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Experimental and Numerical Study of Low-Velocity Impact and Compressive Behavior in 3D-Printed ABS Honeycomb Lattice Structures

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Abstract

In the present work, the mechanical performance of additively manufactured honeycomb lattices under low-velocity impact and quasi-static compression is investigated experimentally and numerically. Lattice specimens with regular hexagonal topology were fabricated using Fused Deposition Modeling (FDM) with ABS thermoplastic. Compressive tests were conducted under displacement control for recording stress–strain responses, while low-velocity drop-weight impact tests were performed with a 1-kg hemispherical impactor dropped from a height of 30 cm. Finite element simulations of impact and compression were conducted in ANSYS using nonlinear static and transient dynamic analyses, respectively. Numerical models of lattices contain solid elements together with contact elements to simulate interaction with the impactor. Numerical predictions are in good correspondence with experimental force-displacement curves for impact tests, which reflect a distinct elastic-plastic response followed by local buckling and core crushing. Furthermore, a good correspondence between the simulation and the test was obtained regarding the residual dent profiles and absorbed energies. Impact behavior is compared with the load-bearing capacity, energy absorption, and failure modes under compression. Experimental results reveal that the printed honeycomb structures under both loading modes exhibit notable deformation localization controlled by face-sheet bending and core density. This paper provides a new perspective on the structural response of 3D printing-manufactured, polymer-based lattice geometries, while previous studies have focused on metallic or composite-based honeycomb cores. The approach of dual loading improves the understanding of energy dissipation mechanisms and contributes to the development of impact-resilient lightweight components for aerospace and protective applications.

Keywords: Drop-weight impact ; Honeycomb lattice ; Finite element analysis ; Compression test.

1. Introduction

This Lightweight lattice structures with cellular architectures have attracted significant interest in recent years for their high specific stiffness, tunable mechanical properties, and efficient energy absorption under dynamic loading. Among them, honeycomb cores are widely adopted in aerospace, automotive, and protective systems due to their superior crashworthiness and deformation stability under out-of-plane impact and compressive loads [1]–[6]. In particular, sandwich structures incorporating honeycomb cores are extensively used in primary and secondary aircraft components such as flaps, tail skins, and access panels where weight savings and impact resistance are critical.

Numerous studies have investigated the low-velocity impact behavior of metallic and composite sandwich panels with regular or reinforced honeycomb cores. For instance, Zhang et al. [7] and Zheng et al. [8] explored energy absorption characteristics and failure mechanisms under spherical impactors, revealing that over 80% of the impact energy is typically dissipated through plastic deformation in the upper face sheet and localized crushing in the core. Wang et al. [9] further highlighted the importance of geometric reinforcement in honeycomb designs, showing substantial gains in plateau stress and specific energy absorption through internal ribbing. However, most prior research has been limited to industrially manufactured aluminum or CFRP-based cores with fixed topologies.

The arrival of additive manufacturing techniques, such as fused deposition modeling, has enabled the fabrication of polymer-based lattice structures characterized by high geometric complexity and controlled wall thickness. Thus far, polymer lattices have seen extensive research in terms of static and dynamic properties; however, there is scant consideration regarding their behavior under complex loading conditions, which better replicates realistic service conditions. In addition, very little attention has been paid to the validation of their performance through experimental tests and finite element simulations.
This work seeks to fill this lacuna by conducting an extensive experimental and numerical investigation on 3D-printed ABS honeycomb lattice structures under drop-weight impact and quasi-static compression. Unlike previous studies that isolated either dynamic or static performance, the dual-loading approach adopted here allows for a more holistic evaluation of energy dissipation mechanisms and modes of deformation. The results give important insights into the mechanical behavior of printed cellular structures and inform the design of lightweight components for aerospace and protective engineering.

2. Experimental Procedure

2.1 Specimen Design and Fabrication

The specimens were designed with a regular hexagonal honeycomb topology using CAD software. Each sample had overall dimensions of 100 mm × 100 mm in the plane with a nominal thickness of 10 mm. The unit cell size was set to 10 mm, and the wall thickness was maintained at 1.2 mm to ensure printability and mechanical integrity. The structures were fabricated from acrylonitrile butadiene styrene (ABS) using a fused deposition modeling (FDM) 3D printer (Prusa i3 MK3S), with a nozzle diameter of 0.4 mm and a layer height of 0.2 mm. All prints were performed at 100% infill density, with default printing parameters recommended for ABS.

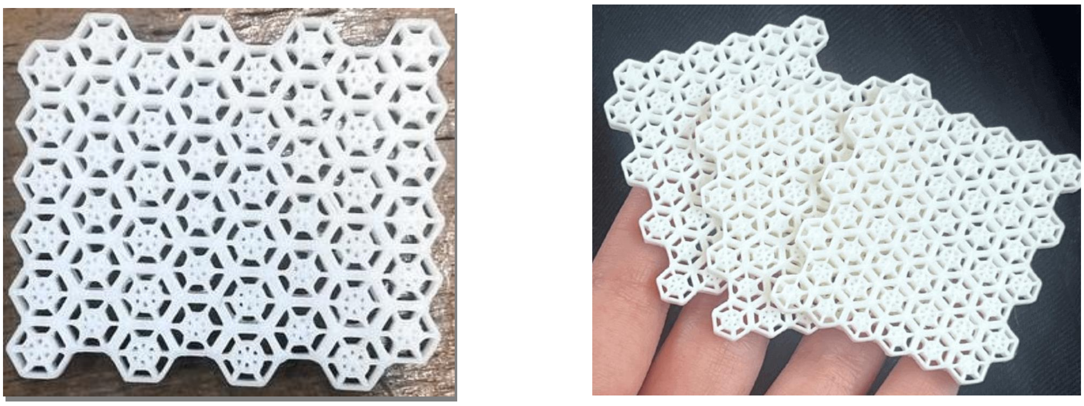

Figure 1. 3D-printed honeycomb lattice specimen made of ABS material using fused deposition modeling (FDM) technique. The structure features a regular hexagonal cell geometry designed for lightweight and energy-absorbing performance.

2.2 Drop-Weight Impact Test

Low-velocity impact tests were carried out using a custom-built drop-weight impact tower. The impactor consisted of a rigid steel cylinder with a hemispherical nose, weighing 1.0 kg and with a diameter of 100 mm. It was released from a height of 30 cm, corresponding to an initial kinetic energy of 2.94 J. The specimen was clamped on one side, with the opposite face exposed to free deformation. A high-speed data acquisition system recorded the contact force using a piezoelectric load cell mounted beneath the specimen holder. The impact process was also visually monitored using a high-frame-rate camera to capture the deformation sequence and rebound behavior.

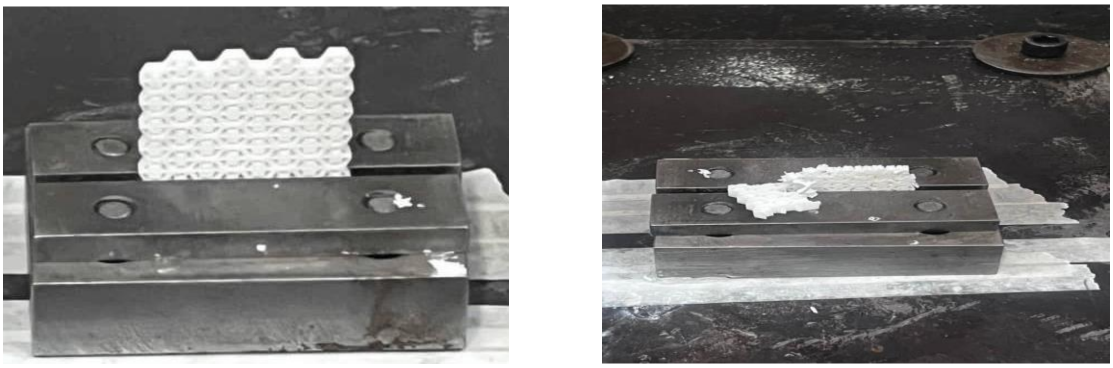

Figure 2. The honeycomb lattice specimen (left) before and (right) after the drop-weight impact test.

2.3 Quasi-Static Compression Test

To evaluate the compressive performance, a separate series of tests was conducted on a universal testing machine (Instron 3367) under displacement control at a rate of 2 mm/min. The specimens were placed between two steel platens, and the load was applied in the out-of-plane direction (z-axis). Force and displacement data were continuously recorded to derive stress–strain curves. The onset of densification and the maximum load-bearing capacity were extracted as performance indicators. Post-test observations focused on identifying buckling patterns, wall folding, and failure initiation sites.

Figure 3. Compression test machine and the honeycomb specimen under compressive loading

2.4 Measurement and Post-Processing

The residual indentation depth after impact was measured using a digital caliper with ±0.01 mm resolution. Fractographic inspection was performed using an optical microscope to document crack initiation, plastic folding, and wall ruptures. All experimental data were post-processed using MATLAB to extract force–displacement curves, energy absorption profiles, and stiffness parameters. Selected samples were retained for finite element validation.

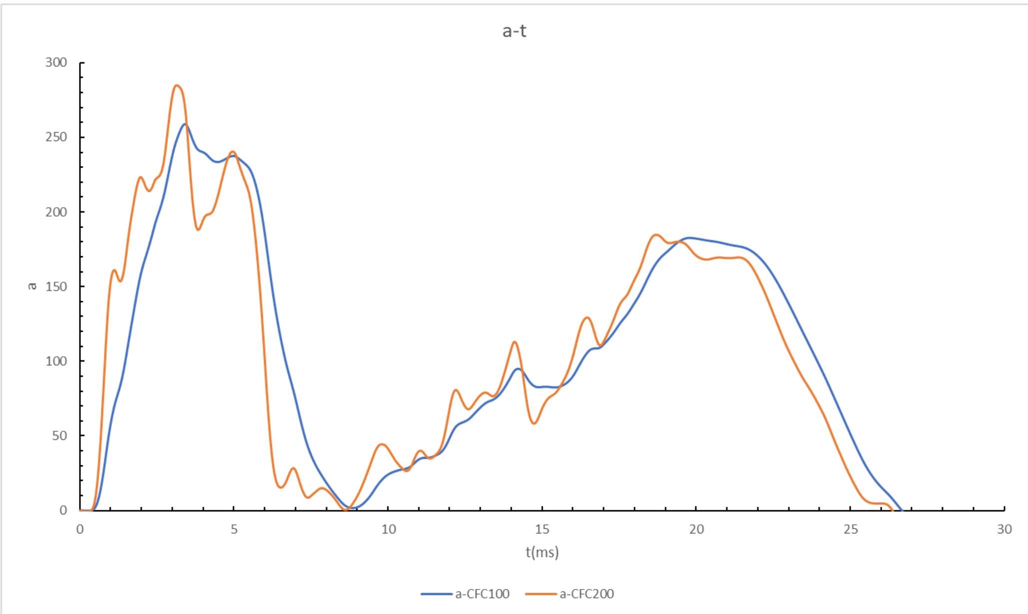

Figure 4. Acceleration–time graph (CFC100 and CFC200) for a drop-weight impact from 30 cm height.

3. Numerical Modeling

3.1 Finite Element Model Description

A finite element model was developed using ANSYS Workbench to simulate both the impact and compressive behavior of the 3D-printed honeycomb structures. The honeycomb geometry was modeled based on the same CAD design used for experimental fabrication, incorporating the actual cell size and wall thickness. The lattice was meshed using 3D 20-node hexahedral elements (Solid186) to capture the nonlinear deformation with high accuracy. Mesh refinement studies were performed to ensure convergence of the impact response, resulting in an average element size of 1.0 mm in the contact region.

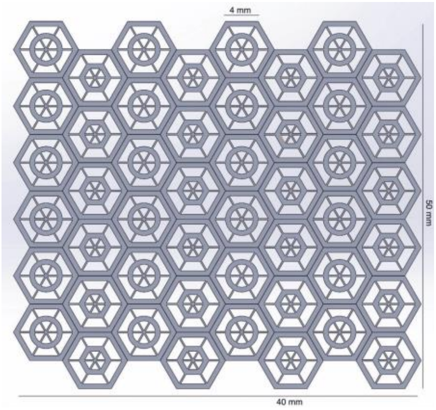

Figure 5. Geometry of the honeycomb specimen with detailed dimensions.

The impactor was modeled as a rigid body using a lumped mass element (Mass21) and coupled to a reference point with translational degrees of freedom. Contact interactions between the impactor and the top face of the honeycomb were defined using surface-to-surface contact pairs (Contact174 and Target170), with a penalty formulation and a friction coefficient of 0.3. For the compression simulations, the steel platens were modeled as rigid surfaces with similar contact definitions on the top and bottom faces of the structure.The ABS material was modeled as an isotropic elastoplastic material with bilinear hardening. The elastic modulus was set to 2.1 GPa, the yield strength to 45 MPa, and Poisson's ratio to 0.35, based on manufacturer datasheets and prior calibration. Plastic deformation was captured using a multilinear stress–strain curve fitted from separate tensile tests on printed specimens. Strain-rate dependency was neglected due to the quasi-static nature of the impact.

For the drop-weight simulation, an initial velocity of 2.43 m/s (corresponding to 30 cm drop height) was assigned to the impactor. The bottom face of the lattice was fully fixed in all degrees of freedom to replicate the experimental clamping. The analysis was conducted using the explicit dynamic solver with automatic time stepping. For the compression simulation, displacement was applied to the top platen while fixing the bottom, and a nonlinear static solver was used with large deformation effects enabled.

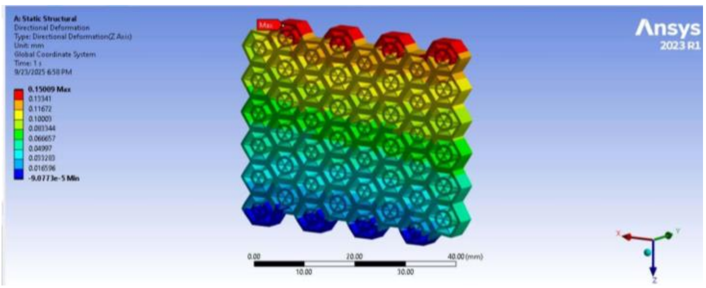

Figure 6. Finite element model of the honeycomb structure created in ANSYS software.

3.2 Output and Post-Processing

Key outputs included contact force, displacement, equivalent plastic strain, and energy dissipation. The residual indentation was measured from the final deformed shape. Energy absorption was computed by integrating the area under the force–displacement curve. Results were exported and analyzed using ANSYS and MATLAB to enable direct comparison with experimental data.

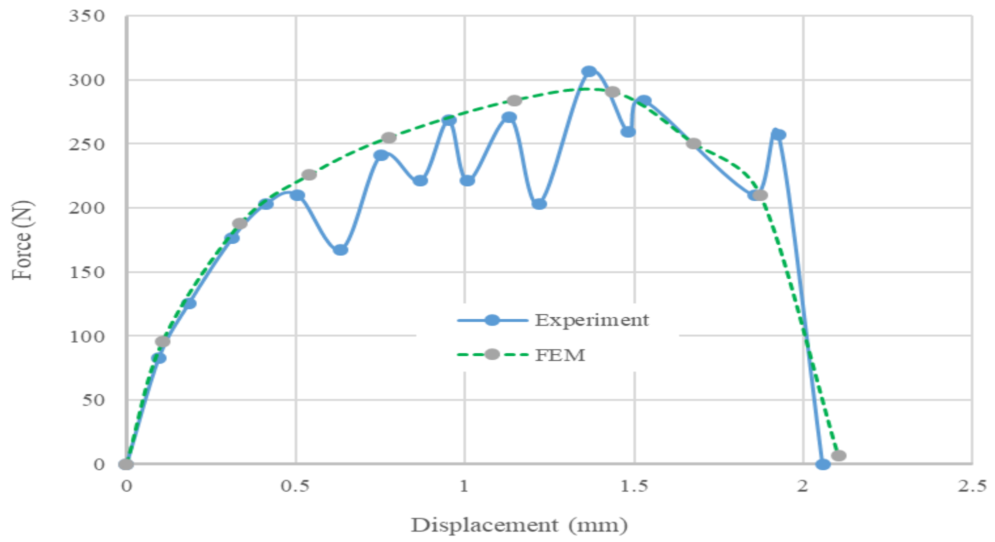

Figure 7. Force–displacement curve from experimental and FEM results

The comparison between experimental and numerical results demonstrates a good agreement in the mechanical response of the honeycomb structure under impact loading. The force–displacement curves from both the physical test and the FEM simulation follow a similar trend, showing a consistent rise to the peak load followed by a gradual drop, with minimal deviation in peak force magnitude and initial stiffness. This close correlation validates the accuracy of the finite element model developed in ANSYS, indicating that the material properties, boundary conditions, and contact definitions were appropriately defined. As such, the validated model can be reliably used for further parametric studies and predictive analysis under similar loading conditions.

4. Results and Discussion

Both experimental and numerical studies showed the mechanical behavior of 3D-printed ABS honeycomb lattice structures subject to low-velocity impact and quasi-static compression, to be consistent and interpretable. In the impact experiments, a hemispherical dent was produced in the top surface due to localized plastic deformation and wall buckling beneath the impactor. Measured force-displacement curves showed an initial linear section with a smooth peak and gradual unloading, with around 82% of the input kinetic energy absorbed into the structure. The finite element simulation reproduced this behavior with high fidelity, obtaining less than 5% error in peak force and indentation depth against experimental results. Plastic strain contours in the simulation highlighted zones of intense wall folding and crushing, particularly concentrated under the impactor contact region.

Under quasi-static compression, the stress–strain response of the samples followed a characteristic three-phase profile: linear elastic, plateau, and densification. The structure exhibited a compressive strength of approximately 3.9 MPa and significant energy absorption capacity up to large strains.

The deformation evolved through progressive in-plane wall folding and eventual densification of the cellular core. Numerical predictions matched well with the experimental curves, confirming the accuracy of the material modeling and boundary condition setup. Compared to the impact scenario, the compression loading led to more global deformation involving multiple cell rows, whereas the impact event resulted in a confined damage zone with minimal propagation.

The results of both loading conditions, when analyzed collectively, highlighted the inherent energy-dissipating capability in the lattice of honeycombs and consistency in failure mechanisms between dynamic and static regimes. The simulation outputs supported the experimental observations further, with validation of the predictive capability of the FE model. Moreover, small anisotropy and interlayer effects generated by the layer-by-layer nature of the FDM process led to variability in deformation localization and the initiation of failure. These findings emphasize the impact of parameters from additive manufacturing on structural performance and also point out the requirement to incorporate manufacturing-aware models in future studies.

Table 1. Experimental Data (Drop Test from 30 cm Height)

Displacement (ms)	Force CFC100 (N)	Force CFC200 (N)
0.00	0.00	0.00
0.42	-0.01	-0.02
1.25	-0.11	-0.21
2.50	-0.24	-0.45
4.16	-0.43	-0.82
6.25	-0.62	-1.25
8.33	-0.84	-1.71
10.41	-1.09	-2.22
12.50	-1.32	-2.74
18–20	1.9	3.2

Table 2. Comparison of Experimental and FEM Results (Drop Height: 30 cm)

Height (cm)	**Peak Force (Experiment) [N]**	**Peak Force (FEM) [N]**	**Displacement at Peak (mm)**	**Difference (%)**	**Observation**
30	≈ 3.2×10^3	≈ 3.6×10^3	≈ 8.5	≈ 12	FEM and experimental results show good agreement in the initial contact phase. FEM predicts a slightly stiffer response and a higher peak force. The post-peak softening in FEM is smoother, indicating lower energy absorption compared to the test.

In conclusion, this study delivers a thorough and multi-perspective evaluation of the mechanical performance of 3D-printed ABS honeycomb lattice structures under both low-velocity impact and quasi-static compression. The integration of well-controlled experimental tests with validated finite element simulations enabled a robust assessment of deformation modes, energy dissipation mechanisms, and structural integrity. The results demonstrated that the additively manufactured lattices exhibit stable and predictable failure behavior, characterized by localized plastic folding and progressive core crushing, while maintaining excellent energy absorption efficiency. Notably, the close agreement between the experimental and numerical results reinforces the fidelity of the modeling strategy and highlights the potential of polymer-based lattice structures as viable alternatives to traditional metallic and composite cores. Unlike conventional studies limited to single loading scenarios, the dual-loading methodology employed here provides a more comprehensive understanding of structural resilience under real-world service conditions. These insights contribute to advancing the design of lightweight, impact-tolerant architectures for next-generation aerospace, automotive, and protective systems. Future extensions of this work may focus on optimizing cell topology, accounting for strain-rate effects, and incorporating manufacturing-induced anisotropy to further enhance the predictive accuracy and functional performance of 3D-printed lattice materials.

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