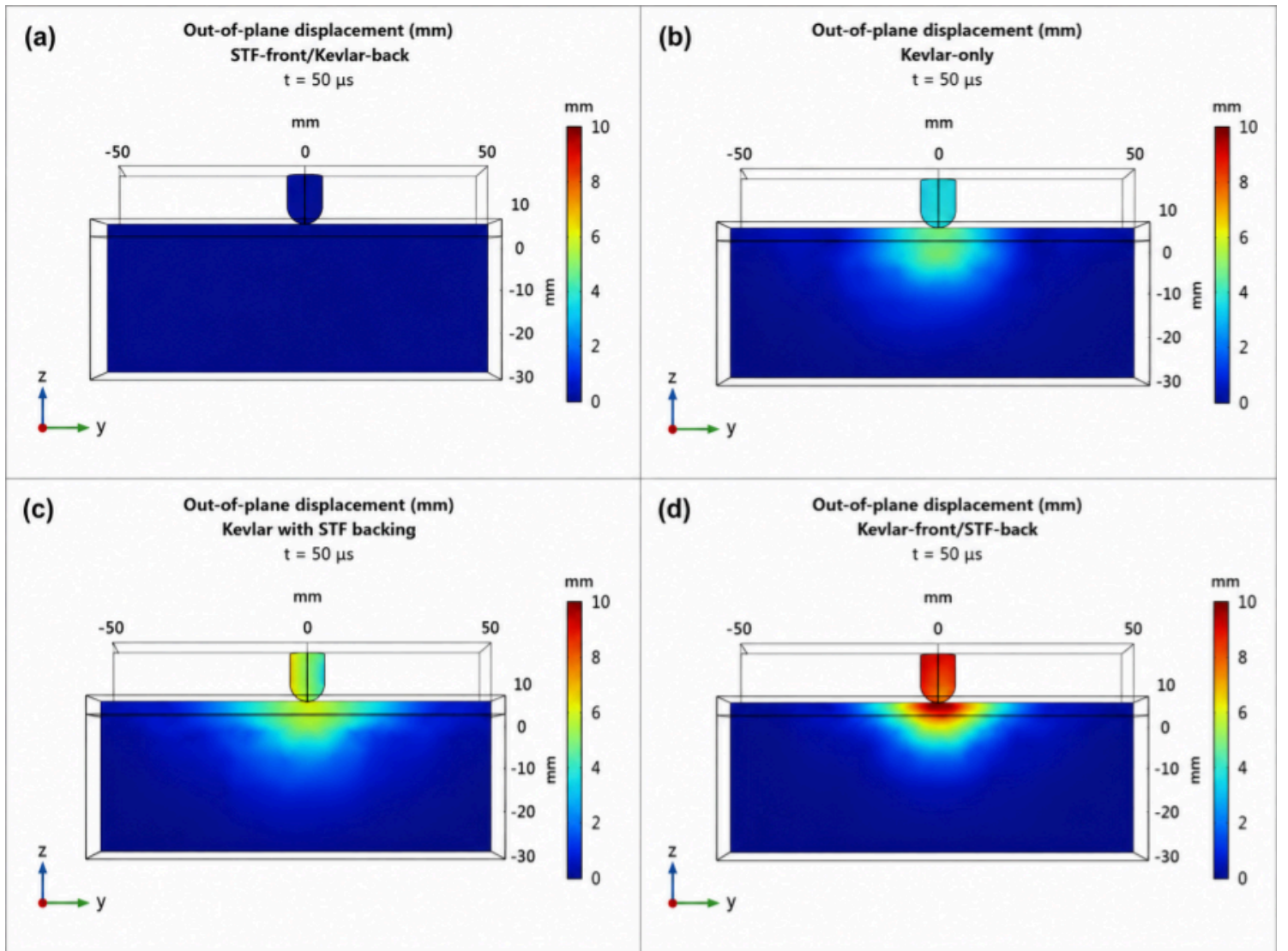


Figure 5

Out-of-plane displacement contours at $t = 50 \mu s$ for four simplified Kevlar/STF laminate configurations subjected to hemispherical impact: (a) 2.25 mm STF-equivalent front layer/2.25 mm Kevlar backing; (b) 4.5 mm Kevlar-only laminate; (c) 4.5 mm Kevlar laminate/2.25 mm STF-equivalent backing layer; and (d) 2.25 mm Kevlar front layer/2.25 mm STF-equivalent backing. The STF-containing domains were represented using an equivalent Kelvin–Voigt viscoelastic formulation. The contours were used to compare the early-stage deformation fields associated with STF placement and laminate configuration.

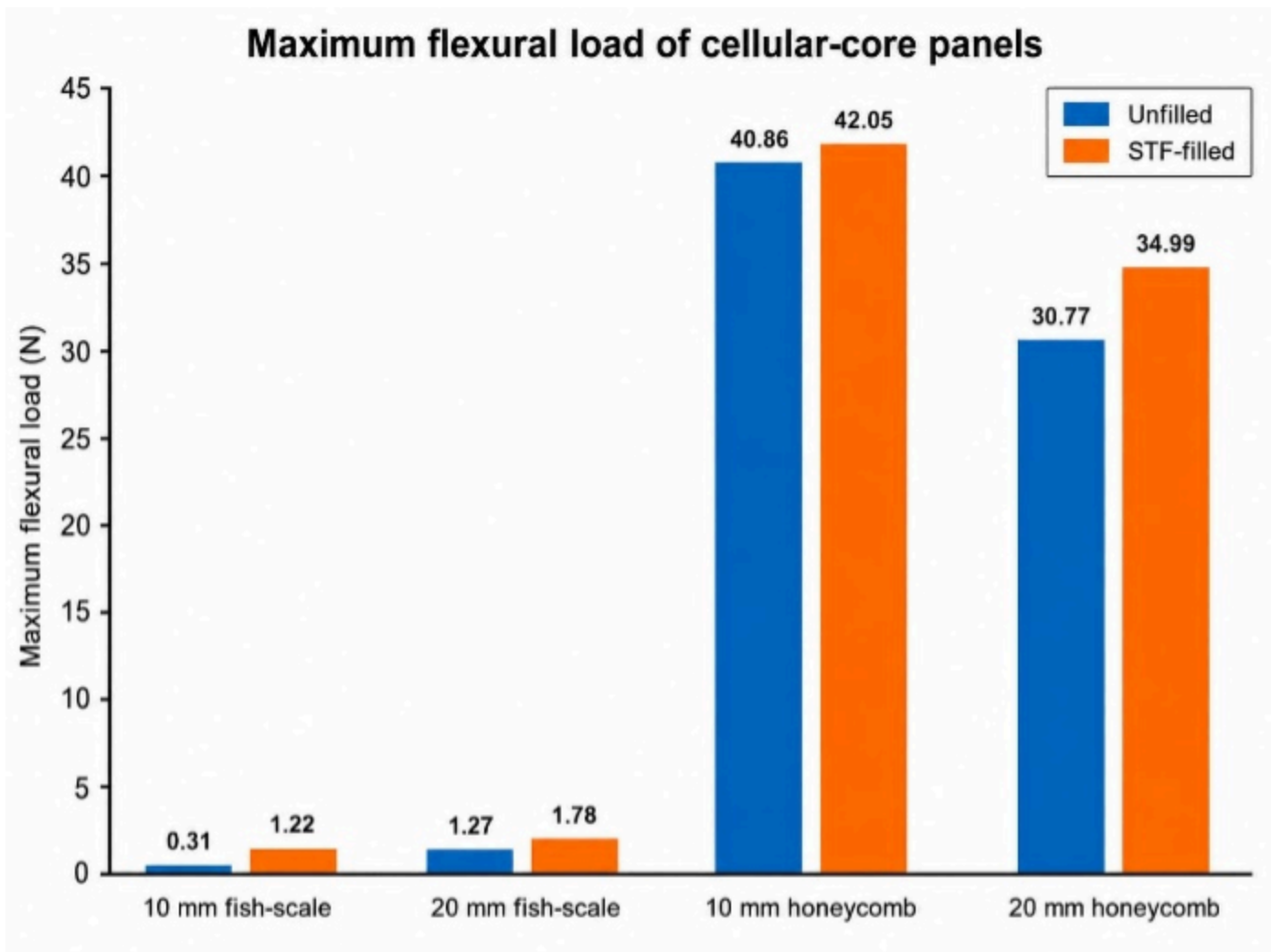


Figure 6

Maximum flexural loads of the unfilled and STF-filled cellular-core specimens measured under three-point bending at a displacement of 3 mm. Honeycomb specimens exhibited substantially greater bending resistance than fish-scale-inspired specimens, whereas the latter retained considerably higher structural compliance. STF filling increased the measured flexural load for all four configurations.



Figure 7

Back-face signature depths of the Kevlar-only reference, unfilled cellular-core panels, and STF-filled composite panels after ballistic impact testing.

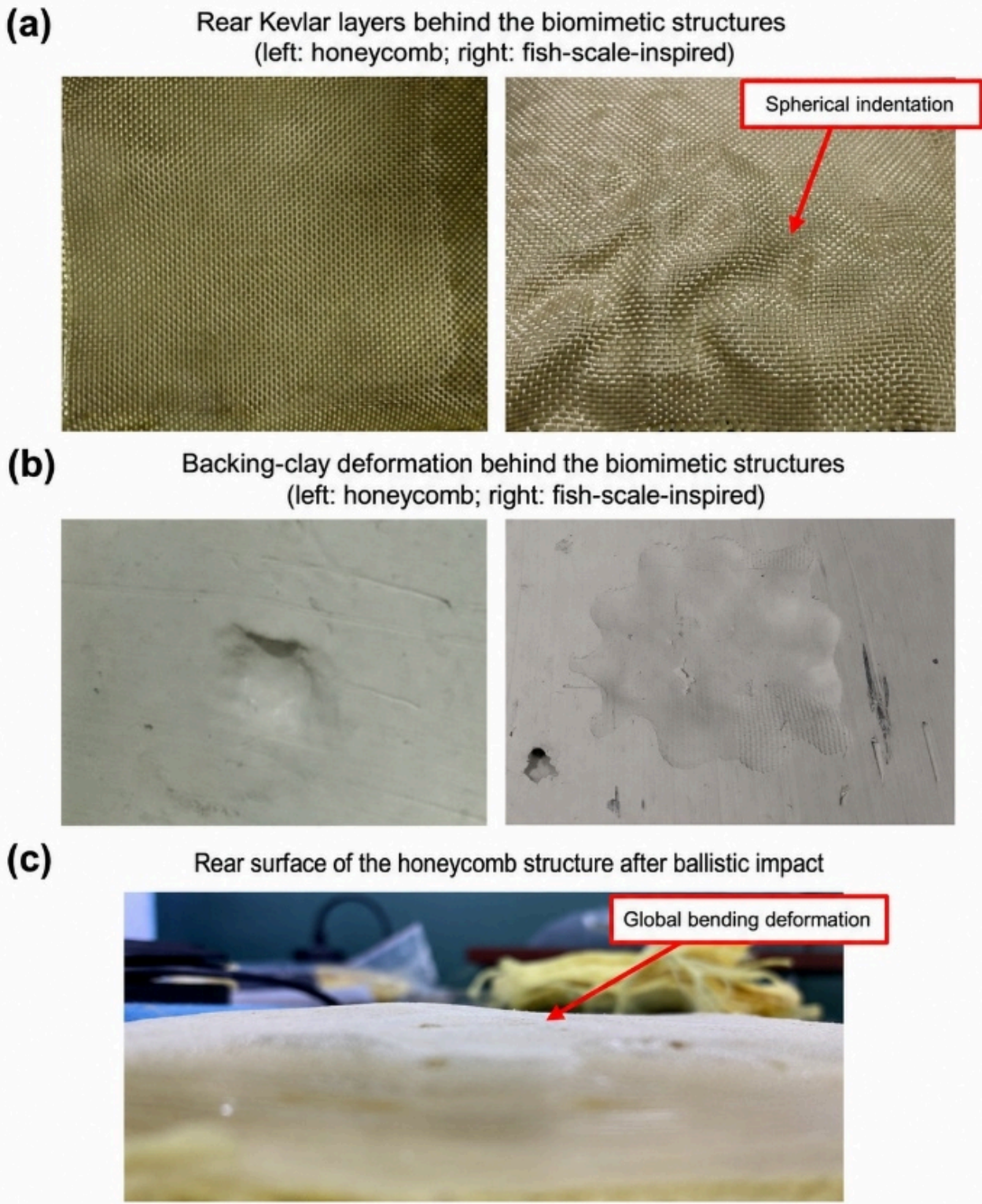


Figure 8

Representative post-impact deformation modes of the cellular-core assemblies. (a) Rear Kevlar layers behind the honeycomb (left) and fish-scale-inspired (right) structures, with the latter exhibiting localized spherical indentation. (b) Backing-clay deformation behind the honeycomb (left) and fish-scale-inspired (right) structures. (c) Rear surface of the honeycomb structure showing global bending deformation after ballistic impact.

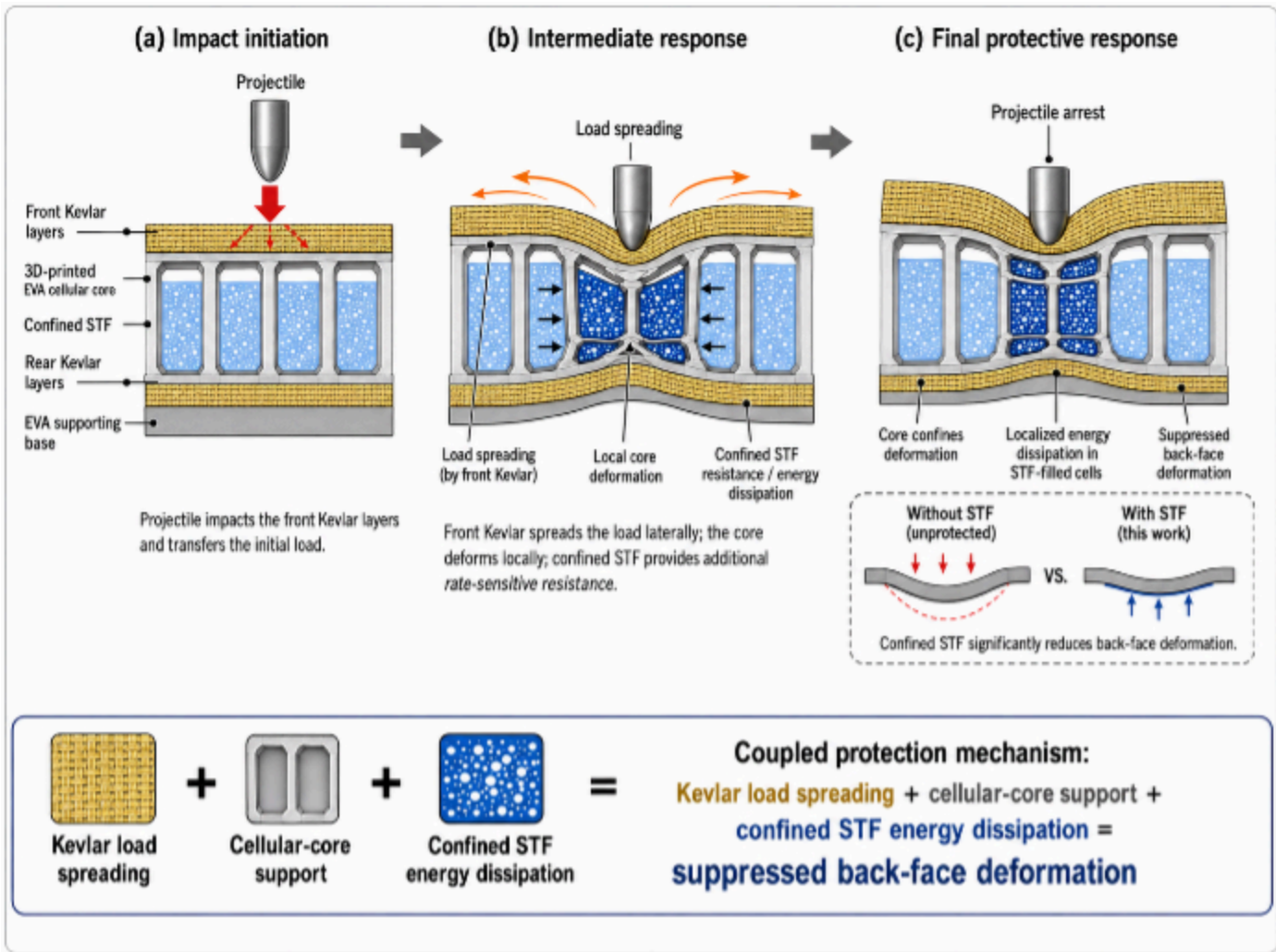


Figure 9

Proposed coupled protection mechanism of the STF-filled cellular-core composite under ballistic impact. The front Kevlar layers initially intercept the projectile and spread the concentrated load laterally. Local deformation of the 3D-printed EVA cellular core subsequently mobilizes the confined STF, providing additional rate-sensitive resistance and energy dissipation. The rear Kevlar layers further redistribute the residual load, thereby suppressing back-face deformation. The illustrated mechanism is inferred from the numerical analysis, ballistic results, and post-impact observations rather than from direct observation of the internal STF flow field.