

Topologically Biomimetic Multicellular Structures Inspired by Pine Nut Shells for Enhanced Energy Absorption

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Abstract: Energy-absorbing structures are critical to modern engineering systems, yet conventional designs often suffer from premature global instability and abrupt load-drop failures under axial compression. Here we report a high-performance bio-inspired topological grid structure designed by abstracting the spatial topological arrangement of pine nut shell sclereids, following a "characterization → biomimicry → simulation → experimentation" workflow. Scanning electron microscopy (SEM) revealed the layered microstructure of pine nut shells, showing the distribution and arrangement of regular and irregular polygonal stone cells. We introduce a Main Feature Structure (MFS) extraction algorithm that converts these biological cells into a set of designable multi-cell geometric configurations. Finite element simulations revealed that the optimized bioinspired topology (PNS-3) achieved a specific strength of 9.74 kg^{-1} (32.2% above the honeycomb control) and a specific stiffness of $35,771.69 \text{ MPa} \cdot \text{kg}^{-1} \cdot \text{mm}^{-1}$ (62.1% improvement). Subsequent quasi-static compression tests on 3D-printed specimens demonstrated that PNS-3 attained a mass-specific energy absorption of 0.787 J/g , a 5.62-fold enhancement over the classical honeycomb configuration. This superior performance arises from a characteristic multi-peak progressive deformation mode—enabled by the synergistic interaction of triangular and parallelogram units—which promotes sequential plastic hinge formation, continuous stress redistribution, and suppresses catastrophic global instability. By integrating structural bionics, computational mechanics, and additive manufacturing, this work establishes a systematic design framework for next-generation lightweight energy absorbers with promising applications in automotive crash protection and aerospace energy dissipation.

Keywords: pine nut shells; biomimetic design; multicellular structure; energy absorption; 3D printing; Structural topology

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1. Introduction

1.1 Background on Energy-Absorbing Structures

Energy-absorbing devices constitute a cornerstone of modern engineering practice, with applications spanning ground transportation, aerospace, and defense systems. In automotive passive safety, for example, such structures govern the dissipation of crash-induced kinetic energy, while in airframe design they are instrumental in mitigating external impact loads. Concurrently, the aerospace sector faces mounting demand for materials that reconcile low mass with superior energy dissipation. The global market for advanced aerospace composites reached USD 32.5 billion in 2022 and is projected to surpass USD 48 billion by 2027, reflecting a compound annual growth rate of 8.1%. Conventional solutions—principally metallic foams and honeycomb cores—are nevertheless constrained by intrinsic limitations, including inadequate specific energy absorption, pronounced plateau-stress fluctuations, and restricted geometric tunability. Multi-cell lattice structures have accordingly emerged as a compelling alternative, combining low density, exceptional mechanical performance, and high design freedom. However, under axial compression, these architectures frequently suffer from global instability, a failure mode that markedly degrades their energy absorption capacity and has, to date, impeded widespread deployment.

Nature, through billions of years of evolutionary refinement, offers a rich repository of structural archetypes capable of informing engineered design. Recent advances in biomimetics have demonstrated the pivotal role of biological gradients in enhancing structural performance, as exemplified by bamboo-segmented tubes and bone-trabecular scaffolds. The pine nut shell, a prototypical natural protective enclosure, must routinely withstand substantial external forces—whether from free-fall impact or predation—yet remains remarkably light and robust, an attribute attributable to its finely distributed cellular architecture and graded mechanical properties [1]. Most prior efforts, however, have remained narrowly focused, targeting either a single biological analogue or superficial geometric mimicry, without recourse to an integrated micro–macro–functional framework. Here, we translate the multi-cellular architecture of the pine nut shell into a set of designable engineering parameters and, through coupled finite-element simulation and additive manufacturing, systematically evaluate the energy-absorption performance of the resulting lattice structures. This approach circumvents the principal bottlenecks of conventional energy absorbers, enriches the theoretical foundation of bio-inspired structural design, and provides a

robust design platform for next-generation lightweight protective systems, with broad implications for safety-critical applications [2].

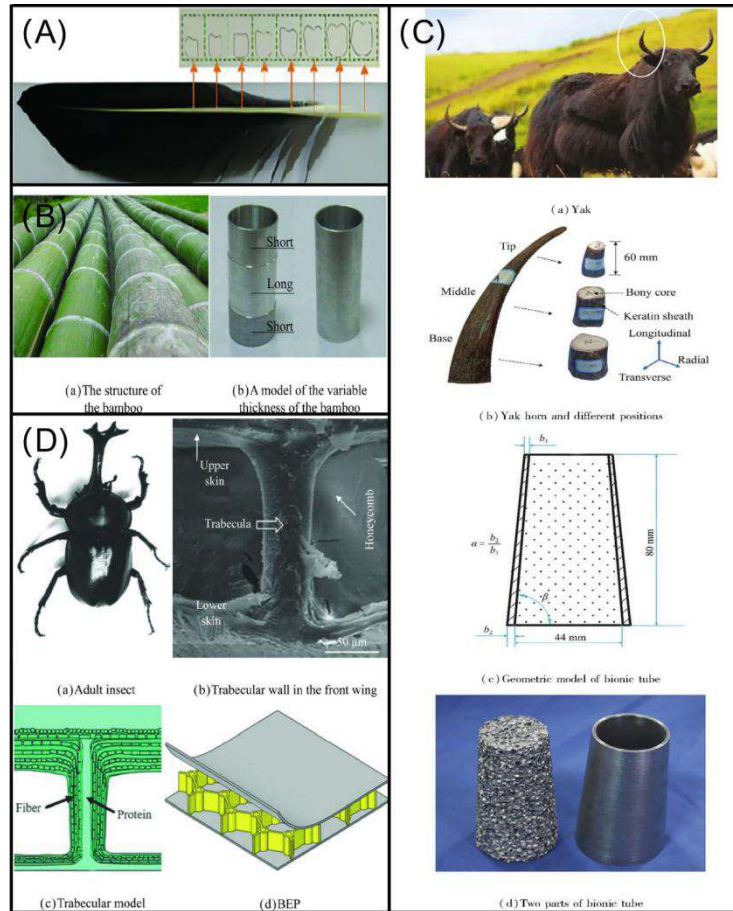
1.2 Current Status of Research on Bionic Energy-Absorbing Structures

The design philosophy underlying bio-inspired energy-absorbing structures stems from the systematic abstraction and engineering translation of efficient biological archetypes—an area that has advanced substantially over the past five years across materials science, mechanical engineering, and aerospace. Conventional energy absorbers, including thin-walled tubes, honeycombs, and foam fillers, remain widely deployed yet suffer from inadequate specific energy absorption, poorly controllable deformation modes, and excessive structural mass [3]. Biological materials, by contrast, achieve optimal function under strict material budgets and have accordingly emerged as a compelling route to overcoming these limitations. The field has evolved from rudimentary shape mimicry toward functional reproduction, with research focus shifting from static geometric replication to the mechanistic understanding and re-engineering of dynamic responses.

Among candidate biological templates, bamboo, bone, nacre, and arthropod cuticle have attracted particular attention because of their distinctive microstructures and superior mechanical performance. Bio-inspired tubular configurations draw on the cross-sectional and macroscopic morphology of bird feather shafts, bamboo culms, ostrich tarsometatarsi, and horsetail stems. Liu and colleagues [4] used micro-computed tomography to characterize the cross-section of a goose feather rachis and identified a serrated wing-tube architecture; combined experimental and numerical studies demonstrated that this bio-inspired configuration delivers markedly superior energy absorption relative to conventional designs. Bamboo-inspired tubular absorbers exploit hierarchical gradient fiber distribution and functionally graded wall thicknesses, with strategically positioned nodes that promote progressive, layer-wise crushing under axial loading and thereby suppress the initial peak stress that often triggers catastrophic failure. Song et al. [5] translated these biological principles into a variable-cross-section structure that simultaneously reduced mass and substantially improved impact resistance and structural stability compared with conventional circular tubes—an attractive design for tubular members and supports subject to demanding energy-absorption and vibration-mitigation requirements. Zhang and co-workers [6]

developed a class of bionic tubular members modeled on the geometry and construction of the ostrich tarsometatarsus; experimental validation confirmed combined benefits of low mass and high structural stiffness, identifying these constructs as promising candidates for protective equipment in endurance running, particularly marathon applications. Deng and colleagues [7] comparatively analyzed the axial-compression response of dual circular tubes and horsetail-inspired thin-walled tubes and showed that the latter exhibits superior specific energy absorption and compression efficiency, providing a theoretical basis and design pathway for elevating the load-bearing ceiling of pressure-resistant tubular components. Zhou et al. [8] investigated the structural characteristics of yak horns and derived the optimal energy-absorption parameters for bionic conical tubes, finding that peak performance is achieved at a cone angle α of 2° and a surface angle β of 82° . Tasdemirci and co-workers [9] drew inspiration from the barnacle to design an innovative balancing device and showed that the synergistic interaction between the core structure and its external cladding, together with the cladding-imposed confinement, drives a 5% increase in mean crush strength under quasi-static loading and a more pronounced 26% increase under dynamic strain conditions.

Bio-inspired plate architectures draw inspiration from a broad spectrum of natural templates, including the beetle exoskeleton, the mantis shrimp impact-absorption mechanism, the layered composite structure of nacre, and the energy-dispersing geometry of the woodpecker beak—each offering distinctive design solutions. Chen et al. [10] designed a bionic plate (BEP) based on the structural features of beetle elytra and benchmarked its compressive performance against honeycomb plates (HPs) of equivalent wall thickness. The BEP exhibited 18% higher specific strength and 112% higher volumetric energy absorption than the HPs. Inspired by the construction of the mantis shrimp dactyl club, Han and colleagues [11] developed a helical-fiber sinusoidal-structure laminate (HSL) and evaluated its low-velocity impact response against three reference systems: unidirectional-fiber flat laminate (UFL), unidirectional-fiber sinusoidal-structure laminate (USL), and helical-fiber flat laminate (HFL). The HSL consistently delivered higher peak impact force while simultaneously suppressing structural degradation—an outcome the authors attributed to its unique helical-sinusoidal geometry, which enhances fracture toughness and arrests crack propagation. These attributes position HSL as a strong candidate for components subject to

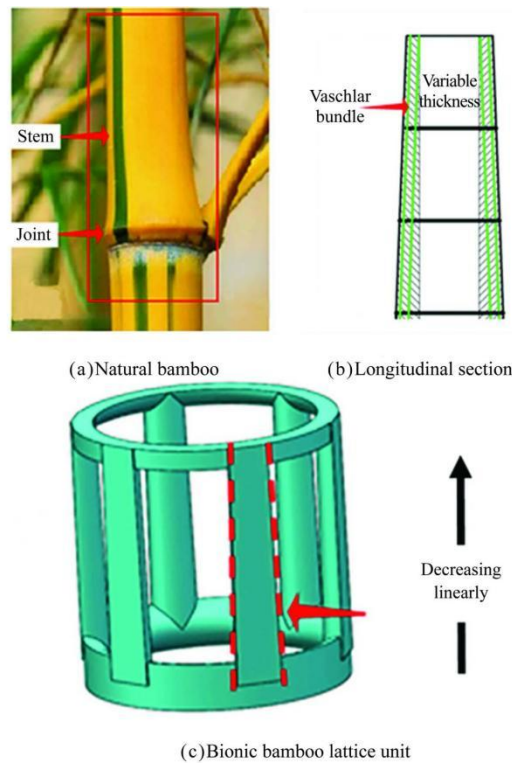


high-impact loading. Separately, the spirally arranged, sandwich-type architecture of beetle exoskeletons has been exploited to engineer lightweight, high-strength panels already finding application in unmanned aerial vehicle fuselages and protective armors.

Figure 1-1. Biomimetic structures inspired by various biological sources: (A) the "serrated" wing tube structure in the cross-section of a bean goose feather. Reproduced from [4], Copyright (2022), with permission from Springer Nature. (B) The structure and model of bamboo. Reproduced from [5], Copyright (2018), with permission from Elsevier. (C) The structure of a yak horn. Reproduced from [8], Copyright (2022), with permission from Taylor & Francis. (D) The structure of a beetle's elytra. Reproduced from [10], Copyright (2021), with permission from Wiley.

Bio-inspired lattice structures are principally derived from biological archetypes such as bamboo and the trabecular networks of marine sponges. Wen and co-workers [12] systematically evaluated the mechanical characteristics and energy-dissipation performance of multiple topological configurations, including cubic lattices, honeycomb arrangements, homogeneous lattices, and bamboo-inspired functionally graded lattices. Their experimental

data reveal that the novel bamboo-inspired and honeycomb architectures exhibit comparable mechanical performance, with both substantially outperforming the remaining topologies.



Figures 1-2 present schematic illustrations of the bionic bamboo configuration.

Figure 1-2. Schematic diagram of a biomimetic bamboo structure. Reproduced from [12] (Wen Z, Li M. *Materials*, 2021, 14(16): 4410), licensed under CC BY 4.0.

From a methodological standpoint, the principal-feature extraction approach provides a critical bridge between biological prototypes and engineering applications [13]. This method identifies the geometric elements and topological relationships that govern the functional behavior of a biological structure, discards non-essential features, and reduces the complex biological template to a parameterizable mathematical model. As an illustrative example, in the trabecular network of marine sponge, researchers have used computed tomography to acquire three-dimensional images, extracted the inter-strut connectivity and spatial distribution, and subsequently assembled parameterized lattice unit libraries—thereby completing the transition from biological observation to engineering implementation. Recent breakthroughs in additive manufacturing provide the technical foundation for the precise replication of bio-inspired structures. Processes such as selective laser melting (SLM) and fused deposition modeling (FDM) enable fabrication of highly complex gradient porous

architectures, circumventing the geometric constraints inherent to conventional manufacturing routes. Bio-inspired components produced via 3D printing achieve dimensional tolerances on the order of 0.1 mm while improving material utilization by more than 60% relative to traditional subtractive machining—together establishing the necessary conditions for the engineering deployment of complex bio-inspired structures. Current research focus is shifting toward multi-scale bio-inspired design, which integrates macroscopic topology optimization with microscopic material design to achieve bio-inspired solutions spanning material selection, microstructure, and overall geometry. This approach holds substantial promise for load-bearing structural components, including aero-engine blades and automotive B-pillars.

1.3 Unique Advantages of the Pine Nut Shell Structure

The pine nut shell is a protective enclosure evolved by Pinaceae to safeguard their seeds, exhibiting a multi-cellular, foam-like microstructure that progressively compresses under external loading. This graded architecture disperses stress and prolongs the energy-dissipation process. Recent scanning electron microscopy (SEM) studies have revealed that the shell is organized into three functionally distinct strata: a dense epidermal layer on the outside, a gradient transition zone in the middle, and a loose core layer toward the interior. The constituent cells range in size from approximately 10 to 50 μm , with cell-wall thickness decreasing proportionally toward the core. This stratified distribution endows the shell with an unusual combination of properties: high puncture resistance at the outer surface and substantial internal deformability that enables efficient impact energy absorption. Quantitative analyses indicate that the specific energy absorption (SEA) of the pine nut shell substantially exceeds that of conventional engineering foams, underscoring its potential as a biological blueprint for novel lightweight energy-absorbing structures.

Beyond its biological function, the pine nut shell represents a substantial forestry by-product. China's pine nut industry produced an estimated 150,000–200,000 tonnes annually between 2019 and 2023, generating an output value exceeding 10 billion RMB, of which pine nut shells constitute approximately 60–70 wt%. The shells exhibit a characteristic elliptical-to-ovoid geometry, typically 8–15 mm in length, 5–8 mm in width, and 0.8–1.2 mm in thickness. The external surface displays a dark brown to blackish-brown coloration with a

smooth, slightly lustrous finish—a feature attributed to gradients in internal chemical composition [14]. Morphologically, each shell tapers to a pointed apex at one end and a rounded base at the other, yielding a streamlined profile that mitigates stress concentrations. Cross-sectional examination reveals pronounced regional variation in wall thickness: the peripheral region measures 0.6–0.8 mm, while the central region reaches 1.0–1.2 mm. The inner surface, smooth and light brown, conforms tightly to the seed kernel and forms an effective protective barrier. The outer surface, in contrast, exhibits subtle textural features linked to the cellular differentiation patterns established during growth. Collectively, the macroscopic morphology of the pine nut shell exemplifies a product of natural selection, with geometric parameters and wall-thickness distribution providing a robust structural foundation for resisting external mechanical impact [15].

2. Materials and Methods

2.1 Microscopic Characterization of Pine Nut Shells (SEM)

The pine nut shells used in this study were obtained as a commercial byproduct from a local pine nut processing plant in Mudanjiang City, Heilongjiang Province, China. These pine nuts were sourced from cultivated/commercially produced pine trees, and the shells were collected after the edible kernels had been removed. No wild plant material was collected. The shells were cleaned, air-dried, and stored at room temperature before SEM characterization.

As shown in Figure 2-1, scanning electron microscopy (SEM) of the pine nut shell cross-section reveals an internal architecture composed of multiple tightly packed cellular layers, with cell morphology varying along a gradient from the outer to the inner surface. The shell is predominantly composed of sclereid (stone) cells that form a continuous sclerenchyma layer; these cells are polygonal in shape and tightly packed. In the outer region, sclereids are relatively small, with diameters of 15–30 μm and a regular hexagonal morphology. The cells are tightly apposed, although without obvious interlocking features. In the inner region, sclereid diameters increase markedly to 30–50 μm , adopting irregular polygonal shapes with substantially thickened cell walls. In contrast to the complex helical intercellular junctions observed in walnut shells and ginkgo seed coats, pine nut shell sclereids are connected relatively simply, relying primarily on direct cell-wall contact to establish mechanical coupling. Overall, the cellular arrangement exhibits a clear radial gradient, with more regular, tightly

packed cells in the outer region and more loosely arranged yet individually larger cells in the inner region . This gradient is both functionally significant and mechanically rational: the dense, high-strength tissue is positioned where external loading is most severe, while the weaker, more compliant tissue is located internally—a design principle that achieves an optimal balance between protection and energy dissipation.[16]

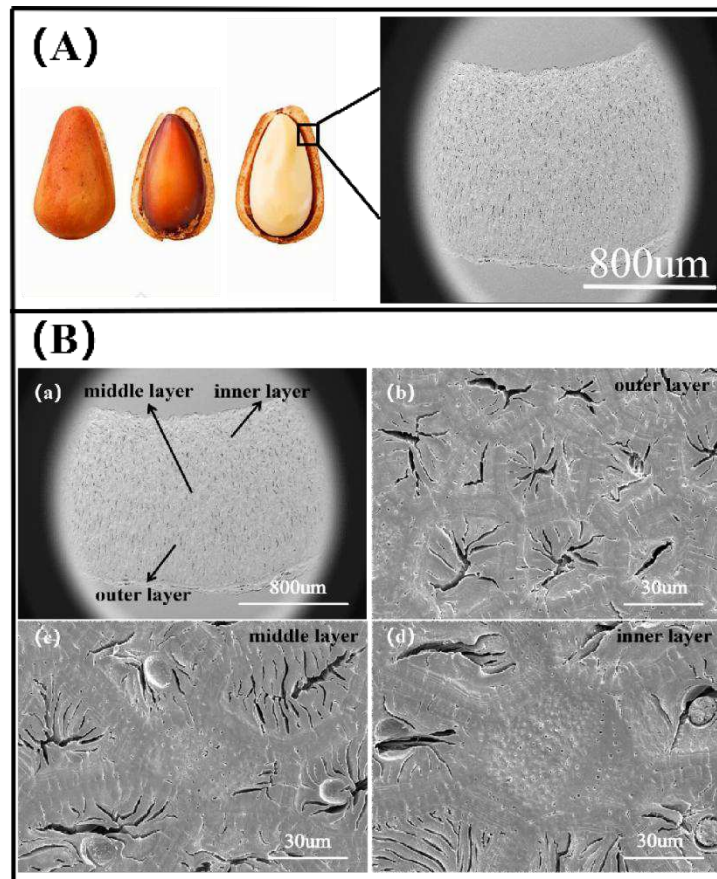


Figure 2-1 (A): Cross-sectional area of the pine nut shell used in this experiment (B): (a) Low-magnification SEM image of the overall cross-section of the shell; (b)–(d) SEM images of the outer, middle, and inner layers at the same magnification

2.2 Analysis and Extraction of Primary Feature Structures

SEM observations reveal that the cross-sectional microstructure of the pine nut shell is predominantly composed of close-packed hexagonal and irregular polygonal cells, exhibiting overall heterogeneity. On the basis of the principle of morphological equivalence and functional topology mapping theory, we extract the typical features of this cross-sectional

microstructure through fitting and regular-polygon approximation, as illustrated in Figure 2-2. This approach not only faithfully captures the geometric characteristics of the shell but also reduces the complex microstructure to tractable, designable elements that are amenable to analysis and modelling. The polygon-fitting procedure enables quantitative characterization of key morphological descriptors—including cell area, perimeter, and interior angles—thereby providing a robust dataset to support subsequent mechanical analysis and bio-inspired design. More broadly, this approximation framework facilitates the transfer of naturally optimized structural principles into engineered materials, informing both design philosophy and practical implementation.

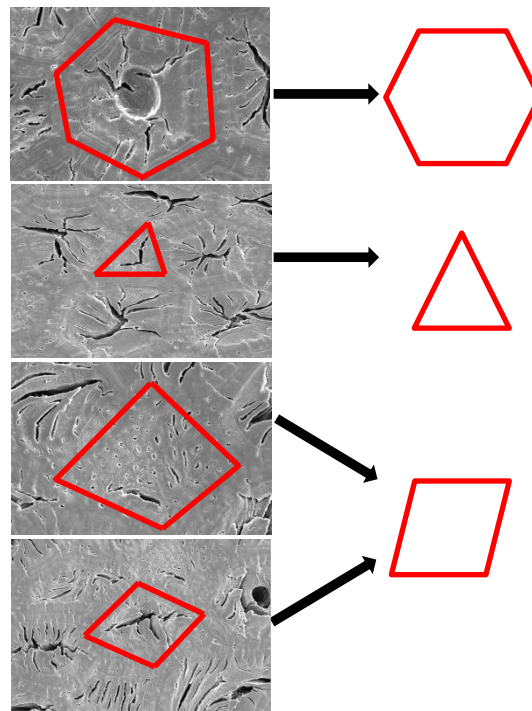


Figure 2-2: Extraction and Regularization of a Typical Contour

The native dimensions of pine nut shell sclereids lie in the micrometer range (single-cell diameter $\approx 10\text{--}50\text{ }\mu\text{m}$), and direct CAD reconstruction at this scale would yield models too small for reliable geometric drawing, meshing, simulation, and physical testing. To address this, we adopted a proportional scaling strategy in the modelling workflow, transferring the microstructure to the millimeter regime so as to ensure the feasibility of geometric modelling, finite element analysis, and experimental validation. Importantly, this scaling is not intended

to directly reproduce the absolute mechanical values of the native micrometer-scale structure; rather, it serves to extract and consolidate the spatial distribution patterns and geometric configurations that govern the internal microstructure. From the perspective of porous-media mechanics and continuum mechanics, the dominant deformation modes under compressive loading—whether bending-dominated or stretching-dominated—and the associated load-transfer mechanisms are governed primarily by dimensionless geometric features. Accordingly, scaling the microstructural features to the millimeter regime and benchmarking them against conventional porous structures (e.g., honeycombs) using an identical matrix material (polylactic acid, PLA) effectively decouples material and absolute size effects, enabling an isolated investigation of the intrinsic mechanical merits of the bio-inspired topology.

SEM observations indicate that hexagonal cells dominate the pine nut shell microstructure, with a secondary population of irregular polygonal cells. Accordingly, in the modelling process the regular hexagonal cells were represented as regular hexagonal prisms, the irregular polygonal cells were uniformly abstracted as parallelogram-based prisms, and the transitional cells located at packing junctions were represented as triangular prisms. The abstraction translates the native sclereids into hexahedral units, with a linear scaling factor of approximately $500\times$ converting the micro-scale to the macro-scale. Given the original cell-diameter range of 10–50 μm , the scaled equivalent falls within 5–20 mm. Adopting this mapping, the edge length of the regular hexahedron was set to $5\sqrt{3}$ mm, yielding a body diagonal of approximately 17.3 mm; the unit height was set to 15 mm, ensuring that the overall dimensions fall within the scaled diameter range. For the irregular cells, the cross-section was simplified to a parallelogram-based prism with an edge length of $5\sqrt{3}$ mm and a height equal to half that of the regular hexahedron, namely 7.5 mm. For the transitional cells, triangular prisms with a length of $5\sqrt{3}$ mm were employed.

In the initial geometric modelling stage, the sclereids were abstracted as solid polyhedra and subjected to stacking combinations. However, the solid model failed to capture the low-density, high-strength characteristics of the natural structure, prompting a progressive refinement: first, the solid units were converted into hollow forms, more closely

approximating the hollow nature of the cell walls; subsequently, perforations were introduced into the unit walls to achieve further weight reduction while preserving the load-bearing skeleton, thereby obtaining high stiffness and strength with reduced material. Integrating the SEM observations, the non-uniform polygonal mesh boundaries, and lightweight design requirements, we introduced a geometric abstraction method and ultimately established a set of lightweight bio-inspired porous units composed of hexagonal, parallelogram, and triangular elements—designated Unit 1, Unit 2, and Unit 3, respectively. The detailed construction procedure and dimensions are illustrated in Figure 2-3.

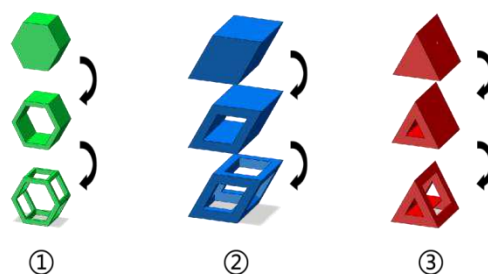


Figure 2-3: Flowchart of the Bionic Unit Construction Process

2.3 Design and Preparation of Biomimetic Nut Shell Structures

The two principal cell types in the pine nut shell exhibit non-trivial differences in geometric scale, spatial orientation, and boundary morphology; their direct juxtaposition typically produces abrupt transitions and heterogeneous interfaces. To address this, we introduced a triangular-prism transition element, designated Unit 3 (highlighted in red in the schematic), into the junction region between the two unit types. This transitional element serves a dual function: on the one hand, it provides geometric continuity, enabling smooth bridging between the polygonal walls of adjacent sclereids; on the other, it enlarges the contact area and establishes mutual support pathways, thereby enhancing the overall continuity and stability of the assembly. This design strategy refines the combination logic of the bio-inspired units, yielding a structure that is more amenable to stacking while better replicating the gradual transitions observed between adjacent cells in the natural shell. Using a layered and zoned design philosophy, we constructed a series of lightweight bio-inspired porous layered structures:

(1) PNS-1:(control, honeycomb architecture): formed by periodic self-assembly of Unit 1.

(2) PNS-2: reproduces the close-packed cell distribution through alternating arrangement of Unit 1 and Unit 3.

(3) PNS-3: adopts a staggered arrangement of Unit 2 and Unit 3, intuitively reflecting the multi-cell packing motif.

(4) PNS-4: maintains the same upper-layer layout as PNS-2 while continuing the PNS-3 layout in the lower layer, enabling further investigation of the effect of structural complexity on mechanical performance.

All four specimens (PNS-1/2/3/4) were designed with essentially identical external dimensions; the mass differences between them arise solely from variations in internal unit configuration and distribution. This design ensures that the four configurations can be evaluated on a common basis through mass-normalized comparison [17]. Figure 2-4 illustrates the configuration of the honeycomb reference structure together with the bio-inspired shell structures. The four configurations were designed with nearly identical external dimensions (Table 2-1), and their porosities fall within a narrow range of 74.33% – 78.90%. This deliberate design ensures that any significant differences in mechanical performance can be attributed primarily to the topological variations among the configurations, rather than to porosity discrepancies. The small porosity variation (within 4.57 percentage points) is considered negligible compared with the substantial topological effects, as further evidenced by the simulation and experimental results presented in Sections 3 and 4.

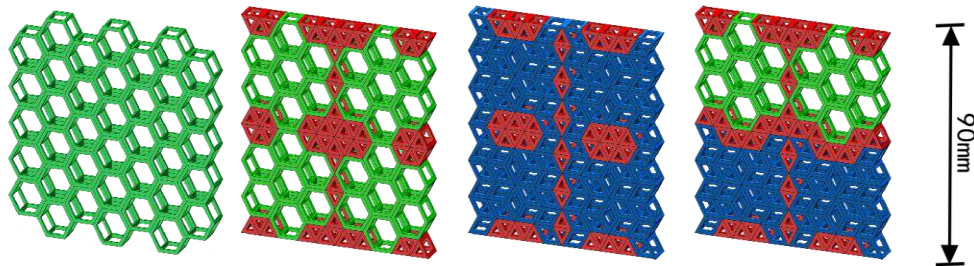


Figure 2-4: Schematic Diagram of a Biomimetic Fruit Shell Configuration

Table 2-1: Dimensional Parameters of Bionic Structures

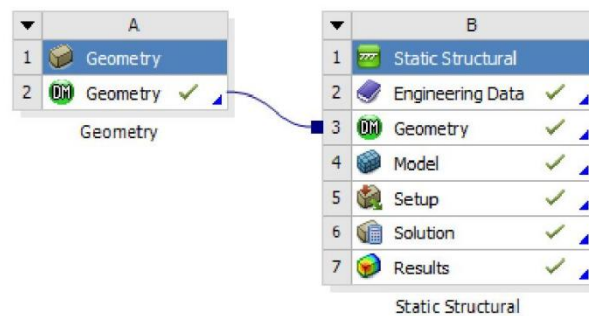
Parameters Name	L (mm)	W (mm)	H (mm)	T (mm)	Apparent Volume (mm ³)	Actual Volume (mm ³)	Porosity (%)
PNS-1	90	87.44	30	2	236088	49805	78.90
PNS-2	90	86.6	30	1.5	233820	50612	78.35
PNS-3	90	86.6	30	1.5	233820	60019	74.33
PNS-4	90	86.6	30	1.5	233820	55315	76.34

3. Finite Element Simulation Analysis

The finite element method (FEM) is a central tool in modern engineering mechanics, providing numerical simulation of the mechanical response of complex structures through discretization-based modelling. The method rests on the principle of continuum discretization, which decomposes the overall geometry into a finite number of elements and nodes and solves the resulting stiffness matrices and equilibrium equations to obtain the displacement and stress fields. In the present study, all simulations were performed on the Ansys Workbench 2024 R1 platform to systematically evaluate the lightweight design, multi-state collaborative load-bearing behaviour, and energy-absorption characteristics of the bio-inspired pine nut shell porous structures. Material anisotropy parameters were calibrated prior to simulation to enhance the fidelity of the bio-inspired modelling.

3.1 Preprocessing for Statics Analysis

Static structural analyses of the bio-inspired pine nut shell configurations were performed using Ansys Workbench 2024 R1. Figure 3-1 shows the Static Structural module

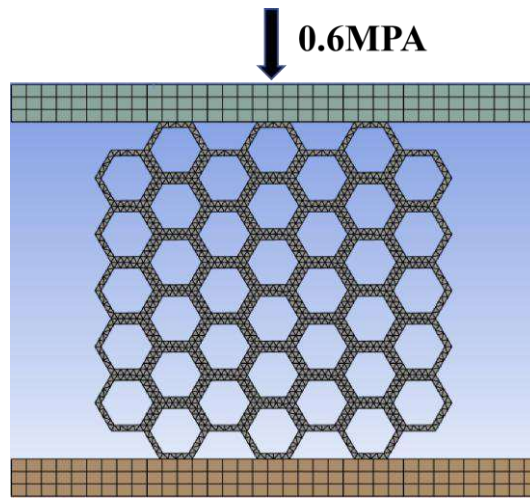


used for the simulations. Polylactic acid (PLA) was adopted as the matrix material, with the relevant mechanical parameters—density, Young's modulus, Poisson's ratio, and yield strength—defined in the Engineering Data module; the specific values are summarized in Table 3-1.

Figure 3-1: StaticStructural Module Simulation of Static Analysis

Table 3-1 Simulation Parameters for PLA Materials

Material	PLA
Density (g/cm ³)	1.24
Poisson's Ratio	0.38
Young's Modulus (MPa)	3000
Bulk Modulus (MPa)	4166
Shear Modulus (MPa)	1087
Yield Strength (MPa)	62

**Figure 3-2: Schematic Diagram of Load Configuration**

The bio-inspired porous structures were designed with periodic topology, and the finite element models were generated following structured meshing criteria. Second-order tetrahedral elements were used for spatial discretization, with a global characteristic element size of 2 mm. The loading configuration is illustrated in Figure 3-2: the bottom face was fully constrained ($u_x = u_y = u_z = 0$), while the top face was subjected to a uniformly distributed normal pressure of 0.6 MPa. It should be noted that the 0.6 MPa static analysis presented herein serves solely as a standardized reference load for comparative assessment of elastic stiffness and initial stress distributions, and is not intended to represent the actual failure load of any configuration. Energy absorption characteristics are evaluated exclusively through the experimental results reported in Section 4. Table 3-2 summarizes the resulting numbers of nodes and elements for the four PNS configurations after meshing.

Table 3-2: Number of Structural Nodes and Elements

Simulation Model	Number of Nodes	Number of Elements
PNS-1	229703	109967
PNS-2	136302	65834
PNS-3	185762	90834
PNS-4	160911	78190

3.1.1 Methods for Evaluating Structural Lightweighting

A cardinal principle in the evolution of biological structures is the ability to sustain greater loading with less material. Structural strength and stiffness are key parameters for quantifying the lightweight performance of a structural component, and their assessment requires the use of well-defined metrics. To this end, we introduce two indices—specific strength and specific stiffness—defined mathematically by equations (3-1) and (3-2), respectively [20]

$$S_{\delta} = \eta_V \frac{\sigma_s}{\rho \sigma_{max}} = \frac{\sigma_s (V_0 - V_s)}{\rho \sigma_{max} V_s} \quad (3-1)$$

$$S_E = \eta_V \frac{E}{\rho D_{max}} = \frac{E (V_0 - V_s)}{\rho D_{max} V_s} \quad (3-2)$$

In the equation:

S_{δ} —— specific strength/kg⁻¹;

S_E —— specific stiffness/MPa·kg⁻¹·mm⁻¹;

η_V —— actual volume fraction/%;

V_s —— true volume/mm³;

V_0 —— apparent volume /mm³;

σ_s —— yield strength/Mpa;

E —— modulus of elasticity/Mpa;

σ_{max} —— Maximum Stress/Mpa;

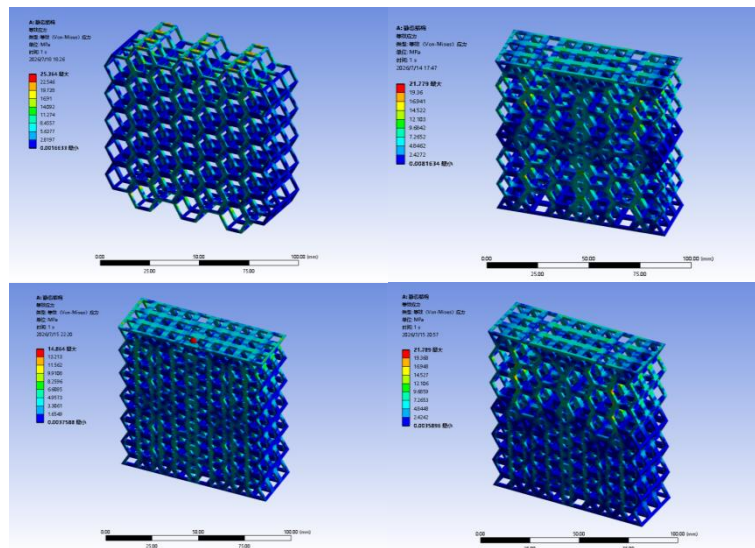
D_{max} —— Maximum Deformation/mm;

ρ —— material density/kg·m⁻³。

In the expressions of Equations (3-1) through (3-2), if the structural system and material parameters are fixed, physical quantities such as the elastic modulus E , material density ρ , and material yield strength σ_s all appear as constant values. In this case, σ_{max} and V_s act as independent variables in the equations. As the structural strength efficiency S_δ increases, σ_{max} and V_s may decrease simultaneously, or one of them may show a downward trend, indicating an inherent tendency for their product, $M = \rho V_s$, to decrease. An increase in structural strength efficiency S_E causes the value of M to decrease; during this process, the two parameters D_{max} and V_s may decrease simultaneously, or only one of them may decrease. Based on the preceding argument, improvements in structural stiffness and strength are often accompanied by a reduction in structural mass, or they may lead to a more stable and rigid structure; together, these two factors reveal the outstanding results of structural lightweight optimization. An increase in the material's specific strength directly reflects the extent to which mass can be reduced while maintaining equivalent strength performance under compressive loads; meanwhile, the structural specific stiffness has a decisive influence on the maintenance of a component's shape and geometric accuracy at the critical point between plastic and elastic deformation.

3.1.2 Evaluation of Structural Specific Strength

This study evaluated the specific strength index S_δ of four groups of biomimetic pine nut



shell structures; this index quantifies a structure's load-bearing capacity per unit mass. The value of specific strength directly reflects the material efficiency required for a structure to achieve a specific strength level under compressive loads; a higher value indicates a more optimized lightweight design. Through numerical simulations of the static response of the four structural models described above, equivalent stress distribution maps for various components were obtained, as shown in Figure 3-3.

Figure 3-3: Structural Equivalent Stress Contour Plot

Using Equation (3-1), the specific strength values for the four structures can be derived, and using Equation (3-2), the specific stiffness results for the four structures can be obtained. Figure 3-4 shows a comparison of the specific strength S_δ and specific stiffness S_E for the four sets of structures. The left vertical axis (diagonal bars) represents the specific strength S_δ of the structures, while the right vertical axis (upright grid) represents the specific stiffness S_E . The broken lines represent the mass of the four sets of structures, and the horizontal axis lists the names of the four sets of structures. Table 3-3 summarizes the detailed results of the static simulation of the biomimetic structures.

Table 3-3: Data from the Statics Simulation of Biomimetic Structures

Properties Name	σ_{max} (Mpa)	D_{max} (mm)	M (kg)	S_δ (kg ⁻¹)	S_E (MPa·kg ⁻¹ ·mm ⁻¹)
PNS-1	25.364	0.41013	6.0023e-002	7.37	22063.70
PNS-2	21.779	0.34409	6.0996e-002	8.31	25451.80
PNS-3	14.864	0.19585	7.2333e-002	9.74	35771.69
PNS-4	21.789	0.29971	6.6663e-002	7.41	26049.88

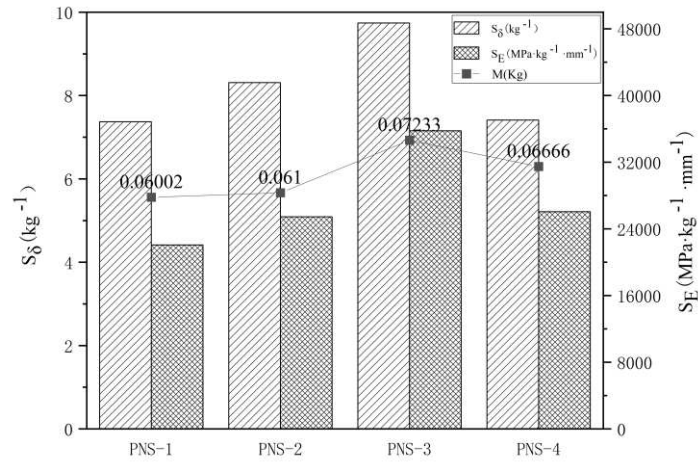


Figure 3-4: Comparison of Specific Strength and Specific Stiffness of Biomimetic Structures

Systematic comparison of the simulation data presented in Figures 3-3 and 3-4 and Table 3-3 yields the following key findings.

(1) Specific strength ranking. Among the four configurations, PNS-3 exhibits the highest specific strength at 9.74 kg^{-1} , followed by PNS-2 at 8.31 kg^{-1} , PNS-4 at 7.41 kg^{-1} , and PNS-1 at 7.37 kg^{-1} (the lowest). This ranking indicates that the staggered parallelogram–triangular arrangement (PNS-3) offers the most efficient material utilization under the 0.6 MPa static loading condition, while the conventional honeycomb (PNS-1) exhibits the lowest strength efficiency among the four topologies.

(2) Improvement over the honeycomb control. Compared with the control PNS-1, PNS-3 delivers a 32.2% enhancement in specific strength (9.74 vs 7.37 kg^{-1}), while PNS-2 delivers a 12.8% improvement (8.31 vs 7.37 kg^{-1}), and PNS-4 shows a marginal 0.5% improvement. The substantial enhancement achieved by PNS-3 confirms that the staggered parallelogram–triangular topology effectively improves strength efficiency by introducing diversified load paths that reduce localized stress concentrations. The relatively modest gains reflect the fact that all four configurations inherit the polygonal topological motifs of pine nut shell sclereids, such that the load transfer paths are already near a local optimum. Nevertheless, both PNS-2 and PNS-3 outperform the conventional honeycomb, confirming that the heterogeneous polygon arrangement of pine nut shell cells effectively enhances structural strength efficiency.

(3) Maximum stress and load transfer path. The maximum stress in PNS-3 is the lowest at 14.864 MPa, compared with 21.779 MPa in PNS-2, 21.789 MPa in PNS-4, and 25.364 MPa in PNS-1. PNS-3 achieves both the lowest peak stress and the highest specific strength, indicating that the staggered parallelogram–triangular arrangement provides the most uniform stress distribution and most efficient load transfer among the four configurations. By contrast, PNS-1 exhibits the highest maximum stress (25.364 MPa) and the lowest specific strength (7.37 kg^{-1}), highlighting the limitations of the conventional honeycomb architecture in stress dispersion and material utilization.

(4) Effect of layer-wise configuration mismatch. PNS-4 (upper layer: PNS-2 layout; lower layer: PNS-3 layout) achieves a specific strength of 7.41 kg^{-1} , which is marginally higher than PNS-1 (7.37 kg^{-1}) by only 0.5%, and substantially lower than PNS-2 (8.31 kg^{-1} , +12.8%) and PNS-3 (9.74 kg^{-1} , +32.2%). Despite adopting the most complex topology among the four configurations, PNS-4 fails to translate its structural complexity into superior strength efficiency. The performance deterioration arises from the geometric discontinuity and abrupt load-path redirection at the inter-layer interface, where the upper PNS-2-type layer and lower PNS-3-type layer are directly joined without a smooth transitional zone. This interfacial mismatch induces local stress concentrations and weakens the collaborative load-bearing capacity between adjacent layers. This observation reveals a critical design principle: in bio-inspired multi-cell structures, higher topological complexity does not necessarily translate into higher strength efficiency. The compatibility between adjacent layer configurations and the smoothness of the transitional interface are equally essential for effective load-bearing; naïve stacking of heterogeneous configurations can in fact degrade performance through interfacial effects.

Summary, Across the four configurations, PNS-3 achieves the highest specific strength (9.74 kg^{-1}) and the best strength efficiency, followed by PNS-2 (8.31 kg^{-1}), PNS-4 (7.41 kg^{-1}), and PNS-1 (7.37 kg^{-1}). PNS-1, the conventional honeycomb, exhibits both the lowest specific strength and the highest maximum stress (25.364 MPa), confirming its inferior material utilization efficiency. PNS-4 suffers from inter-layer configuration mismatch, resulting in moderate strength efficiency despite its topological complexity. Collectively, these results demonstrate that the staggered parallelogram–triangular topology (PNS-3) offers

the most effective improvement in strength efficiency among the bio-inspired designs, validating the engineering value of heterogeneous polygonal arrangements derived from pine nut shell sclereids for lightweight structural design.

3.1.3 Evaluation of Structural Stiffness

We next evaluated the specific stiffness of the four bio-inspired pine nut shell configurations. Specific stiffness characterizes a structure's resistance to elastic deformation under external loading: higher values indicate that the structure retains its geometric integrity more effectively in the elastic regime—a property critical for components subject to tight dimensional tolerances. Quasi-static finite element analysis yielded the total deformation contour plots for all four configurations in Figure 3-5.

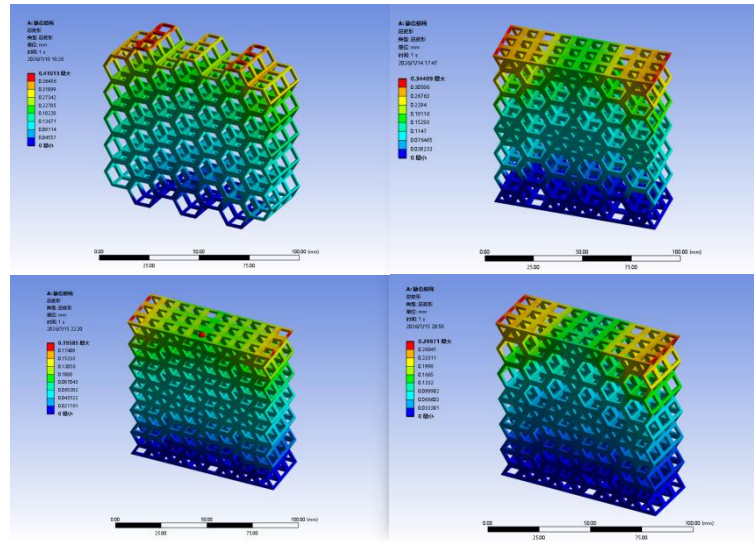


Figure 3-5: Contour plot of total structural deformation

under this specific reference load, Systematic comparison of the data presented in Figures 3-4 and 3-5 yields the following key findings.

(1) Specific stiffness ranking. Among the four configurations, PNS-3 exhibits the highest specific stiffness at $35,771.69 \text{ MPa} \cdot \text{kg}^{-1} \cdot \text{mm}^{-1}$, followed by PNS-4 at $26,049.88 \text{ MPa} \cdot \text{kg}^{-1} \cdot \text{mm}^{-1}$, PNS-2 at $25,451.80 \text{ MPa} \cdot \text{kg}^{-1} \cdot \text{mm}^{-1}$, and PNS-1 at $22,063.70 \text{ MPa} \cdot \text{kg}^{-1} \cdot \text{mm}^{-1}$ (the lowest). At equal mass, PNS-3 displays the smallest elastic deformation under load, indicating the most effective resistance to elastic deformation among all four topologies.

(2)Improvement over the honeycomb control. Compared with the control PNS-1 (22,063.70 MPa·kg⁻¹·mm⁻¹), PNS-3 delivers a 62.1% enhancement in specific stiffness (35,771.69 MPa·kg⁻¹·mm⁻¹), PNS-4 delivers an 18.1% improvement (26,049.88 MPa·kg⁻¹·mm⁻¹), and PNS-2 delivers a 15.4% improvement (25,451.80 MPa·kg⁻¹·mm⁻¹). This result confirms that bio-inspired structures with staggered parallelogram–triangular elements (PNS-3) most effectively utilize material to achieve higher structural stability. The substantial improvement arises from the oblique load paths introduced by parallelogram elements, which convert vertical loading into axial forces along inclined members, thereby substantially enhancing the elastic stiffness of the structure.

(3) PNS-2 vs PNS-3: vertical versus diagonal load transfer. The specific stiffness of PNS-2 (25,451.80 MPa·kg⁻¹·mm⁻¹) is lower than that of PNS-3 (35,771.69 MPa·kg⁻¹·mm⁻¹) and also slightly lower than PNS-4 (26,049.88 MPa·kg⁻¹·mm⁻¹), but remains substantially higher than PNS-1 (22,063.70 MPa·kg⁻¹·mm⁻¹). The PNS-2 configuration combines hexagonal and triangular elements in alternating arrangement; its load transfer path is predominantly vertical, and lateral constraint is correspondingly weaker, leading to greater deformation under identical loading compared with PNS-3. This contrast indicates that the introduction of parallelogram elements—present in both PNS-3 and PNS-4—provides a more diversified load transfer network and superior diagonal bracing mechanism, thereby enhancing the overall deformation resistance of the structure. The slightly higher stiffness of PNS-4 over PNS-2 suggests that the layer-wise configuration in PNS-4, despite its interfacial mismatch, still benefits from the diagonal load paths introduced by the parallelogram elements in its lower layer.

(4) Effect of layer-wise configuration mismatch on stiffness. PNS-4 achieves a specific stiffness of 26,049.88 MPa·kg⁻¹·mm⁻¹, which is higher than PNS-2 (25,451.80) and PNS-1 (22,063.70), but substantially lower than PNS-3 (35,771.69). This ranking indicates that the introduction of parallelogram elements in PNS-4's lower layer provides beneficial diagonal load paths that improve stiffness relative to the all-hexagonal PNS-1 and the hexagonal–triangular PNS-2. However, compared with the fully staggered PNS-3 configuration, PNS-4 still underperforms by 27.2% (35,771.69 vs 26,049.88). The performance gap between PNS-4 and PNS-3 is attributed to the geometric discontinuity at the inter-layer interface, where the

upper PNS-2-type layer and lower PNS-3-type layer are directly joined. This abrupt configuration change causes load transfer paths to be redirected and refracted at the interface, weakening the overall stiffness response under vertical loading. This finding reinforces a central design principle: in bio-inspired multi-cell structures, the matching of adjacent layer configurations and the continuity of the transitional interface are decisive for structural stiffness, and naïve stacking of heterogeneous configurations can in fact degrade deformation resistance through interfacial effects—even though individual layers may individually offer high stiffness contributions.

(5) Mass–deformation trade-off. Examination of the mass and maximum deformation data in Table 3-3 reveals that PNS-3, despite having the highest mass (7.2333×10^{-2} kg), exhibits the smallest maximum total deformation (0.19585 mm), indicating that the material distribution achieves the most favorable elastic response. By contrast, PNS-1, with the lowest mass (6.0023×10^{-2} kg), exhibits the largest maximum deformation (0.41013 mm) and the lowest specific stiffness ($22,063.70 \text{ MPa} \cdot \text{kg}^{-1} \cdot \text{mm}^{-1}$), further confirming the limitations of the conventional honeycomb architecture in resisting elastic deformation. PNS-2 (0.34409 mm) and PNS-4 (0.29971 mm) fall between the two extremes, with PNS-4 showing better deformation resistance than PNS-2 due to its more constrained layer-wise configuration, despite its inter-layer interface mismatch.

Summary. Across the four configurations, PNS-3 achieves the highest specific stiffness ($35,771.69 \text{ MPa} \cdot \text{kg}^{-1} \cdot \text{mm}^{-1}$) and the best deformation resistance ($D_{\max} = 0.19585 \text{ mm}$), followed by PNS-4 ($26,049.88 \text{ MPa} \cdot \text{kg}^{-1} \cdot \text{mm}^{-1}$), PNS-2 ($25,451.80 \text{ MPa} \cdot \text{kg}^{-1} \cdot \text{mm}^{-1}$), and PNS-1 ($22,063.70 \text{ MPa} \cdot \text{kg}^{-1} \cdot \text{mm}^{-1}$, the lowest). The conventional honeycomb PNS-1 exhibits both the lowest stiffness and the largest elastic deformation ($D_{\max} = 0.41013 \text{ mm}$), confirming its inferior resistance to elastic deformation. PNS-4, despite its inter-layer mismatch, benefits from the diagonal load paths introduced by the parallelogram elements in its lower layer, achieving higher stiffness than PNS-2. However, the interfacial discontinuity between the upper and lower layers prevents PNS-4 from reaching the stiffness level of the fully staggered PNS-3 configuration. Collectively, these results demonstrate that bio-inspired multi-cell structures based on the heterogeneous polygon arrangement of pine nut shell sclereids—particularly the PNS-3 configuration with its staggered parallelogram and triangular

elements—achieve effective improvements in deformation resistance by introducing diversified load transfer paths and superior diagonal bracing, providing a useful reference for engineering lightweight structural design.

3.2 Analysis of Simulation Compression Experiments

In the compression simulations, all four configurations were discretized using tetrahedral elements with a uniform edge length of 2 mm. A displacement-controlled loading scheme was adopted, in which a downward displacement of 10 mm was prescribed on the top face of each model while the bottom face was fully fixed. This loading configuration mirrors the quasi-static compression experiments and provides a consistent basis for extracting the stress and deformation fields used in the calculation of specific strength and specific stiffness. To investigate the deformation mechanisms of the bio-inspired pine nut shell structures under compression, the loading was applied as a displacement ramp with a constant downward velocity of 0.5 mm s^{-1} . The time-stepping configuration used in the Static Structural module is illustrated in Figure 3-6.

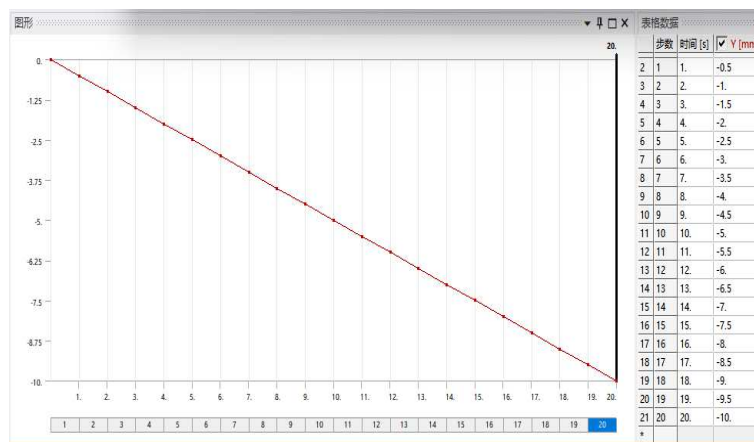


Figure 3-6: Load Step Settings

Through systematic comparison of the equivalent stress and equivalent strain fields obtained from the finite element compression simulations, we evaluated the load-bearing performance of the four configurations. The stress field distributions each configuration are presented in Figure 3-7.

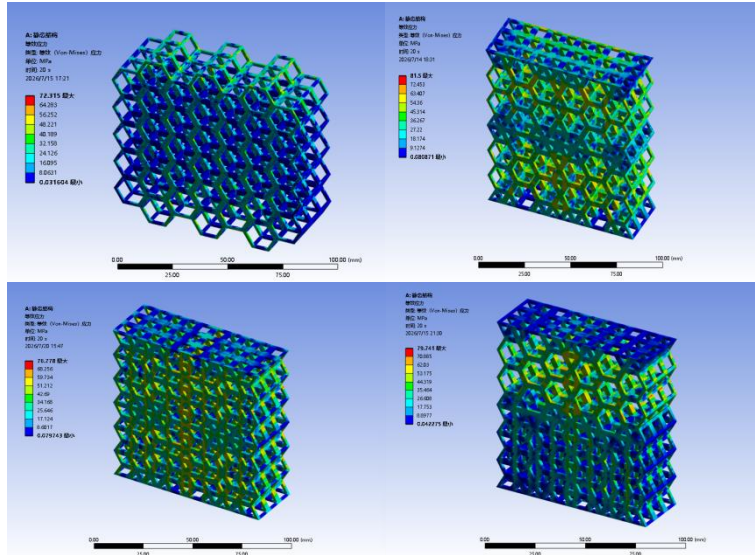


Figure 3-7: Structural Equivalent Stress Contour Plot

The equivalent stress and strain fields during the simulated compression process are illustrated in Figure 3-8, with the underlying numerical data summarized in Table 3-4.

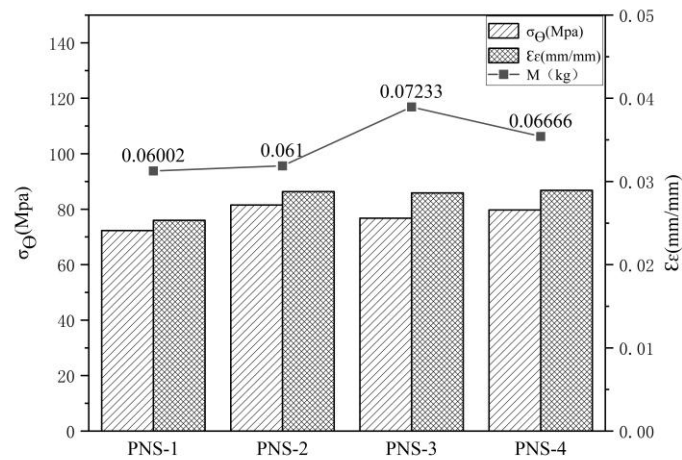


Figure 3-8: Comparative Analysis of the Equivalent Stress and Equivalent Strain Distribution
Characteristics of Biomimetic Structural Models.

Table 3-4 presents the quantitative analysis results of compression simulation experiments on biomimetic structures.

Comparison Metrics	σ_{θ}	$\epsilon\epsilon$	M
Name	(Mpa)	(mm/mm)	(kg)
PNS-1	72.315	0.025336	6.0023e-002

PNS-2	81.5	0.028786	6.0996e-002
PNS-3	76.778	0.028622	7.2333e-002
PNS-4	79.741	0.028934	6.6663e-002

Comparative analysis of the data presented in Figures 3-7 and 3-8 and Table 3-4 yields the following insights.

Among the four configurations, PNS-1 exhibits the lowest equivalent stress (72.315 MPa) and the lowest equivalent strain (0.025336) under the same applied displacement. The stresses in PNS-1 are 11.3%, 5.8%, and 9.3% lower than those in PNS-2, PNS-3, and PNS-4, respectively, while its strains are 11.3%, 11.5%, and 12.4% lower. The lower stress–strain response of PNS-1 indicates that the regular hexagonal honeycomb has the lowest elastic stiffness among the four configurations. This is attributed to the uniformly distributed, vertically oriented cell walls in the honeycomb architecture, which provide fewer load-transfer paths than the hybrid topologies and therefore result in a lower resistance to elastic deformation.

Stiffness and energy absorption synergies. Although the honeycomb exhibits the lowest stiffness, this does not imply that higher stiffness compromises energy absorption. On the contrary, PNS-2 and PNS-3 achieve both higher elastic stiffness (Section 3.1.3) and substantially enhanced energy absorption (Table 4-3). Their stiffness advantage arises from the introduction of triangular and parallelogram elements, which create diagonal load paths and a more constrained deformation field under compression. More importantly, these same topological features promote sequential plastic hinge formation and progressive buckling during the post-yield stage, enabling a larger volume of material to participate in plastic dissipation. Therefore, the energy absorption enhancement of PNS-2 and PNS-3 is not achieved by sacrificing stiffness, but rather by a synergistic combination of improved elastic load capacity and superior plastic deformation modes.

Summary. PNS-1 exhibits the lowest stiffness in the elastic regime due to its simple, vertically oriented load paths. By contrast, PNS-2 and PNS-3 demonstrate higher stiffness and simultaneously achieve superior energy absorption efficiency through topology-induced progressive deformation modes. This synergy between elastic stiffness and plastic energy

dissipation highlights the effectiveness of the pine nut shell-inspired multi-cell topology in optimizing both load-bearing and energy-absorbing functions.

4. Research on 3D-Printed Bionic Structures and Energy Absorption

4.1 Selection of 3D Printing Processes

The bio-inspired pine nut shell specimens were fabricated by fused deposition modeling (FDM) using a Bambu Lab 3D printer (Fig. 4-1). Additive manufacturing overcomes the geometric constraints inherent to conventional subtractive routes and enables the controlled preparation of fine structural features, including the graded and perforated porous architectures investigated here. By sequentially stacking material from bottom to top, the process also allows local microstructural features to be tuned along the build direction, providing a versatile route to graded mechanical properties. The specific printing parameters employed in this study are summarized in Table 4-1



Figure 4-1: Bambu H2S 3D Printer

Table 4-1 Printer Settings

Print Speed (mm/s)	Layer Height (mm)	Wall Thickness (mm)	Build Volume (mm)	Fill Density (%)	Number of Wall Passes
200	0.2	1.2	340*320*340	100%	2

Table 4-2 PLA Material Parameters

Material	PLA
Density (g/cm ³)	1.24
Poisson's Ratio	0.38
Young's Modulus (MPa)	3000
Bulk Modulus (MPa)	4166
Shear Modulus (MPa)	1087
Yield Strength (MPa)	62

4.2 Compression Test

To characterize the energy absorption performance of the bio-inspired pine nut shell configurations, systematic quasi-static uniaxial compression tests were performed on all four specimen types using a universal testing machine. The as-printed specimens used in the tests are shown in Figure 4-2.

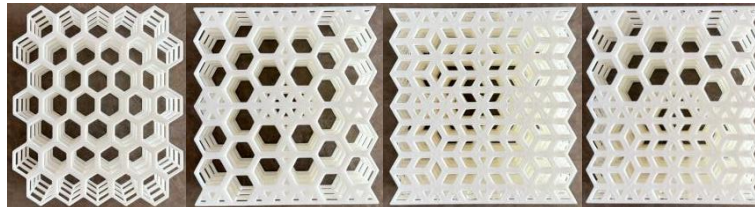


Figure 4-2: 3D-Printed Prototype

Quasi-static compression tests were performed on a SANS CMT 5305 electronic universal testing machine (MTS Systems, China). Figure 4-3 illustrates the testing process for the four bio-inspired configurations. To capture the progressive deformation and collapse characteristics, the crosshead speed was set to 0.5 mm s^{-1} and the compression stroke was set to 10 mm.

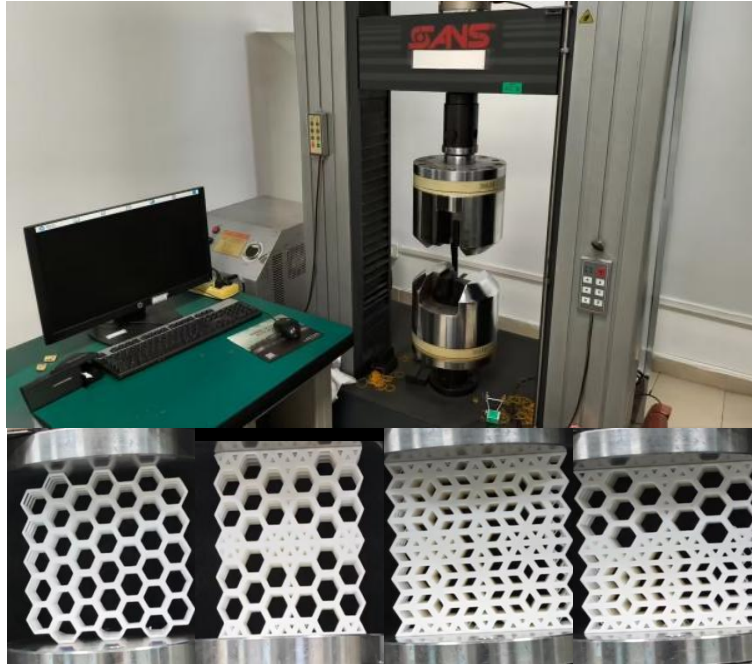


Figure 4-3: Compression Test Process for a Biomimetic Structure

4.2 Evaluation of Energy-Absorption Metrics

To evaluate the energy absorption characteristics of the four configurations, the displacement-load curves for each configuration were integrated to obtain the total energy absorption values, mass-specific energy absorption coefficients, and volume-specific energy absorption coefficients for each configuration [21, 22].

(1) Total Energy Absorption (EA)

By integrating the displacement-load curves of the four sets of test specimens, this method quantitatively analyzes the work done by the applied load and the total energy absorbed by the four sets of specimens during the process from the initial compression stage to the consolidation stage. The mathematical expression for this is given in Equation (4-1).

$$EA = \int_0^{\delta} F dx \quad (4-1)$$

In the equation:

EA — Total energy absorption (J);

F — Load (N);

δ – Density point.

(2) Mass-to-Energy-Absorption Ratio ($SEAm$)

The mass-to-energy-absorption ratio ($SEAm$) is defined as the ratio of total energy absorption (EA) to the mass of the specimen (m). It is used to quantify the energy absorption efficiency per unit mass of material; its mathematical expression is given in Equation (4-2).

$$SEAm = \frac{EA}{m} = \frac{\int_0^{\delta} F dx}{m} \quad (4-2)$$

In the equation:

$SEAm$ – specific energy absorption, in $J \cdot g^{-1}$;

m — mass of the specimen, in g.

(3) Volume-to-energy-absorption ratio ($SEAv$)

Volume-specific energy absorption is defined as the ratio of the total energy absorption (EA) to the volume of the specimen (v), and is used to measure the amount of energy that can be absorbed per unit volume of material; its mathematical expression is given in Equation (4-3).

$$SEAv = \frac{EA}{v} = \frac{\int_0^{\delta} F dx}{v} \quad (4-3)$$

In the equation:

$SEAv$ – volumetric specific energy absorption, $J \cdot cm^{-3}$;

v — sample volume, cm^3 .

4.3 Analysis of Compression Test Results

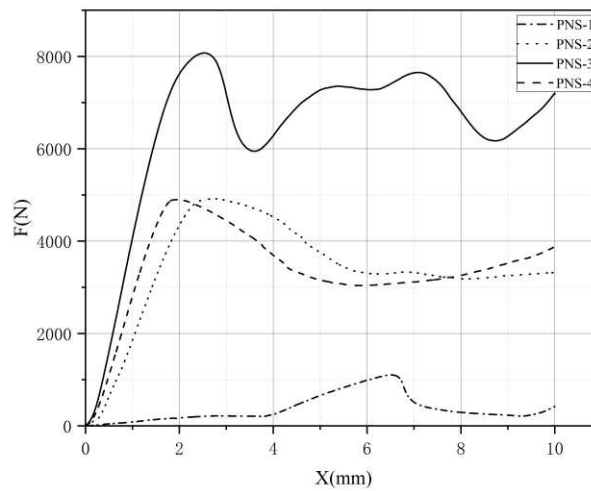


Figure 4-5: Comparative analysis of the relationship between displacement and load changes in biomimetic structures under loading.

By integrating Equation (4-1), the total energy absorption value EA for the four structural systems was determined; by integrating Equation (4-2), the energy absorption index per unit mass $SEAm$ for the four structural systems was calculated; and by integrating Equation (4-3), the energy absorption characteristic per unit volume $SEAv$ for the four structural systems was also determined. Figure 4-5 illustrates the differences in energy absorption performance among the four configurations, while Table 4-3 provides a detailed record of the energy absorption performance parameters corresponding to the four configurations.

Table 4-3: Energy Absorption Performance Data for Biomimetic Structures

Energy Absorption Index Name	FP (N)	EA (J)	$SEAm$ (J/g)	$SEAv$ (J/cm ³)
PNS-1	1105.10	8.38	0.140	0.168
PNS-2	4916.5	36.99	0.606	0.731
PNS-3	8093	56.93	0.787	0.949
PNS-4	4896.46	21.54	0.323	0.389

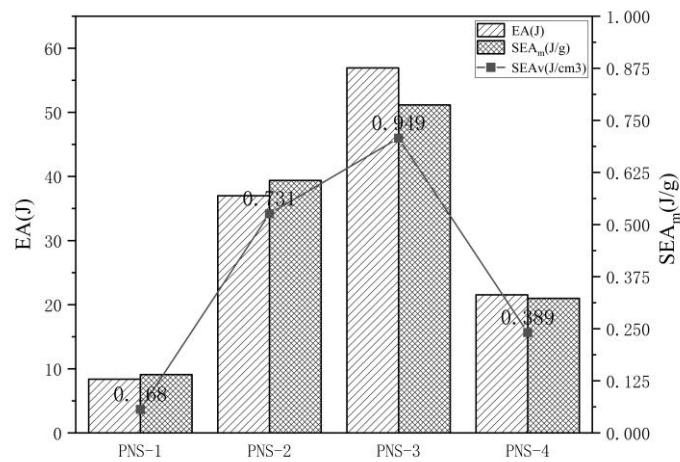


Figure 4-6 Comparison of Energy-Absorption Performance of Biomimetic Structures

Comparative analysis of the data presented in Figures 4-5 and 4-6 and Table 4-3 yields the following insights.

PNS-1 (honeycomb control). PNS-1 exhibits the lowest energy absorption metrics among the four configurations, with a peak compressive load of 1105.10 N, a total energy absorption EA of 8.38 J, a specific energy absorption by mass SEAm of 0.140 J g^{-1} , and a specific energy absorption by volume SEAv of 0.168 J cm^{-3} . The load--displacement curve displays a single sharp drop immediately after yielding, followed by a relatively flat, low-stress plateau devoid of secondary peaks. This behavior confirms the canonical 'single-buckling, global-instability' failure mode of regular honeycomb structures: because its elastic stiffness is the lowest among the four configurations (as shown in Section 3.1.3, PNS-1 exhibits the lowest specific stiffness), the honeycomb offers limited resistance to buckling initiation, and once the first row of cells collapses, the structure lacks redundant load paths to sustain further loading. Consequently, the post-yield deformation mode is monotonous, lacking multi-stage energy dissipation channels, and the energy absorption efficiency is severely limited.

PNS-2 exhibits substantially enhanced energy absorption, with a peak load of 4916.5 N, EA of 36.99 J, SEAm of 0.606 J g^{-1} , and SEAv of 0.731 J cm^{-3} ---improvements of 341.4%, 341.4%, 332.9%, and 335.1%, respectively, over PNS-1 (EA: 8.38 J, SEAm: 0.140 J/g , SEAv: 0.168 J/cm^3). In the elastic deformation stage, the load increases linearly with displacement. Upon transitioning into the plastic regime, the load response exhibits a non-equilibrium characteristic, marked by a sharp initial drop followed by a gradual recovery. This progressive deformation mode enables the structure to sustain continuous energy absorption without undergoing sudden catastrophic collapse. The introduction of triangular elements disrupts the single load transfer path of the hexagonal honeycomb: the acute-angle geometry of the triangular units induces the sequential formation of local plastic hinges, enabling internal stress redistribution and delaying global instability.

PNS-3 achieves the highest energy absorption metrics across all four configurations, with a peak load of 8093 N, EA of 56.93 J, SEAm of 0.787 J g^{-1} , and SEAv of 0.949 J cm^{-3} ---improvements of 579.4%, 579.4%, 462.1%, and 464.9%, respectively, over PNS-1 (EA: 8.38 J, SEAm: 0.140 J/g , SEAv: 0.168 J/cm^3). The load--displacement curve exhibits the most

dense and stable fluctuations in the yield stage, indicating the most stable progressive deformation mode among the four configurations. The parallelogram units function as beam-like load-bearing members aligned with the compression direction, storing strain energy through elastic bending; the triangular units serve as rigid nodes that transfer load diagonally to adjacent cells, forming a diversified stress diffusion network. The synergistic action of these two elements distributes plastic hinges more uniformly throughout the structure, avoiding stress concentration on a few weak regions and achieving a leap-forward improvement in both load-bearing capacity and energy absorption efficiency.

PNS-4 exhibits a peak load of 4896.46 N, EA of 21.54 J, SEA_m of 0.323 J g^{-1} , and SEA_v of 0.389 J cm^{-3} ---improvements of 157.0%, 157.0%, 130.7%, and 131.5%, respectively, over PNS-1 (EA: 8.38 J, SEA_m : 0.140 J/g, SEA_v : 0.168 J/cm^3). Although these values are significantly higher than PNS-1, they are notably lower than those of PNS-2 and PNS-3. The higher stiffness but lower energy absorption of PNS-4 indicates a mode transition at the interface: the upper layer deforms primarily by bending, while the lower layer resists via shear. This shear-dominated deformation, while elastically stiffer, promotes premature localized failure and reduces the volume of material engaged in plastic dissipation. The load--displacement curve exhibits a clear load drop at the inter-layer interface, indicating that the geometric discontinuity between the upper PNS-2 and lower PNS-3 layers causes an abrupt redirection of the load transfer path at the interface. The interface region becomes the preferential site for deformation and failure, and the lower layer does not fully realize its energy absorption potential before the interface is fully compacted. This finding underscores the decisive influence of inter-layer configuration matching and the smoothness of the transitional interface on the energy absorption efficiency of multi-cell structures with gradient or layered architectures, and further suggest that functional gradient designs must prioritize continuous or gradually transitional interfaces to avoid premature failure localization and fully exploit the energy absorption capacity of each constituent layer.

Cross-configuration comparison. Across the four configurations, both SEA_m and SEA_v follow the consistent ranking $PNS-3 > PNS-2 > PNS-4 > PNS-1$, with PNS-3 and PNS-2 achieving $5.62\times$ and $4.33\times$ the SEA_m (0.787 vs 0.140 J/g ; 0.606 vs 0.140 J/g), and $5.65\times$ and $4.35\times$ the SEA_v (0.949 vs 0.168 J/cm^3 ; 0.731 vs 0.168 J/cm^3), of the

honeycomb control, respectively. The consistency between mass- and volume-normalized metrics indicates that the differences in energy absorption efficiency arise from topology-controlled material distribution and deformation mechanisms, rather than from variations in absolute load-bearing capacity. Notably, although PNS-3 has the highest mass (7.2333×10^{-2} kg), it also achieves the highest SEA_m , demonstrating that the additional mass is fully and effectively converted into plastic dissipation---material utilization efficiency does not degrade with mass increase. This observation provides further evidence for the superiority of the parallelogram--triangular staggered arrangement in achieving rational material distribution.

Summary, The bio-inspired multi-cell structures PNS-2 and PNS-3 comprehensively outperform the conventional hexagonal honeycomb (PNS-1) in all energy absorption metrics. PNS-3, in particular, leverages the geometric coupling between parallelogram and triangular units to construct a multi-path load distribution network and a stepwise energy dissipation system, ensuring sustained and stable energy absorption under compression. Its total energy absorption and specific energy absorption by mass are $6.79\times$ and $5.62\times$ those of the honeycomb structure, respectively (56.93 vs 8.38 J; 0.787 vs 0.140 J/g), demonstrating outstanding performance competitiveness. PNS-2 also comprehensively surpasses the honeycomb, validating the effectiveness of the hexagonal--triangular alternating strategy. Although PNS-4 underperforms relative to PNS-2 and PNS-3 due to inter-layer interface effects, its energy absorption metrics remain significantly superior to those of PNS-1, confirming the universal value of bio-inspired topological design for energy absorption enhancement.

5. Conclusion

Here, we present a systematic biomimetic design framework—"microstructural characterization $\rightarrow$ key feature extraction $\rightarrow$ biomimetic design $\rightarrow$ simulation validation $\rightarrow$ experimental evaluation"—to engineer a novel class of multi-cellular energy-absorbing structures featuring heterogeneous polygonal topology, inspired by natural pine nut shells. Scanning electron microscopy (SEM) analysis of sclereid cell morphology in pine nut shells enabled the identification and abstraction of dominant structural motifs. The irregular polygonal cell architecture was simplified into three canonical geometric configurations—

hexagonal, parallelogram, and triangular—from which four distinct topologies (designated PNS-1 through PNS-4) were derived. Quasi-static compression tests were performed on additively manufactured specimens, complemented by finite element simulations, to systematically evaluate the specific strength, specific stiffness, and energy dissipation capacity of each configuration. The principal findings are as follows:

(1) Polygonal topology of pine nut shell sclereids and its biomimetic design value. SEM observations revealed a densely packed polygonal arrangement of sclereid cells, with smaller (15–30 μm), morphologically regular cells in the outer layer transitioning to larger (30–50 μm), increasingly irregular cells in the inner layer. Guided by the principle of morphological equivalence, the sclereid architecture was abstracted into hexagonal, parallelogram, and triangular elementary units, establishing a geometric prototype for biomimetic multi-cellular structural design.

(2) Under the 0.6 MPa reference loading condition, finite element simulations revealed the lightweight and load-bearing advantages of the biomimetic configurations. The PNS-3 topology achieved the highest specific strength of 9.74 kg^{-1} , surpassing the honeycomb control (PNS-1, 7.37 kg^{-1}) by 32.2% , while PNS-2 follows with 8.31 kg^{-1} (12.8% improvement). For specific stiffness, PNS-3 again exhibits the highest value at $35,771.69 \text{ MPa}\cdot\text{kg}^{-1}\cdot\text{mm}^{-1}$, representing a 62.1% improvement over PNS-1 ($22,063.70 \text{ MPa}\cdot\text{kg}^{-1}\cdot\text{mm}^{-1}$), with PNS-4 and PNS-2 achieving intermediate values of 26,049.88 and 25,451.80 $\text{MPa}\cdot\text{kg}^{-1}\cdot\text{mm}^{-1}$, respectively. Although PNS-3 has the highest mass ($7.2333 \times 10^{-2} \text{ kg}$), it simultaneously records the lowest maximum stress (14.864 MPa) and minimum deformation (0.19585 mm) among all four groups, highlighting the substantial contribution of parallelogram elements in introducing oblique load transfer paths that enhance both structural strength efficiency and elastic stiffness.

(3) Comprehensive superiority of biomimetic configurations in energy absorption over conventional honeycombs. Quasi-static compression experiments confirmed the exceptional energy absorption performance of the biomimetic designs. The PNS-3 configuration outperformed all counterparts, achieving a total energy absorption of 56.93 J, with mass-specific and volume-specific energy absorption values of 0.787 J/g and 0.949 J/cm^3 , respectively—all metrics ranking first among the four configurations tested. Relative to the

PNS-1 structure, PNS-3 exhibited a 579.4% increase in total energy absorption, a 462.1% enhancement in mass-specific energy absorption, and a 464.9% gain in volume-specific energy absorption. The PNS-2 configuration achieved a specific energy absorption (SEA_m) of 0.606 J/g, representing a 4.33-fold improvement over PNS-1 (0.140 J/g), with a total energy absorption of 36.99 J (341.4% improvement) and a volume-specific energy absorption of 0.731 J/cm³ (335.1% improvement). The PNS-4 configuration, despite its inter-layer mismatch, still delivered an EA of 21.54 J (157.0% improvement), an SEA_m of 0.323 J/g (130.7% improvement), and an $SEAv$ of 0.389 J/cm³ (131.5% improvement), confirming the universal effectiveness of bio-inspired topological design. The performance superiority of the biomimetic topologies stems from the diversified load transmission pathways enabled by their topological hybridization: the acute-angle geometry of triangular units induces sequential plastic hinge formation, while the beam-like elongated edges of parallelogram units provide a stable flexural deformation mode. Their synergistic interaction engenders a characteristic "multi-peak progressive" deformation mode during compression, effectively circumventing the catastrophic global instability typical of conventional honeycomb structures.

Taken together, the pine nut shell-inspired biomimetic multi-cellular structures exhibit substantial engineering potential for automotive crashworthiness and aerospace energy dissipation applications. In automotive passive safety, the PNS-3 configuration—with its outstanding mass-specific energy absorption of 0.787 J/g (a 4.62-fold improvement over the honeycomb control) and stable progressive crushing pattern—is ideally suited as the core energy-absorbing element for bumper crash boxes, side-door impact beams, and related components, enabling superior collision energy absorption at equivalent mass while its characteristic "multi-peak progressive" deformation effectively mitigates secondary impact peaks transmitted to occupants, enhancing crash-pulse waveform control. In aerospace applications, the PNS-3 configuration further distinguishes itself with the highest specific strength (9.74 kg⁻¹) and specific stiffness (35,771.69 MPa·kg⁻¹·mm⁻¹) among all four topologies, rendering it a prime candidate for load-bearing energy-absorbing structures where both strength and lightweight design are critical; its exceptional volume-specific energy absorption (0.949 J/cm³) also provides a high-efficiency solution for crashworthiness

protection in space-constrained avionics compartments. Meanwhile, the PNS-2 configuration, with its moderate specific strength (8.31 kg^{-1}) and lower mass relative to PNS-3, offers a viable lightweight alternative for applications where structural mass is the primary constraint; its mass-specific energy absorption of 0.606 J/g (a 4.33-fold improvement over PNS-1) still substantially outperforms the conventional honeycomb architecture. Furthermore, the "biological characterization $\rightarrow$ feature extraction $\rightarrow$ topological reconstruction $\rightarrow$ additive manufacturing" design paradigm established herein is broadly extendable to the biomimetic engineering of other natural multi-cellular materials—such as nut shells, bone, and wood—laying a methodological foundation for the customized design of next-generation lightweight multifunctional protective structures. With continued advances in multi-material additive manufacturing and topology optimization algorithms, this biomimetic design strategy is expected to further expand into high-speed train crash energy absorption, impact-resistant unmanned aerial vehicle fuselages, and buoyant load-bearing structures for deep-sea submersibles, accelerating the translation of high-performance energy-absorbing devices from biomimetic concept to engineering reality.

Declarations

Plant material statement

The pine nut shells used in this study were obtained from commercial pine nut processing by-products. No wild plant material was collected, and therefore no wild plant certification or collection permit was required.

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Competing interests

The authors declare no competing interests. Author Contributions Statement

Y.L. conceived the original research idea, designed the biomimetic structural framework, and performed the microscopic characterization (SEM), the Main Feature Structure (MFS) extraction, and the finite element simulations. Y.L. and Y.Y. carried out the 3D printing of the specimens and the quasi-static compression experiments. Y.L. analyzed the data and wrote the main manuscript text. Y.Y. prepared all figures and tables. J.Z. supervised the entire study, provided critical guidance on experimental design and data interpretation, and revised the manuscript. All authors reviewed and approved the final manuscript.

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