Design of Additively Manufactured Biomimetic Goat Horn-inspired Lattice Structures and Simulation Study on Their Compressive Mechanical Properties

Yibo Huang, Tianle Gong, Shengkai Feng, Yichi Jia, Haoran Liu, Xinzhou Zhang, Lan Chen*

School of Mechanical Engineering, Jiangsu University, Zhenjiang, Jiangsu 212013, China

Abstract

To address the limitations in load-bearing and energy absorption of traditional lattice structures, a bio-inspired conical spiral lattice structure was designed based on the impact resistance of goat horns. Numerical simulations were employed to compare its quasi-static compressive properties with the BCC structure and investigate the effects of relative density (20%–50%). The results indicate that the initial peak stress and specific energy absorption of the bio-inspired structure increased by 205.7% and 171.2%, respectively, compared to the BCC structure. With the increase of relative density, the structural strength exhibits non-linear growth, while the failure mode transitions from ductile yielding to brittle collapse. Comprehensive analysis suggests that a relative density of 40% offers the optimal balance between strength and energy absorption stability.

Keywords

Lattice Structure; Bio-inspired Design; Relative Density; Mechanical Properties.

1. Introduction

In the field of aerospace manufacturing, amidst an increasingly complex strategic environment, the demands for the lightweighting, monolithic integration, and system consolidation of equipment have become exceptionally urgent. The emergence of additive manufacturing technologies-particularly the development of selective laser melting (SLM) has expanded the degrees of freedom in structural design, making the fabrication of lattice structures with complex micro-topologies a reality [1-3]. Among available material systems, aluminum alloys have emerged as a premier choice owing to their excellent specific strength and corrosion resistance. Nevertheless, research by Shaoting Cao et al. [4] indicates that due to their inherent characteristics-such as high thermal conductivity, high laser reflectivity, and a broad solidification range-aluminum alloys are highly susceptible to metallurgical defects, including porosity and intergranular solidification cracking, during the SLM (also known as laser powder bed fusion, LPBF) forming process.

Traditional lattice structures face limitations in load-bearing efficiency and isotropy; consequently, bio-inspired design based on biological principles has emerged as a research hotspot to break through these bottlenecks [5]. Zhaohui Zhang et al. [6], who designed a laminated structure based on the helicoidal features of shrimp claws, and Quanwei Li et al. [7], who developed a diagonal support structure inspired by glass sponges, have both demonstrated the significant advantages of bio-inspired architectures in enhancing impact resistance and specific strength. Furthermore, given the internal geometric complexity of lattice structures, finite element analysis (FEA) has become a crucial tool for revealing their failure mechanisms. Studies by Huan Liu et al. [8] and Smith et al. [9] indicate that

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simulation analyses incorporating accurate constitutive models can effectively capture local plastic deformation and high strain-rate responses, thereby demonstrating exceptional reliability.

In summary, although the SLM processing of aluminum alloys and associated simulation methods have grown increasingly mature, there remains a scarcity of research applying the "spiral" characteristics of goat horns to metallic lattice structures and systematically investigating their mechanical responses. To address the deficiencies of traditional structures in energy absorption and load-bearing capacity, this study extracts the geometric features of goat horns to design a novel bio-inspired lattice. By combining the SLM process with numerical simulation, this paper thoroughly investigates the quasi-static compression performance of AlSi10Mg bio-inspired specimens across varying relative densities (20%–50%). Ultimately, it reveals the failure mechanism governing the transition from ductile yielding to brittle collapse, thereby providing a theoretical foundation for the design of lightweight aerospace protective structures.

2. Design of Bio-inspired Goat Horn Lattice Structure

2.1 Establishment of the Bio-inspired Prototype

Goats, as highly representative ruminant mammals in nature (as shown in Figure 1), possess horn structures that feature excellent specific strength and outstanding energy absorption efficiency, making them a crucial blueprint for the design of bio-inspired lightweight structures. From the perspective of geometric configuration, goat horns exhibit unique spiral characteristics (as shown in Figure 2). This complex spatial morphology is the result of biological evolution adapting to high-intensity intraspecific competition.

Biomechanical studies indicate that bovids (such as bighorn sheep and goats) can reach impact velocities of 6–9 m/s during combat, with instantaneous peak impact forces exceeding 3400 N, which can even equate to tens of times their body weight [10]. However, under such extreme dynamic loading, their brain soft tissues and skulls are rarely damaged, indicating that the horn structure possesses a highly efficient energy dissipation mechanism.

This exceptional impact resistance stems from the synergistic effect of its macroscopic geometric configuration and microscopic material distribution. At the macroscopic level, the spiral structure can effectively regulate the propagation behavior of stress waves: when the horn tip is subjected to an axial impact, the spiral curvature induces the transformation of longitudinal pressure waves into transverse shear waves [11]. This wave mode conversion significantly extends the propagation path and dissipation time of the stress waves, thereby attenuating the instantaneous peak stress transmitted to the base of the skull. At the microscopic level, the gradient porous structure of the keratinous sheath-which is hard on the exterior and tough on the interior-provides additional fracture toughness and damping properties, further inhibiting crack propagation [12]. Based on the aforementioned mechanisms, this study selects the spiral structure of goat horns as the bio-inspired prototype, extracting its key geometric features for impact resistance to be applied in the design of lattice structures.

Figure 1. Goat

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Figure 2. Goat head structure

2.2 Bio-inspired Lattice Unit Cell Design Scheme

Given that the true biological structure of goat horns exhibits highly complex spiral features with variable curvature, direct reverse modeling struggles to meet the standardization requirements for reproducible engineering manufacturing and mechanical analysis. Therefore, it is urgently necessary to reasonably simplify and abstract its geometric topology.Considering the mechanical transmission characteristics at the connection between the goat horn root and the skull, this study abstracts the root feature responsible for load transmission as the "Handle"; the primary load-bearing paths extending upward and branching from the horn body are simplified as the "Trunk" and the terminal "Branch" respectively. Through this feature extraction, a skeleton model with explicit load-transmission paths was constructed (as shown in Figure 3), laying the geometric foundation for the subsequent parameterized unit cell design.

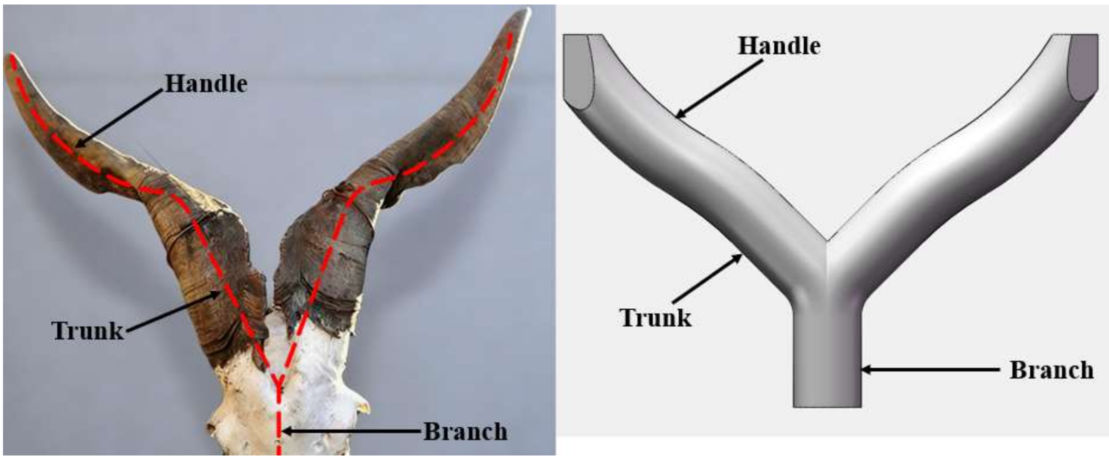

Figure 3. Simplified diagram of the goat head structure

Based on the simplified model above, cross-sectional feature lines were further extracted to determine the fundamental two-dimensional geometric configuration of the lattice unit cell (as shown in Figure 4). This configuration consists of an upright handle at the bottom and a bifurcating curve at the top. Its key geometric dimensions are parametrically defined as follows: the total structural height h_1 is set to 5 mm, and the height of the bifurcation critical plane h_2 is 2.5 mm. To precisely control the curve morphology, the height of the intermediate feature point h_3 is defined as 1.94 mm, and the handle length h_4 is 1.23 mm. Additionally, the bending degree of the structure is controlled via angle parameters, with the critical node angles set to $\alpha_m = 135°$ and $\beta_m = 120°$. The strut diameter d is uniformly set to 1 mm.

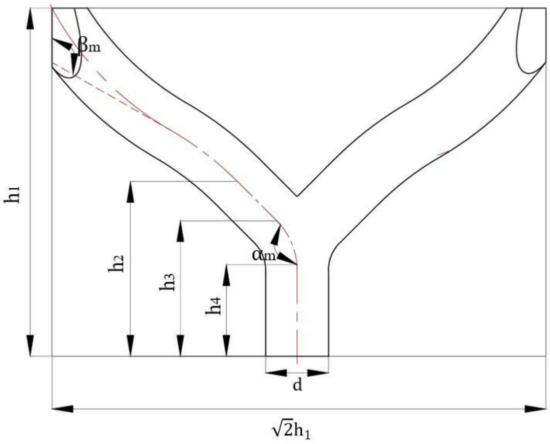

Figure 4. Schematic diagram of geometric dimensions for the feature structure

To realize the transformation from a two-dimensional feature to a three-dimensional spatial structure, rotation and mirror symmetry operations were employed to construct a complete spatial unit cell. First, using the central axis of the handle (Z-axis) as the rotation reference, the 2D feature structure was rotated 90° along the circumferential direction to form an orthogonal spatial support skeleton. Subsequently, the horizontal plane at height h_2 was selected as the symmetry reference plane to perform a mirroring operation on the aforementioned structure, thereby generating a fully bio-inspired goat horn unit cell with top-bottom symmetry, as shown in Figure 5.

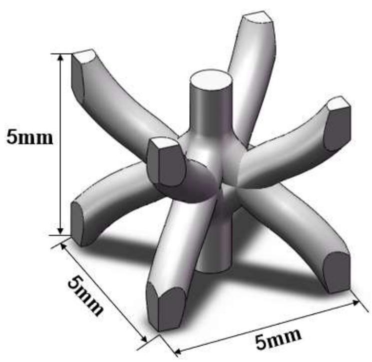

Figure 5. Bio-inspired goat horn unit cell structure

Finally, taking this unit cell as the Representative Volume Element (RVE), a periodic array was generated along the three orthogonal directions (X, Y, and Z). This study constructed a 3×3×3 lattice structure specimen model with overall geometric dimensions of 15 mm × 15 mm × 15 mm, as shown in Figure 6. These design dimensions satisfy the standard requirements for quasi-static compression testing.

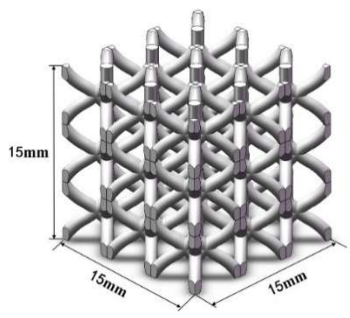

Figure 6. 3×3×3 bio-inspired goat horn lattice structure

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3. Performance Study of Bio-inspired Lattice Structures

3.1 Design and Preparation of Quasi-Static Compression Specimens

The bio-inspired lattice structure proposed in this paper is inspired by the microscopic impact-resistant architecture of goat horns. The 3D model was established by varying the relative density of the bio-inspired unit cells.The unit cell dimensions were set to 5 mm × 5 mm × 5 mm, and a 3×3×3 periodic array was selected for modeling, resulting in a lattice structure with overall dimensions of 15 mm × 15 mm × 15 mm.To eliminate boundary effects and ensure the uniform transmission of compressive loads, solid compression plates (20 mm × 20 mm × 0.5 mm) were placed at both the top and bottom surfaces (along the Z-axis direction) of the lattice structure, as shown in Figure 7.

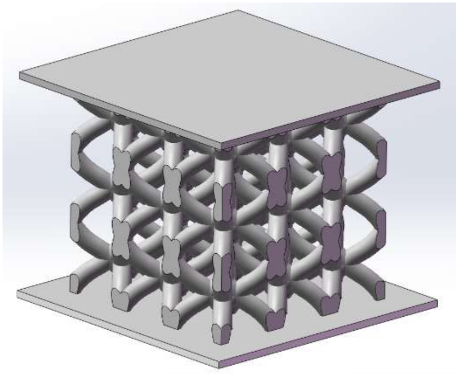

Figure 7. Lattice structure with added compression plates

3.2 Numerical Simulation Methods

Finite element numerical simulations were conducted utilizing the Abaqus/Explicit dynamic solver. Modified quadratic tetrahedral elements (C3D10M) were selected for meshing to accommodate the complex geometric topology of the lattice structure. To accurately describe the plastic flow and damage evolution behavior of the AlSi10Mg aluminum alloy under quasi-static compression, the Johnson-Cook (J-C) constitutive model (Equation (1)) and corresponding fracture criteria were introduced. Based on the literature [13], the material parameters are listed in Table 1. The flow stress expression for the Johnson-Cook model is:

$$\sigma_s = (A + B\varepsilon^n)(1 + C\ln\varepsilon_0)(1 - (T^*)^m) \quad (1)$$

Where:σ_s is the von Mises flow stress; A is the yield strength at the reference strain rate; B is the strain hardening coefficient; n is the strain hardening exponent; C is the strain rate sensitivity coefficient;m is the thermal softening coefficient; and ε_0 is the effective plastic strain. Because quasi-static compression is primarily conducted at room temperature and at a low strain rate, the temperature term $(1 - (T^*)^m)$ and its influence are typically negligible.

Table 1. Material Parameters of SLM-formed AlSi10Mg Aluminum Alloy

Density ρ (g/cm^3)	Elastic Modulus E (GPa)	Poisson's Ratio (ν)	Yield Strength A (MPa)
2.68	68.5	0.33	250
Hardening Coefficient B (MPa)	Hardening Exponent (n)	Strain Rate Coefficient (C)	Temperature Coefficient (m)
1592	0.81	0.0169	1.43

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Regarding boundary conditions,a fully fixed constraint (U1=U2=U3=UR1=UR2=UR3=0) was applied to the bottom surface of the model (XOY plane); a unidirectional displacement load was applied to the top surface along the Z-axis direction. To eliminate oscillations caused by inertial effects, the loading process was controlled using a Smooth Step amplitude curve to ensure the simulation process satisfied quasi-static loading conditions.

3.3 Evaluation of Mechanical Performance Advantages of Bio-inspired Lattice Structures

To thoroughly evaluate the mechanical performance advantages of the bio-inspired goat horn lattice structure, this study selected the classic Body-Centered Cubic (BCC) lattice structure to establish a control group. Adhering to the principle of controlling variables, the BCC control group model maintained identical macroscopic geometric dimensions (15 mm × 15 mm × 15 mm) and AlSi10Mg material constitutive parameters as the bio-inspired specimens. Additionally, the strut diameter of the BCC lattice was kept consistent with that of the bio-inspired lattice (d = 1 mm). For the FEA setup, the boundary conditions and loading strategies detailed in Section 2.2 were strictly applied: a fully fixed constraint on the bottom surface and a quasi-static displacement load with a Smooth Step amplitude applied along the Z-axis on the top surface. This experimental design aims to eliminate interference introduced by size effects and boundary conditions, thereby isolating the intrinsic impact of the topological configuration on the structural mechanical response.

Figure 8 presents the comparative stress-strain response curves of the bio-inspired lattice and the BCC lattice under quasi-static compression conditions. Generally, both structures exhibit a distinct linear elastic phase followed by plastic yielding characteristics; however, they demonstrate significant differences in their stress response levels.

Comparative analysis indicates that at equivalent strain levels, the flow stress of the bio-inspired lattice structure is consistently and significantly superior to that of the BCC structure. Specifically, the steeper curve slope of the bio-inspired lattice during the elastic phase indicates a higher initial stiffness and greater resistance to elastic deformation. As loading progresses, the bio-inspired structure rapidly reaches its peak stress, demonstrating outstanding compressive strength; in contrast, the stress increase in the BCC lattice is more gradual, with a relatively lower peak stress. These phenomena robustly verify that, under identical boundary and material conditions, the bio-inspired topological design proposed in this paper significantly enhances the overall load-bearing efficiency of the lattice structure.

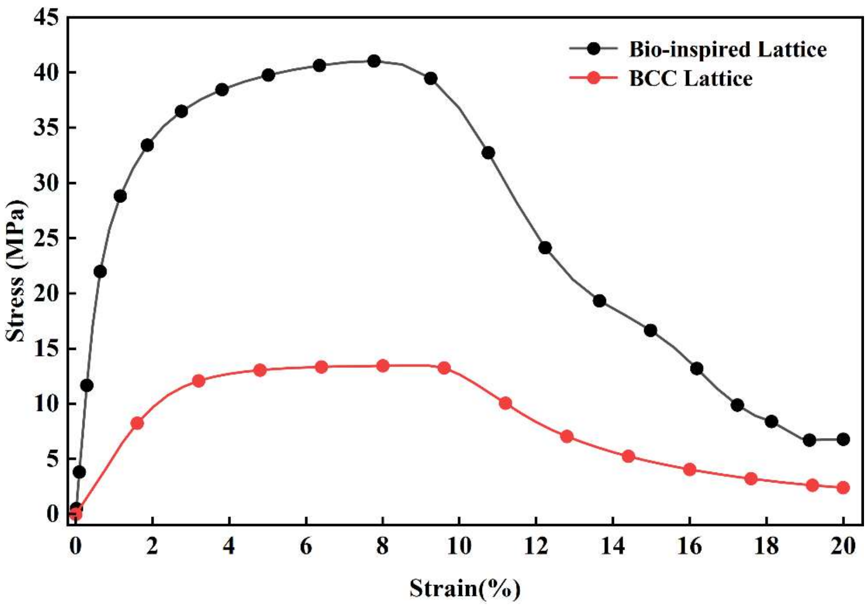

Figure 8. Quasi-static compression stress-strain curves of the BCC lattice structure and the bio-inspired lattice structure

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To comprehensively evaluate the mechanical advantages of the bio-inspired lattice structure, this study selected Initial Peak Stress (IPS), specific strength (σ_s/ρ), Energy Absorption (EA), and Specific Energy Absorption (SEA) as the primary evaluation metrics.

Figure 9 details the IPS and specific strength (σ_s/ρ) values for both the bio-inspired lattice and the BCC lattice. The data indicates that the IPS of the BCC lattice is merely 13.46 MPa, whereas the IPS of the bio-inspired lattice reaches an impressive 41.15 MPa. Compared to the BCC structure, the initial peak stress of the bio-inspired lattice increased by approximately 205.7%, achieving a multiplier effect in load-bearing capacity. Furthermore, after factoring in lightweight considerations, the bio-inspired lattice maintains a massive advantage: its specific strength reaches 76.77 MPa/(g/cm³), which is far superior to the 28.22 MPa/(g/cm³) of the BCC lattice, representing an enhancement of approximately 172%. This result strongly proves that, without sacrificing lightweight advantages, this bio-inspired design substantially optimizes material utilization and achieves the design goal of being lightweight and high-strength.

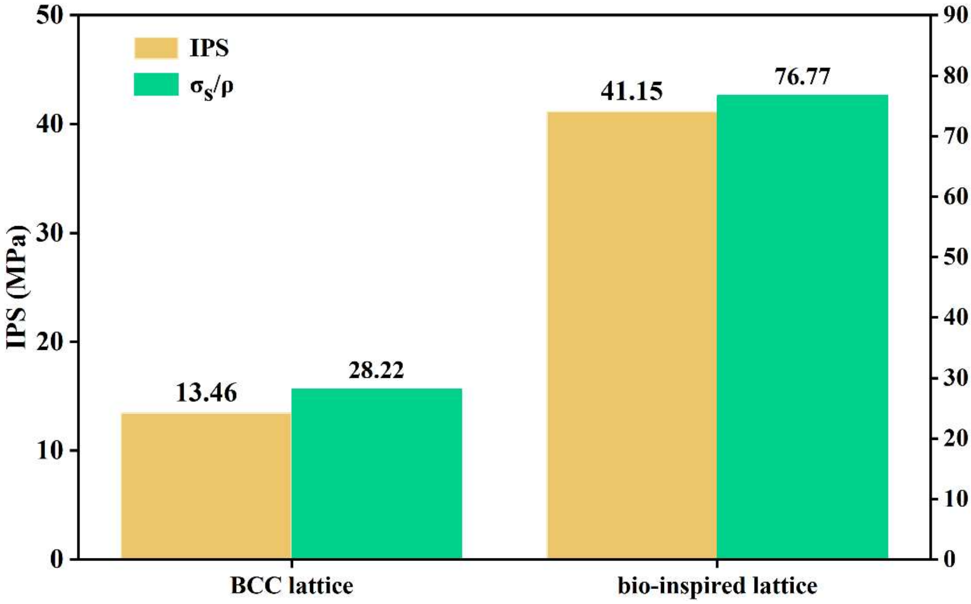

Figure 9. Comparison of IPS and σ_s/ρ values between the BCC lattice and the bio-inspired lattice

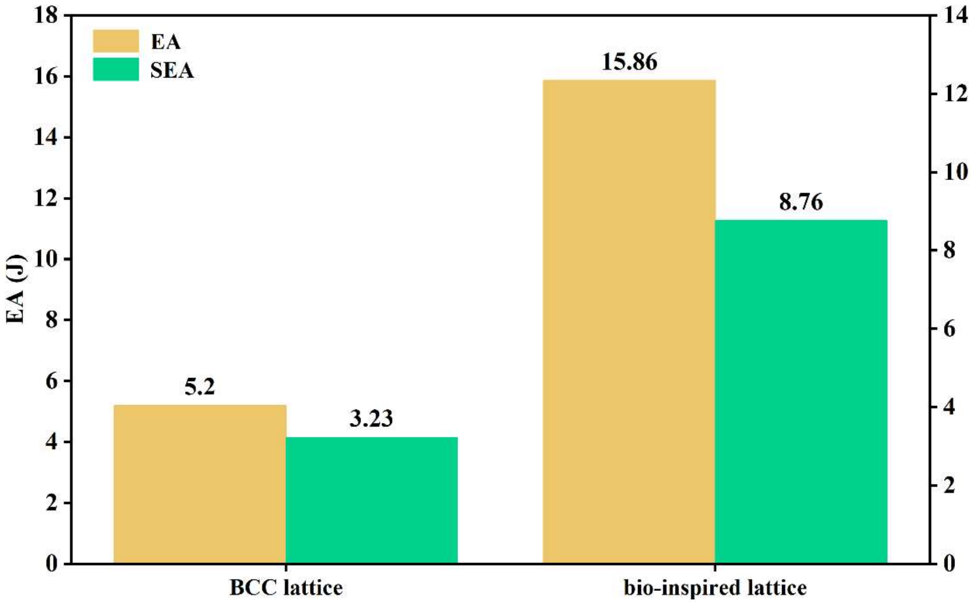

Figure 10. Comparison of EA and SEA values between the BCC lattice and the bio-inspired lattice

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In addition to load-bearing capacity, excellent energy absorption is a crucial metric for protective structures. Figure 10 compares the EA and SEA of the two structures during compression at a strain of $\varepsilon = 20\%$. It is evident that the bio-inspired lattice comprehensively outperforms the traditional BCC lattice in energy absorption. The EA of the BCC lattice is 5.2 J, and its SEA is 3.23 J/g. Under identical conditions, the EA of the bio-inspired lattice surges to 15.86 J, an increase of roughly 205% relative to the BCC lattice; its SEA reaches 8.76 J/g, a relative increase of approximately 171.2%. This demonstrates that the bio-inspired lattice not only possesses robust load-bearing capacity but can also dissipate more external energy through efficient internal structural deformation when yielding occurs.

In summary, the bio-inspired lattice structure designed in this study comprehensively surpasses the traditional BCC lattice in mechanical performance. The specific numerical comparisons are presented in Table 2. Whether in terms of absolute load-bearing capacity (IPS), lightweight strength metrics (σ_s/ρ), or energy absorption efficiency (EA, SEA), the bio-inspired lattice exhibits manifold performance enhancements. This indicates that this bio-inspired topological configuration holds immense application potential in scenarios demanding high load-bearing and energy-buffering capabilities.

Table 2. Structural Performance

Structure	Mass m (g)	20% Strain EA(J)	20% Strain SEA(J/g)	IPS (MPa)	σ_s/ρ (Mpa/(g/cm^3))
BCC Lattice	1.61	5.2	3.23	13.46	28.22
Bio-inspired Lattice	1.81	15.86	8.76	41.15	76.77

3.4 Mechanical Performance Analysis of Bio-inspired Goat Horn Lattice Structures Under Different Densities

The Relative Density of a lattice structure is defined as the ratio of the solid material volume to the macroscopic envelope volume of the lattice [14]. It is the core geometric parameter that determines the solid fill ratio of a porous structure, thereby regulating its mechanical performance and lightweight level. Figure 11 presents the stress-strain response curves of the bio-inspired lattice structures at four different relative densities (20%, 30%, 40%, 50%) under room-temperature quasi-static compression. Although all curves exhibit the typical stage characteristics of "elasticity to yielding to plasticity/failure", the evolutionary laws of each stage show significant differences as density increases:

(1) Elastic Stage: In the initial loading phase ($\varepsilon < 2\%$), all specimens exhibit a significant linear stress increase, corresponding to the elastic deformation behavior of the mesoscopic struts. Comparing the curve slopes reveals that as relative density increases from 20% to 50%, the initial stiffness of the structure shows a marked upward trend, indicating that increasing the solid material fraction can substantially elevate the equivalent elastic modulus of the structure.

(2) Plastic Plateau and Failure Stage: After surpassing the yield point, specimens of different densities exhibit distinctly different post-yield characteristics:

Low Relative Density Group (20%, 30%): After reaching peak stress, the curves enter a long and stable stress plateau region without violent stress fluctuations. This characteristic indicates that low-density structures possess excellent toughness and deformation stability, facilitating continuous energy dissipation.

High Relative Density Group (50%): The curve exhibits distinct brittle failure characteristics, with stress plummeting rapidly after reaching its peak (dropping below 20 MPa). This indicates that under high-density configurations, the structure is prone to localized brittle collapse or instability of the struts, resulting in post-deformation load-bearing stability that is significantly weaker than that of low-density structures.

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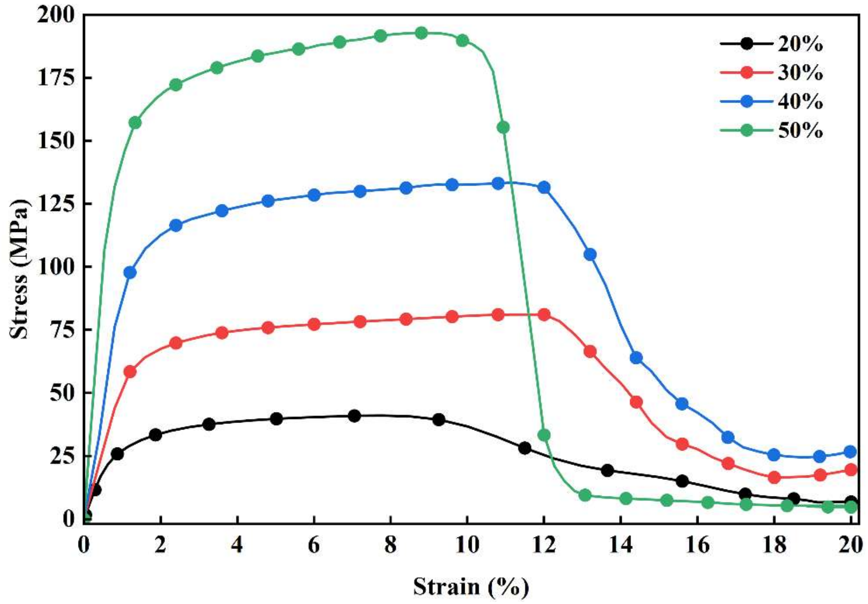

Figure 11. Stress-strain curves of bio-inspired lattice structures with different densities under quasi-static compression

To further quantify the impact of relative density on ultimate load-bearing capacity, Figure 12 compares the compressive strength (peak stress) of each specimen group. The results show that the compressive strength of the bio-inspired lattice structure exhibits a significant non-linear growth trend with increasing relative density. Specifically, as the relative density increases incrementally from 20% to 50%, the compressive strength sequentially reaches 41 MPa, 81 MPa, 133 MPa, and 193 MPa. Notably, a 2.5-fold increase in relative density (from 20% to 50%) yields approximately a 4.7-fold increase in strength (from 41 MPa to 193 MPa). This pronounced non-linear amplification effect confirms that increasing relative density is an effective method for enhancing the load-bearing efficiency of this bio-inspired structure.

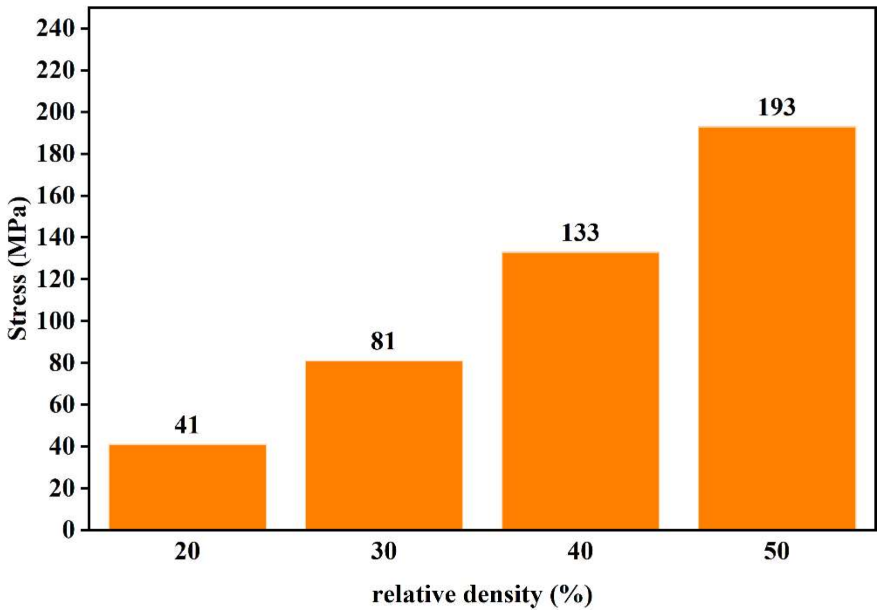

Figure 12. Compressive strength of bio-inspired lattice structures with different densities

Beyond focusing on the ultimate load-bearing capacity (compressive strength) of the structure, its energy absorption capability during deformation is also a critical metric for assessing structural

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impact resistance and protective performance. Energy Absorption per Unit Volume (W_V) characterizes the structure's ability to dissipate external work during compressive deformation. Mathematically, it is defined as the integral area under the nominal stress-strain curve, representing the total energy dissipated per unit volume when the structure is compressed to a specific strain ε. The calculation formula can be expressed as:

$$W_v = \int_0^{\varepsilon} \sigma(\varepsilon)\, d\varepsilon \tag{2}$$

Where: σ is the instantaneous compressive stress, and ε is the corresponding compressive strain.

Figure 13 illustrates the cumulative energy absorption-strain evolution curves for the four relative density (20%–50%) bio-inspired lattice structures. Overall, the energy absorption work of all specimen groups shows a monotonically increasing trend with strain, and relative density exerts a significantly reinforcing effect on the energy absorption level.

Specifically, during the early stage of elastic loading ($\varepsilon < 5\%$), the increase in energy absorption for all groups is slow, and differences are marginal. As deformation enters the plastic plateau region, the curve slopes diverge significantly. High relative density (40%, 50%) structures, relying on higher flow stress, demonstrate superior energy dissipation efficiency per unit deformation. Taking the 20% strain point as an example, when the relative density increases from 20% to 50%, the cumulative energy absorption value surges from 5.5 MJ/m^3 to 19.2 MJ/m^3 (approximately 3.5 times the former), which is highly consistent with the evolutionary pattern of compressive strength discussed earlier.

However, it is worth noting that a phenomenon of diminishing marginal returns exists in the energy absorption gains of high-density structures. Although the peak strength of the 50% specimen (193 MPa) far exceeds that of the 40% specimen (133 MPa), the difference in their energy absorption in the later stages of strain is only 1.4 MJ/m^3. In contrast, while the 40% specimen has slightly lower strength, it achieves a better balance between strength and energy absorption stability due to its smooth plastic flow characteristics.

In conclusion, increasing relative density can significantly elevate the upper limit of energy absorption for the bio-inspired lattice structure, but the marginal benefits of its energy absorption growth will diminish in the later stages.

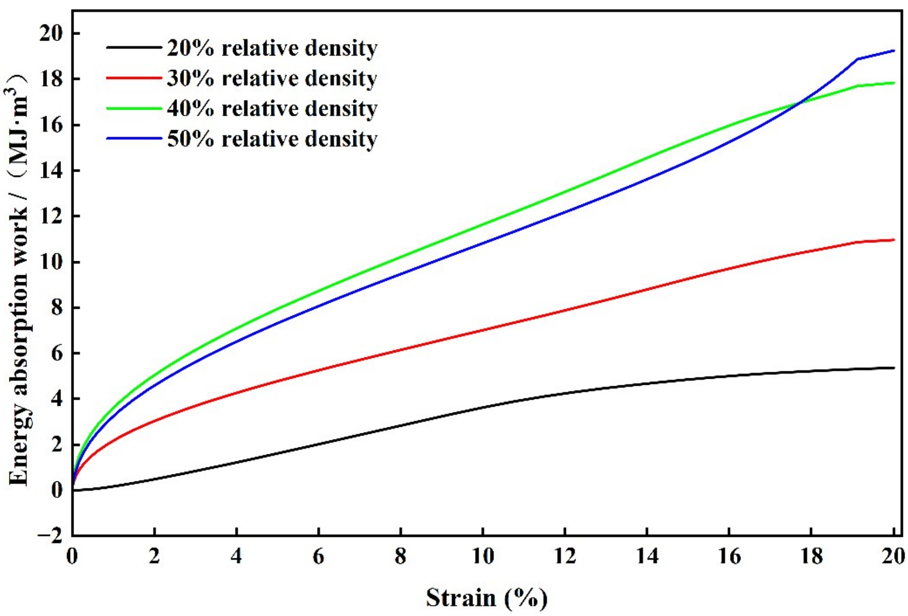

Figure 13. Energy absorption work of bio-inspired lattice structures with different densities

Simulation data indicates that relative density is the core parameter determining the mechanical response of the bio-inspired lattice structure, showing a significant positive correlation with both compressive strength and energy absorption capacity. When the relative density is increased from 20% to 50%, the structure's compressive strength realizes a non-linear growth from 41 MPa to 193 MPa, and the energy absorption capacity per unit volume also increases by approximately 3.5 times. However, a competitive relationship exists between the enhancement of ultimate load-bearing capacity and deformation ductility. Although the 50% relative density specimen possesses the highest compressive strength, the 40% relative density specimen effectively balances stability during the energy absorption process while achieving high strength, thereby demonstrating optimal comprehensive mechanical efficacy.

4. Conclusion

In this paper, a finite element analysis method was employed to simulate the quasi-static compression performance of a bio-inspired goat horn lattice structure. Differences in mechanical performance between it and a traditional BCC lattice structure were compared, and the evolutionary rules regarding the influence of different relative densities (20%–50%) on the load-bearing capacity, energy absorption characteristics, and deformation behavior of the bio-inspired structure were further investigated. The main conclusions are as follows:

(1) The bio-inspired configuration comprehensively surpasses the traditional BCC structure in load-bearing and energy absorption performance. Under identical conditions, the Initial Peak Stress (IPS) of the bio-inspired lattice structure reached 41.15 MPa, an increase of approximately 205.7% over the BCC structure, and specific strength increased by approximately 172%, successfully achieving the design goal of being lightweight and high-strength. Concurrently, the Energy Absorption (EA) and Specific Energy Absorption (SEA) of the bio-inspired structure increased by 205% and 171.2%, respectively, proving that this topological configuration holds significant advantages in energy buffering and protective applications.

(2) Increasing relative density can significantly enhance the mechanical performance of the structure, though it exhibits a non-linear growth trend. As relative density increases from 20% to 50%, the compressive strength of the structure surges from 41 MPa to 193 MPa (an increase of roughly 4.7 times); the energy absorption value per unit volume (at $\varepsilon = 20\%$ strain) also grows from 5.5 MJ/m^3 to 19.2 MJ/m^3 (an increase of roughly 3.5 times). This indicates that the load-bearing level of the structure can be adjusted over a wide range by regulating the relative density.

(3) Relative density significantly regulates the macroscopic mechanical response characteristics of the lattice structure. Low relative density (20%, 30%) specimens exhibit a broad and stable flow stress plateau in the post-yield stage, demonstrating excellent toughness and load-bearing stability. In contrast, while the high relative density (50%) specimen possesses extremely high peak strength, the significant stress drop following the peak limits the continuous transmission of subsequent loads, resulting in a trend of diminishing marginal returns in energy absorption efficiency during the post-yield stage.

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