Impact Response and Residual Performance of Hybrid Graded Sandwich Panels for UAV Structural Applications

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Abstract*- Composite sandwich structures are widely employed in unmanned aerial vehicle (UAV) components due to their high stiffness- to-weight ratio; however, their susceptibility to impact induced damage remains a major limitation. Conventional uniform foam and honeycomb cores often exhibit either excessive permanent indentation or localized brittle collapse, leading to significant degradation in post-impact stiffness. In this study, a combined experimental and numerical investigation is conducted on full-scale hybrid graded sandwich panels designed to enhance impact tolerance and residual structural performance for UAV applications. Sandwich panels incorporating carbon-fiber-reinforced polymer (CFRP) face sheets and three core configurations—uniform foam, uniform honeycomb, and hybrid graded foam–honeycomb—were fabricated and tested under 25 J low-velocity impact (n=3 per configuration) followed by residual bending. A validated finite element framework was developed using Abaqus/Explicit, integrating Hashin intralaminar damage for the composite face sheets, cohesive-zone modeling for skin–core delamination, and crushable-foam plasticity for the core. Numerical predictions of impact force history, absorbed energy, and damage morphology showed good agreement with experimental results, with deviations within 10%. The hybrid graded core configuration exhibited a stable force–displacement response, improved energy absorption efficiency, and effective damage confinement. Most notably, hybrid panels retained more than 90-92% of their original bending stiffness after impact, significantly outperforming panels with uniform core architectures. The results demonstrate that graded core designs offer a practical and lightweight solution for improving the impact tolerance and damage resilience of UAV sandwich structures.

Keywords: Sandwich composites; graded cores; UAV structures; low-velocity impact; residual bending; damage tolerance

1. INTRODUCTION

Composite sandwich structures are extensively employed in unmanned aerial vehicle (UAV) components such as fuselage skins, control surfaces, fairings, and access panels due to their high stiffness-to-weight ratio and design flexibility. The combination of stiff composite face sheets and lightweight cores enables significant weight reduction while maintaining structural efficiency, which is critical for improving flight endurance and payload capacity. Despite these advantages, sandwich structures remain particularly vulnerable to impact loading encountered during ground handling, take-off and landing operations, and accidental debris strikes. Composite sandwich structures are widely recognized for their high stiffness-to-weight ratio, yet their vulnerability to low-velocity impact remains a critical limitation in aerospace applications (Daniel 2002). Honeycomb cores often fail by localized brittle collapse (Aktas 2017), while foam cores suffer permanent indentation and stiffness loss (Zhang 2018).

Low-velocity impact events can introduce complex and interacting damage mechanisms in sandwich composites, including matrix cracking and fiber fracture in the face sheets, interlaminar delamination at the skin–core interfaces, and crushing or buckling of the core material [1,3,4]. Such damage is often barely visible on the surface yet can lead to a substantial reduction in residual stiffness and load-carrying capability. For UAV structures, where repeated service loads are common and inspection opportunities may be limited, maintaining post-impact structural integrity is of paramount importance [15–17].

Extensive research has been conducted on the impact behaviour of sandwich panels with uniform core architectures. Honeycomb-core sandwich structures typically exhibit high initial stiffness and peak impact forces but are prone to localised brittle collapse and extensive delamination under impact loading [6–8]. In contrast, foam-core sandwich panels tend to show smoother load–displacement responses due to progressive crushing of the core, albeit at the expense of large permanent indentation and reduced post-impact stiffness [5,7]. These inherent trade-offs highlight the limitations of conventional uniform core designs when impact tolerance and residual performance are simultaneously required. Recent advances in graded and bio- inspired cores demonstrate improved energy absorption and damage tolerance (Li 2019), but most studies remain at coupon scale. This work extends graded-core concepts to full-scale UAV panels, addressing a gap in practical applicability.

Recent advances demonstrated that tailoring core architecture through layering, grading, or bio-inspired designs can significantly enhance energy absorption efficiency and damage tolerance [9]. By redistributing stiffness and strength through the thickness of the core, graded sandwich structures can promote progressive damage evolution, reduce peak impact forces, and delay catastrophic failure. However, many of these studies are restricted to coupon scale specimens or rely heavily on numerical simulations, limiting their direct applicability to full-scale UAV structural components.

To address this gap, the present work investigates the impact response and residual mechanical performance of full-scale hybrid graded sandwich panels specifically designed for UAV applications [9–11]. Sandwich panels incorporating carbon-fiber-reinforced polymer (CFRP) face sheets and three different core configurations—uniform foam, uniform honeycomb, and hybrid graded foam–honeycomb—are examined through a combined experimental and numerical approach. Low-velocity impact tests followed by residual bending experiments are conducted to quantify damage tolerance and stiffness retention. In parallel, a validated finite element framework is developed to capture intralaminar damage, interfacial delamination, and progressive core crushing. The study aims to provide experimentally grounded design insights into the effectiveness of graded core architectures for improving the impact resilience of lightweight UAV sandwich structures.Proposed approach builds on survivability principles explored in vehicular and IoT networks (Sivabalan 2020) (Settu & Ramalingam 2021), reframing structural resilience as a systems-level requirement for UAV mission reliability.

Contribution:

- Full-scale graded-core validation under LVI and residual bending.
- Coupled FEM reproducing peak force and absorbed energy within ≤10%.
- Quantified stiffness retention >90% post-impact in hybrid panels

2. MATERIALS AND EXPERIMENTAL METHODS

2.1 SANDWICH PANEL CONFIGURATION

All sandwich panels investigated in this study consisted of carbon-fiber-reinforced polymer (CFRP) face sheets bonded to lightweight cores with three different architectural configurations: (i) uniform polymer foam core, (ii) uniform honeycomb core, and (iii) hybrid graded foam–honeycomb core. The CFRP face sheets were designed using a symmetric laminate stacking sequence to ensure balanced in-plane stiffness and adequate resistance to impact-induced damage

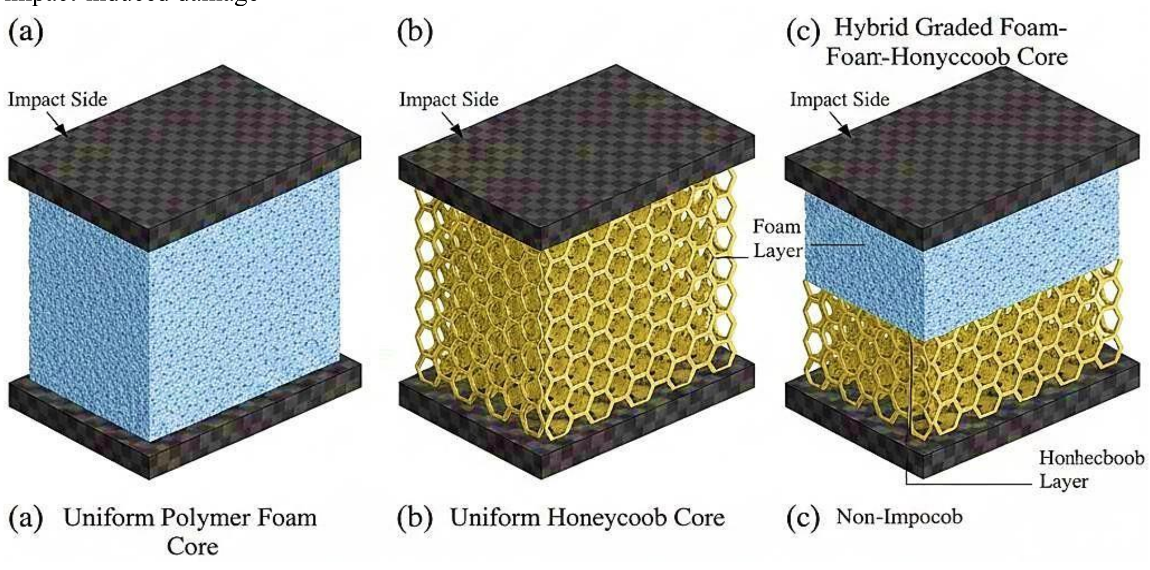

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Figure 1. Schematic illustration of sandwich panel configurations: (a) uniform foam core, (b) uniform honeycomb core, and (c) hybrid graded foam–honeycomb core.

For the hybrid graded configuration, the polymer foam layer was positioned on the impact side, while the honeycomb layer was placed on the non-impact side. This arrangement was selected based on graded-core design principles reported in recent sandwich structure studies, where a compliant outer layer initiates progressive crushing and attenuates peak impact forces, while a stiffer inner layer maintains global structural stiffness and load-carrying capacity.

2.2 MANUFACTURING PROCESS

The sandwich panels were fabricated using an autoclave-assisted curing process to ensure consistent consolidation and reliable skin–core bonding. CFRP face sheets were laid up from pre-impregnated carbon fiber plies and bonded to the core materials using a structural epoxy adhesive. The curing cycle followed the manufacturer-recommended temperature and pressure profiles. After curing, panels were allowed to cool under controlled conditions and subsequently trimmed to the required dimensions. Visual inspection and tap-testing were performed to verify uniform bonding and to ensure the absence of manufacturing-induced defects prior to mechanical testing. Impact tests followed ASTM D7136 (drop-weight impact) and residual bending followed ASTM D7137 compression-after-impact methodology. Cohesive-zone parameters were calibrated using Mode I (DCB, ASTM D5528) and Mode II (ENF, ASTM D7905) fracture toughness tests. A 5 kg hemispherical impactor (diameter 16 mm) was dropped from 0.5 m, imparting 25 J impact energy. Hybrid graded cores consisted of 10 mm foam (impact side) and 15 mm honeycomb (non-impact side). Mesh convergence was verified by reducing element size in the impact zone from 2 mm to 1 mm, with peak force variation <5%. Explicit time integration stability was ensured without artificial mass scaling.

2.3 COUPON-LEVEL MATERIAL CHARACTERIZATION

Coupon-level mechanical tests were conducted to obtain material properties required for numerical modeling and to ensure experimental traceability. Quasi-static tensile and compressive tests were performed on CFRP laminate specimens to determine elastic moduli, Poisson's ratios, and strength parameters used in intralaminar damage modeling. Interlaminar fracture properties were characterized through Mode I double cantilever beam (DCB) and Mode II end-notched flexure (ENF) tests. The critical strain energy release rates obtained from these tests were used to calibrate the cohesive-zone model governing skin–core delamination. Core materials were characterized using out-of-plane compression and shear tests. For foam cores, stress–strain responses were employed to define crushable-foam plasticity parameters, including yield behavior and volumetric hardening. Honeycomb cores were characterized in terms of effective orthotropic stiffness and compressive crushing strength. These parameters enabled accurate representation of progressive core collapse during impact.

2.4 LOW-VELOCITY IMPACT TESTING

Low-velocity impact experiments were conducted using an instrumented drop-weight impact tower in accordance with ASTM D7136 guidelines. All sandwich panels were fully clamped along their four edges to replicate service-relevant boundary conditions typically encountered in UAV skin structures. A hemispherical impactor was used to apply a prescribed impact energy representative of accidental ground-handling and debris-strike scenarios. During each test, impact force–time, displacement–time, and absorbed energy histories were recorded. After impact, specimens were visually inspected to identify surface indentation, delamination initiation, and core crushing patterns.

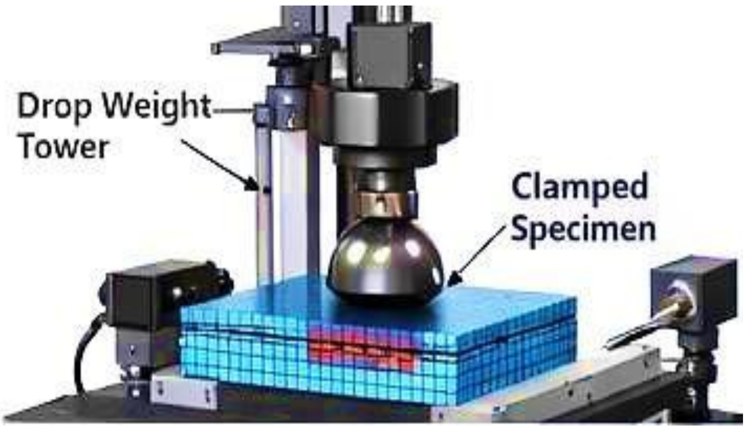

Figure 2. Experimental setup for low-velocity impact testing showing clamping arrangement and impactor geometry.

2.5 RESIDUAL BENDING TESTS

Following impact testing, the same specimens were subjected to residual bending tests to quantify post-impact stiffness and load-carrying capacity. Three-point bending tests were performed under displacement control, inducing combined bending and shear stresses representative of in-service loading conditions for UAV sandwich panels. For reference, undamaged panels of each core configuration were also tested under identical conditions to establish baseline stiffness and failure behavior. Residual stiffness retention was calculated as the ratio of post-impact to pristine bending stiffness, providing a direct measure of damage tolerance. Interlaminar fracture properties were calibrated using Mode I (DCB, ASTM D5528) and Mode II (ENF, ASTM D7905) tests, directly informing cohesive-zone parameters (Benzeggagh & Kenane 1996).

Figure 3. Three-point bending test configuration used to evaluate residual stiffness after impact.

Intralaminar damage in CFRP face sheets was modeled using Hashin's failure criteria(Hashin 1980), while mixed-mode delamination followed the Benzeggagh–Kenane interaction law.

3. FINITE ELEMENT MODELING

3.1 MODELING STRATEGY

Finite element simulations were carried out using Abaqus/Explicit to replicate the low-velocity impact and subsequent residual bending behavior of the sandwich panels. The numerical framework was developed to capture the coupled damage mechanisms governing impact response, including intralaminar damage in the composite face sheets, interfacial delamination, and progressive core crushing.

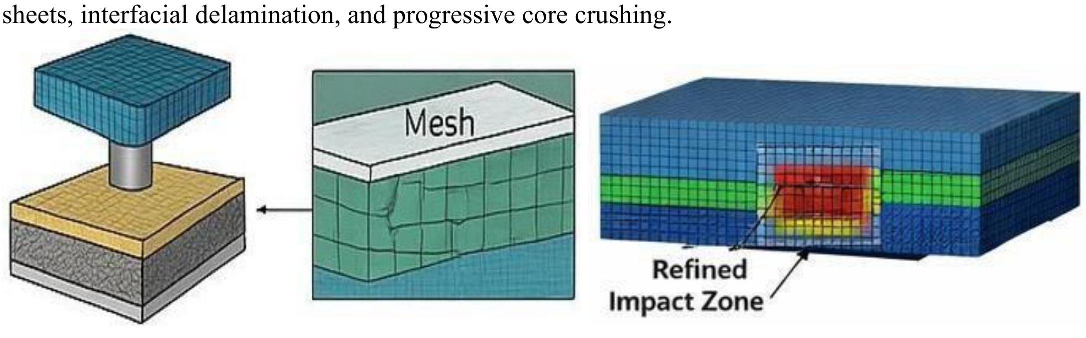

Figure 4. Finite element model of the sandwich panel highlighting mesh refinement in the impact region.

CFRP face sheets were modeled using four-node reduced-integration shell elements to accurately represent bending, membrane, and damage evolution behavior while maintaining computational efficiency. Core materials were represented using eight-node reducedintegration solid elements to capture through-thickness crushing and shear deformation. Zerothickness cohesive elements were inserted at the skin–core interfaces to simulate interlaminar debonding. Mesh refinement was applied in the impact region, where high stress gradients and localized damage

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were expected. Element sizes were selected based on mesh convergence studies to ensure stable predictions of peak impact force and absorbed energy.

3.2 MATERIAL CONSTITUTIVE MODELS

Intralaminar damage in the CFRP face sheets was modeled using the Hashin failure criteria with progressive stiffness degradation. Damage initiation accounted for fiber tensile and compressive failure as well as matrix tensile and compressive cracking. Damage evolution was governed by energy-based degradation laws calibrated from coupon-level experimental data. Foam cores were modeled using a crushable-foam plasticity model with volumetric hardening to represent progressive crushing under impact loading. Honeycomb cores were treated as equivalent orthotropic continua with defined elastic and crushing properties in the out-of-plane direction. Skin–core delamination was simulated using a bilinear cohesive-zone model, with mixed-mode damage evolution governed by the Benzeggagh–Kenane criterion. Material properties and damage parameters used in the simulations were obtained from experimental characterization and are summarized in Table 1.

3.3 BOUNDARY CONDITIONS AND LOADING

For impact simulations, the impactor was modeled as a rigid hemispherical body with an initial velocity corresponding to the experimentally applied impact energy. All panel edges were fully constrained to replicate the clamped boundary conditions used in the impact tests. General contact interactions were defined between all contacting surfaces with a friction coefficient of
0.2. Residual bending simulations were performed using the damaged configurations obtained from the impact analyses. Boundary conditions and loading rates were matched to the experimental three-point bending tests to ensure direct comparability between numerical and experimental results.

3.4 MODEL VALIDATION

Model validation was achieved through direct comparison between numerical predictions and experimental measurements of impact force–time histories, absorbed energy, and observed damage patterns. The finite element model successfully reproduced the overall response trends for all core configurations. Deviations in peak impact force and absorbed energy remained within 10%, confirming the robustness and predictive capability of the numerical framework.

Table 1. Elastic properties, strength parameters, and damage constants used in the finite element model.

Material	Parameter	Value	Purpose / Description
CFRP Face Sheets (Orthotropic)	E_1 (GPa)	138	Governs stiffness along fiber direction
	$E_2 = E_3$ (GPa)	9.2	Controls matrixdominated deformation
	$G_{12} = G_{13}$ (GPa)	5.1	Governs in-plane shear response
	G_{23} (GPa)	3.9	Controls transverse shear behavior
	ν_{12}	0.29	Defines orthotropic coupling
	X_T / X_C (MPa)	2150 / 1520	Fiber tensile / compressive failure initiation
	Y_T / Y_C (MPa)	68 / 225	Matrix cracking / crushing initiation
	G_f^{fiber} (kJ m^{-2})	52	Governs fiber damage evolution
	G_f^{matrix} (kJ m^{-2})	5.4	Governs matrix damage Evolution

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Foam Core	Density (kg m^{-3})	115	Defines mass and inertia
	Elastic modulus (MPa)	128	Initial elastic response
	Yield / plateau stress (MPa)	2.4 / 1.9	Controls onset and progression of crushing
	Densification strain	0.65	Defines end of crushing plateau
Honeycomb Core	Density (kg m^{-3})	82	Effective mass representation
	Out-of-plane modulus (E_z) (MPa)	310	Provides throughthickness load support
	Compressive strength (MPa)	8.8	Governshoneycomb crushing resistance
Skin–Core Interface (CZM)	(K_n / K_s) (N mm^{-3})	(1.0×10^6 / 8.5×10^5)	Ensures numerical stability before damage
	(T_n / T_s) (MPa)	36 / 47	Delamination initiation in normal / shear modes
	(G_{IC} / G_{IIC}) (kJ m^{-2})	0.39 / 1.25	Resistance to opening / sliding delamination
	BK parameter (\eta)	1.75	Mixed-mode damage interaction

Table 2. Summary of numerical parameters used in finite element modelling

Parameter	Value	Purpose
Skin element type	S4R	Captures laminate bending and membrane behavior
Core element type	C3D8R	Models three-dimensional crushing and shear response
CZM stiffness	(1 × 10^{6}) N mm^{-3}	Ensures stable skin–core interface prior to damage
Mode-I fracture energy	0.39 kJ m^{-2}	Controls resistance to opening delamination
Mode-II fracture energy	1.25 kJ m^{-2}	Controls resistance to sliding delamination
Foam densification strain	0.65	Governs termination of crushing plateau
Honeycomb modulus	310 MPa	Provides stiffness along out-of-plane (ribbon) direction
Contact friction coefficient	0.2	Controls sliding between impactor and face sheets
Time integration scheme	Automatic (explicit)	Ensures numerical stability in dynamic impact simulations
Mesh size (impact zone)	1 mm	Accurately captures damage initiation and evolution

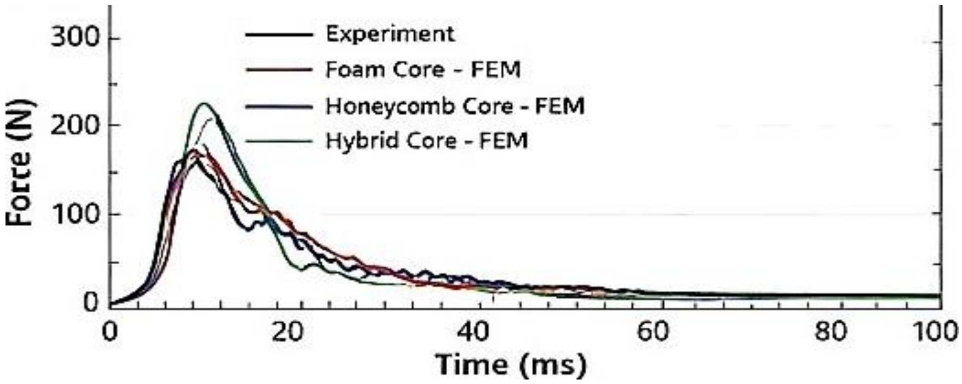

Figure 5. Comparison of experimental and numerical impact force–time histories.

Figure 6. Numerically predicted damage contours showing face-sheet damage, core crushing, and interfacial delamination after impact.

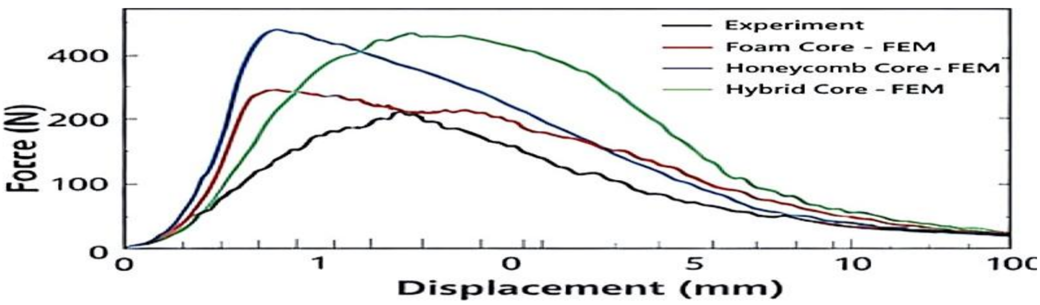

Figure 7. Impact force–displacement responses for sandwich panels with different core architectures.

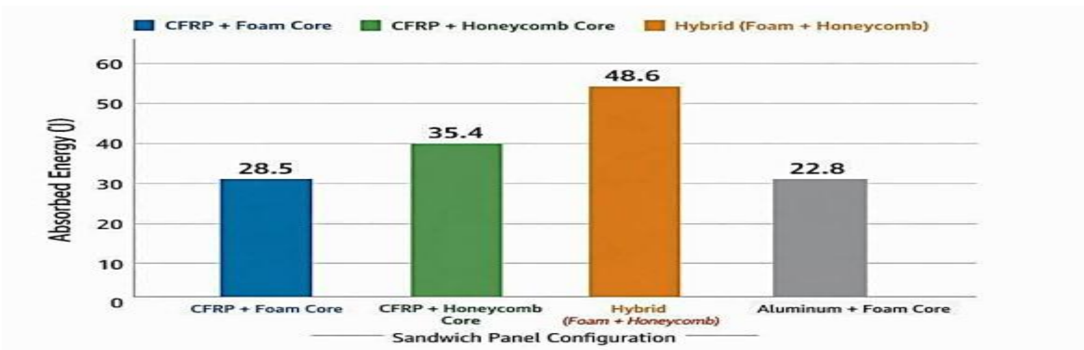

Figure 8. Comparison of absorbed impact energy among different sandwich panel configurations .

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Under identical clamped boundary conditions and impact energies, the hybrid graded foam– honeycomb panels exhibited a sustained force plateau and retained 92–95% of pristine bending stiffness, indicating effective damage confinement and preserved load transfer across the thickness. Cohesive-zone parameters were calibrated from Mode I/II fracture tests (DCB/ENF), and mixed-mode evolution followed the Benzeggagh–Kenane criterion; numerical peak force and absorbed energy agreed with experiments within 10% across all core architectures. Positioning a compliant foam layer on the impact side attenuated peak force via progressive crushing, while the honeycomb layer on the non-impact side maintained global stiffness; this graded arrangement mitigated the foam–honeycomb trade-off without a measurable mass penalty per unit area.

4. CONCLUSION

A comprehensive experimental and numerical investigation of hybrid graded sandwich panels for UAV structural applications has been presented. Compared with conventional uniform foam and honeycomb core configurations, hybrid graded foam–honeycomb panels exhibited improved impact force modulation, enhanced energy absorption efficiency, and superior damage containment. Damage confinement in hybrid panels—progressive foam crushing followed by honeycomb restraint—reduced delamination area compared to honeycomb-only cores. This validates the graded layering principle for balancing peak force attenuation and global stiffness. For UAV fuselage skins and control surfaces, hybrid graded cores should be prioritized where impact tolerance and stiffness retention are critical, with foam on the impact side and honeycomb on the non-impact side."

Low-velocity impact tests demonstrated that graded cores promote controlled progressive crushing, reducing damage severity in the face sheets. Residual bending experiments revealed that hybrid panels retained more than 90% of their original stiffness after impact, highlighting their enhanced damage tolerance. Finite element simulations showed good agreement with experimental results, confirming the reliability of the developed numerical framework.The results indicate that hybrid graded sandwich architectures offer a promising pathway for improving the impact resilience and structural reliability of lightweight UAV components. Future work will focus on extending the approach to curved panels, repeated impact scenarios, and optimization of graded core configurations for specific mission requirements.

5. FUTURE DIRECTIONS

Future work may extend the present study to curved and shell-type sandwich panels representative of actual UAV structures, where curvature effects may influence impact damage evolution and residual performance. The behavior of hybrid graded sandwich panels under repeated and multi-impact loading should also be investigated to assess damage accumulation and long-term structural reliability. Temperature and humidity effects must be assessed to ensure operational robustness. Integration with architected cores via additive manufacturing offers opportunities for next-generation impact-tolerant UAV structures. Optimization of foam– honeycomb thickness ratios and material distributions could maximize energy absorption per unit mass, supporting UAV payload and endurance requirements. Coupling graded core design with AI-driven mission reliability frameworks (Settu et al., 2024) will enable holistic UAVsurvivability systems. Further research may focus on optimization of graded core architecture, including layer thickness and material distribution, to maximize energy absorption while minimizing weight. Studies addressing higher impact velocities and environmental effects such as temperature and moisture exposure would broaden the applicability of graded sandwich concepts. Additionally, the integration of additive manufacturing and architected core designs presents promising opportunities for developing next-generation impact-tolerant sandwich structures.

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