

Full length article

Mechanically efficient disordered metamaterials: Synergistic strength and energy-absorption enhancement

Yong Liu^{a,b,c}, Ye Zhou^b, Kai Wei^b, Gary P.T. Choi^c, Baizhan Xia^{a,b,*}

^a State Key Laboratory of Advanced Design and Manufacturing Technology for Vehicle, Hunan University, Changsha, 410082, China

^b College of Mechanical and Vehicle Engineering, Hunan University, Changsha, 410082, China

^c Department of Mathematics, The Chinese University of Hong Kong, Hong Kong, 999077, China

ARTICLE INFO

Keywords:

Disordered metamaterials
Stable post-buckling bearing interval
Strength-energy absorption synergy
Defect insensitivity
Failure modulation

ABSTRACT

Disordered metamaterials exhibit excellent defect tolerance and progressive collapse energy dissipation. However, their disordered topologies lack efficient force transmission paths, creating an inherent challenge in simultaneously achieving high strength and energy-absorption capacity. To address this limitation, a stable post-buckling load-bearing reinforcement strategy based on asymmetric configurations is proposed, diverging from conventional buckling suppression strategies. Inspired by the microstructure of cuttlebone, a biomimetic disordered metamaterial system is constructed to validate the strategy. Systematic investigations, including building block simulation, single/multilayer metamaterial design, defect perturbation tests, and failure modulation, demonstrate that such a strategy endows the system with integrated advantages of high strength, enhanced energy-absorption capacity, damage isolation, and controllable collapse. The designed single-layer structure achieves an ultrahigh bearing capacity equivalent to 140,000 times its self-weight. Furthermore, the multilayer structure retains over 90% of its mechanical performance under single-defect conditions and enables the regulation of the transition between crush-dominated and shear failure modes. This work provides new theoretical insights and design strategies for high-performance and highly robust protective metamaterials.

1. Introduction

Periodic mechanical metamaterials [1–3] offer high stiffness [4,5], high strength [6,7], and predictable mechanical responses through highly controllable microstructures [8]. Recent research in periodic cellular and lattice architectures has further expanded their mechanical performance through the rational design of truss, plate, shell, and closed-cell configurations. For example, rib reinforcement of TPMS shell lattices can suppress micro-architectural buckling and improve load-bearing efficiency, while closed-cell plate and microlattice architectures have demonstrated enhanced stiffness, energy absorption, and, in appropriately designed configurations, mechanical isotropy [6,7,9]. Architected paper- and carbon-based lattices have also shown that the combination of cellular topology and material processing can provide competitive strength and energy-absorption performance [10,11]. These developments demonstrate the considerable potential of ordered architectures for achieving high mechanical efficiency. However, their ordered architectures can be sensitive to defects and localized damage, which may trigger penetrating shear bands and abrupt global collapse

[12]. In contrast, disordered metamaterials suppress instability propagation and stress localization through geometric heterogeneity [13–15], enabling progressive collapse, efficient energy absorption, and enhanced defect tolerance [16,17]. These advantages, however, are accompanied by less coordinated load-transfer pathways, generally reduced stiffness and strength [18–20]. The central challenge is therefore to improve load-bearing efficiency without sacrificing the progressive collapse and damage tolerance enabled by disorder.

Recent studies have addressed this challenge through different non-periodic, instability-regulated, and bio-inspired design routes. Fully disordered structures mainly regulate topology, connectivity, and spatial heterogeneity [13,16,18–21], whereas quasi-disordered architectures introduce controlled perturbations into periodic parent lattices [22], and quasicrystalline structures employ deterministic aperiodicity to distribute deformation and suppress global instability [23]. Buckling-regulated metamaterials instead manipulate the onset, sequence, or spatial progression of instability [24–28]. Meanwhile, biological cellular materials have increasingly motivated disordered designs: natural-cellular-inspired quasi-disordered lattices exploit

* Corresponding author at: State Key Laboratory of Advanced Design and Manufacturing Technology for Vehicle, Hunan University, Changsha 410082, China.
E-mail address: xiabz2013@hnu.edu.cn (B. Xia).

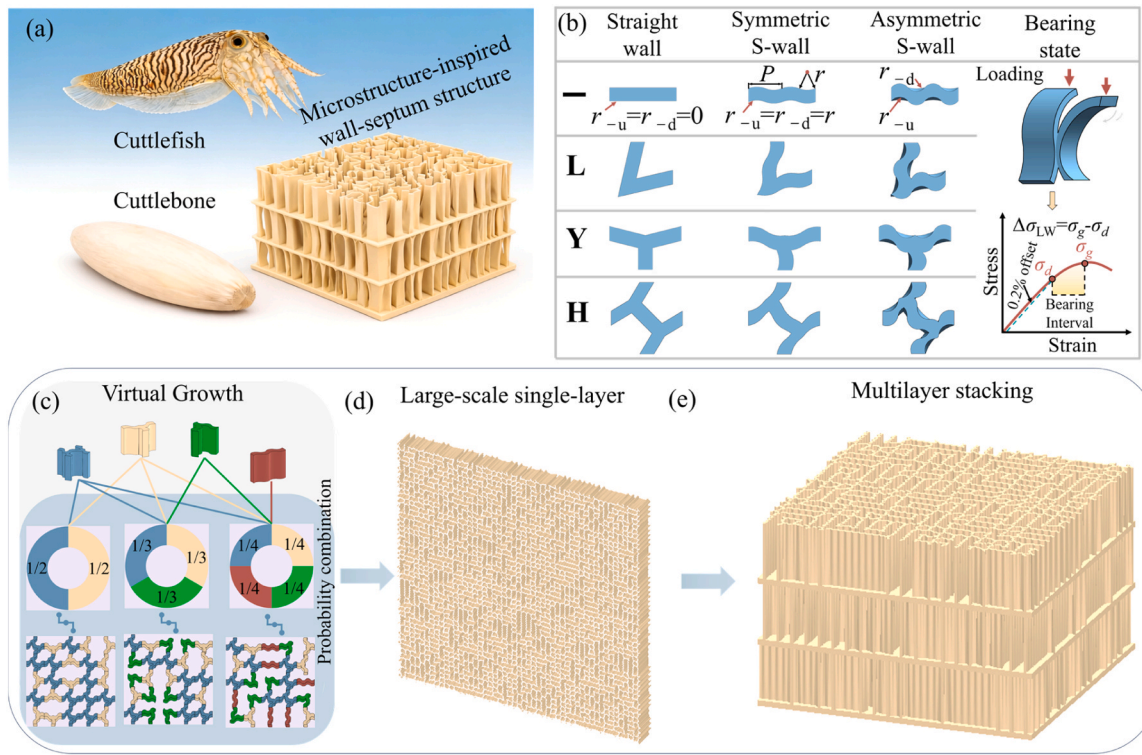


Fig. 1. Design framework and building block configurations of disordered metamaterials. (a) Deep-sea cuttlebone and its corresponding microstructure. (b) Four categories of basic building blocks. Sequentially displaying straight-wall, symmetric S-shaped wall, and asymmetric S-shaped wall configurations from left to right. The buckling state of the straight-wall configuration of the "-" shaped building block is illustrated on the far right. The 0.2% offset construction used to determine the characteristic onset stress σ_d is illustrated in the stress-strain schematic. The offset line is parallel to the initial linear response and shifted by 0.002 along the strain axis; its intersection with the macroscopic stress-strain curve defines σ_d . (c) Virtual growth strategy. By setting probability combinations for the building blocks, disordered metamaterials with geometric heterogeneity are constructed. (d) Large-scale disordered metamaterials generated via the virtual growth strategy. (e) Multilayer disordered metamaterial constructed by stacking single-layer structures with partition layers, corresponding to the layered wall-septum architecture of the cuttlebone microstructure shown in (a).

controlled geometric perturbations [22], disorder-hierarchy coupling has been introduced to enhance progressive deformation and energy absorption [29], growth-inspired strategies regulate the spatial distribution of disordered building blocks to program nonlinear responses [30], and recent cuttlebone-inspired structures exploit controlled disorder to improve strength, energy absorption, and mechanical isotropy [31]. These approaches primarily employ the degree, distribution, hierarchy, or sequence of disorder and instability as design variables.

The present work focuses on a different mechanical target. Rather than modifying the degree of disorder or programming the sequence of buckling events, we exploit the stable load-bearing regime that exists after pronounced local buckling develops but before global structural instability occurs. This regime is defined as the stable post-buckling bearing interval (hereafter the post-buckling bearing interval). Asymmetric wall configurations are introduced at the building-block scale to elevate the stress level and enlarge the width of this interval. The overall architecture remains probabilistically disordered, while the local asymmetric geometry acts as a load-bearing reinforcement mechanism. Therefore, the essential novelty of the present strategy lies not simply in introducing disorder, asymmetry, or buckling, but in using geometric asymmetry to reinforce the mechanically useful post-buckling regime within a disordered architecture. This approach is intended to compensate for the inefficient load transfer associated with disorder while retaining its progressive deformation, energy-dissipation, and damage-tolerance characteristics.

This concept is inspired by cuttlebone, whose asymmetric curved walls and layered partitions combine high load-bearing capacity with non-catastrophic failure under pressure [32–34]. Rather than directly replicating the biological morphology, we abstract these features into

two complementary design principles: asymmetric curved walls reinforce the post-buckling bearing interval at the building-block scale, while layered partitions spatially distribute instability at the structural scale. A cuttlebone-inspired disordered metamaterial is then constructed through a virtual-growth strategy. Finite-element simulations and theoretical analyses are employed to elucidate geometry-dependent deformation and buckling tendencies, while compression experiments quantitatively evaluate single-layer strengthening, multilayer energy dissipation, defect tolerance, and failure-mode regulation.

2. Design framework of disordered metamaterials

The design framework is inspired by the wall-partition architecture of cuttlebone (Fig. 1). The lightweight nature and high bearing capacity of cuttlebone do not derive from a simple periodic stacking of regular straight-wall structures [35], but depend instead on an irregular topological network composed of curved walls, branched walls, junction nodes and layered partitions at the microscale (Fig. 1a). Representative local units are abstracted into four building blocks, namely "-" , "L", "Y", and "H" (Fig. 1b). Furthermore, each of which is further assigned straight-wall, symmetric S-wall, or asymmetric S-wall configurations. The asymmetric configuration captures the characteristic curved-wall geometry of cuttlebone and constitutes the primary functional unit investigated in this work.

The building-block geometry is characterized by period P and curvature radius r . The period is fixed at 2.5 mm, whereas r is varied according to the design requirement. The "-" -shape building block comprises two complete periods, while the numbers of periods in the "L"- , "Y"- , and "H"-shaped blocks adapt to their junction geometry.

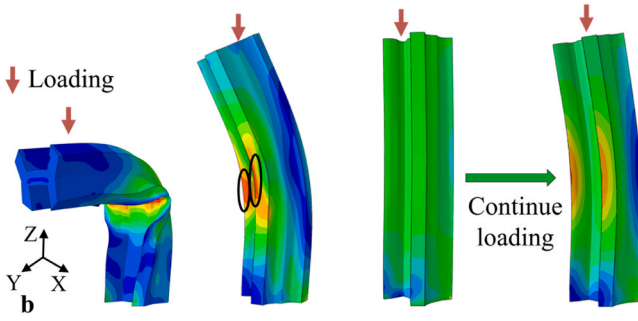


Fig. 2. Finite element models of "H"-shape building blocks. The buckling behaviors of straight-wall, symmetric, and asymmetric configurations are presented from left to right, and the evolution state of asymmetric configurations under continuous loading is displayed on the far right.

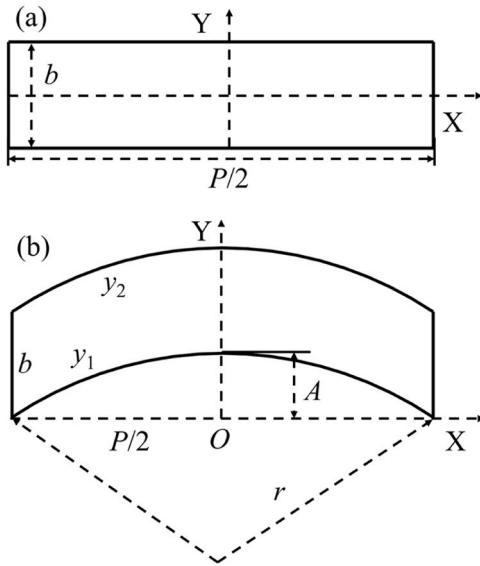


Fig. 3. Cross-sectional geometry used for the comparative theoretical analysis. (a) Straight wall. (b) Symmetric S-shaped wall.

Within one period, the straight-wall configuration of the "H"-shape building block is defined by $r_u = r_d = 0$ (where r_u and r_d denote the curvature radii of the upper and lower planes, respectively). Symmetric configurations satisfy $r_u = r_d = r$, while asymmetric configurations satisfy $r_u \neq r_d$. The curvatures of the "L"-shape, "Y"-shape, and "H"-shape building blocks are described by (r_{Lu}, r_{Ld}) , (r_{Yu}, r_{Yd}) , and (r_{Hu}, r_{Hd}) , respectively (Fig. 1b).

Asymmetric configurations serve as the core functional units that enhance the post-buckling bearing

interval. To quantitatively characterize the buckling evolution and stable load-carrying capacity mediated by these configurations, multiple evaluation metrics are established herein (Fig. 1b). The post-buckling bearing interval is defined as the stable load-bearing regime after pronounced local buckling develops but before global structural instability. Its width is $\Delta\sigma_{LW} = \sigma_g - \sigma_d$, where σ_d is the characteristic onset stress determined from the macroscopic stress-strain curve using a 0.2% offset construction [36], and σ_g is the critical stress corresponding to global instability. The 0.2% offset is used only as a reproducible operational measure of departure from the initial linear structural response and as a proxy for pronounced buckling-induced nonlinearity; it does not represent constitutive material yielding. Thus, $\Delta\sigma_{LW}$ characterizes a geometrically nonlinear structural post-buckling regime in which local buckling has developed while the metamaterial remains globally stable. The initial Young's modulus E_0 and specific strength are introduced

simultaneously as supplementary evaluation metrics to quantify the strength enhancement induced by the asymmetric configuration. For multilayer metamaterials, the energy-absorption response under compression is further employed to quantify structural energy-dissipation capability. Throughout this work, this energy-based metric is used to characterize the deformation and dissipation performance of the structure rather than fracture toughness.

On this basis, a virtual growth strategy is adopted in this work (Fig. 1c, Appendix A). Different types of building blocks are randomly distributed in space according to predefined probability combinations, large-scale disordered metamaterials with the structural characteristics of single-layer cuttlebone are reproduced (Fig. 1d). Here, the term "disordered" specifically refers to topological or architectural disorder arising from stochastic assembly under prescribed probabilistic and connectivity constraints. Unlike periodic lattices, the resulting architectures do not possess a translationally repeatable unit cell, and their local connectivity, chamber geometry, branching patterns, and spatial arrangements vary among independently generated realizations. The disorder considered here is therefore constrained rather than unrestricted: the available building blocks, local connection rules, and characteristic geometric scale are prescribed by the virtual-growth framework, whereas the spatial occurrence of the building blocks and the resulting topology are probabilistically generated. Subsequently, single-layer disordered metamaterials are coupled and stacked with layered partitions to construct multilayer disordered metamaterials (Fig. 1e), providing a platform for further investigation of the dissipation effects of the asymmetric configuration in multilayer structures.

3. Performance testing of disordered metamaterials

3.1. Finite element analysis of building block deformation and buckling tendencies

Building-block-scale finite-element analyses are performed in ABAQUS/Standard to compare geometry-dependent deformation modes and relative buckling tendencies rather than to quantitatively reproduce material yielding, fracture, or complete experimental collapse. The resin is modeled as an isotropic linear-elastic solid with the Young's modulus of 2649–2731 MPa, Poisson's ratio of 0.40–0.44, a density of 1.12–1.18 g/cm³ is assigned, although inertial effects are not involved in the present quasi-static analysis. A general static step with geometric nonlinearity is used. The lower surface is fixed in all translational degrees of freedom, and a progressively increasing uniform axial pressure is applied to the upper surface. C3D8R elements are used with mesh-sensitivity verification. No contact, self-contact, or initial geometric imperfection is introduced. Accordingly, the simulations are interpreted only as comparative assessments under identical idealized conditions.

Fig. 2 compares the H-shaped building blocks under identical loading. The straight-wall configuration exhibits the largest deformation and preferential X-axis buckling. Introducing symmetric curvature ($r_{Hu} = r_{Hd} = 1$ mm) reduces the deformation but produces an additional Y-direction buckling tendency near the wall edge. The asymmetric configuration ($r_{Hu} = 0.8$ mm, $r_{Hd} = 2.6$ mm) shows substantially smaller deformation at the same pressure, with pronounced buckling developing only upon further loading. The same relative trend is observed for the "L"-, "Y"-, and "H"-shaped blocks (Appendix B).

3.2. Theoretical analysis of buckling behavior

To interpret the geometry-dependent buckling tendency, the straight-wall and symmetric configurations are compared using an idealized Euler analysis. The geometric slenderness of the representative wall segment was also checked before applying the Euler approximation. The effective segment height is $h_b = 20$ mm, and the wall thickness is $b = 1$ mm, giving a height-to-thickness aspect ratio of $h_b/b = 20$. Nevertheless, because the complete H-, Y-, and L-shaped building blocks

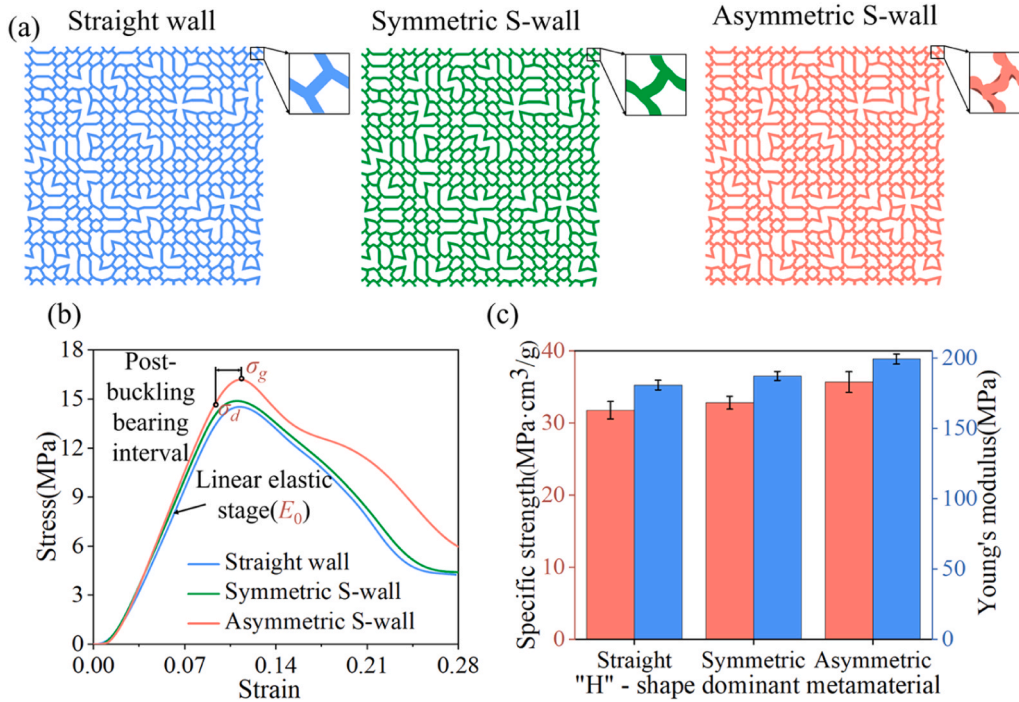


Fig. 4. Mechanical performances of disordered metamaterials. (a) Morphologies of three types of disordered metamaterials dominated by "H"-shape building blocks. (b) Stress-strain curves of the three disordered metamaterials. The regions corresponding to the post-buckling bearing interval are marked. (c) Specific strength and Young's modulus of the three disordered metamaterials.

contain branching junctions and additional constraints, the Euler formulation is used only for local comparative interpretation rather than for quantitative prediction of their global critical buckling loads. For identical material properties, boundary conditions, and structural height, the idealized Euler critical load P_b is governed by the area moment of inertia [17]:

$$P_b = \frac{\pi^2 EI_b}{k_b h^2} \quad (1)$$

Where P_b is the idealized Euler critical buckling load used for comparative theoretical analysis, E represents the material's elastic modulus, k_b denotes the constraint coefficient, and I_b indicates the area moment of inertia.

The beam segments within a single period exhibit geometric symmetry. Therefore, a half-period model is adopted to establish the models for the area moments of inertia of various configurations. The area moment of inertia of the straight wall is first formulated with reference to Fig. 3a. The area moment of inertia I_{ZX} of the straight wall about the X-axis is defined as:

$$I_{ZX} = \int_S y^2 dS_z \quad (2)$$

Where S_z denotes the total cross-sectional area, dS_z represents the differential area of the cross-section, and y is the perpendicular distance from dS_z to the X-axis. The differential area is formulated as:

$$dS_z = \frac{P}{2} dy \quad (3)$$

The area moment of inertia I_{ZX} can be further expressed as:

$$I_{ZX} = \int_{-\frac{b}{2}}^{\frac{b}{2}} \frac{P}{2} y^2 dy = \frac{Pb^3}{24} \quad (4)$$

The area moment of inertia I_{ZY} of a straight wall about the Y-axis is expressed as:

$$I_{ZY} = \int_S x^2 dS = \int_{-\frac{p}{4}}^{\frac{p}{4}} bx^2 dx = \frac{bp^3}{96} \quad (5)$$

Where x refers to the perpendicular distance from the differential area to the Y-axis. The area moment of inertia of the symmetric S-shaped wall is further formulated with reference to Fig. 3b. The arc curve equations y_2 and y_1 for the upper and lower boundaries of the S-shaped wall are expressed respectively as:

$$y_1 = \sqrt{r^2 - x^2} + A - r \quad (6)$$

$$y_2 = \sqrt{r^2 - x^2} + A - r + b \quad (7)$$

When the area moment of inertia I_{SX} of the S-shaped wall about the X-axis is calculated, the differential area is expressed as follows:

$$dS_s = 2 \left(\sqrt{r^2 - (y + r - A - b)^2} - \sqrt{r^2 - (y + r - A)^2} \right) dy \quad (8)$$

Based on Eq. (8), the area moment of inertia I_{SX} can be expressed as:

$$I_{SX} = 2 \int_S \left(\sqrt{r^2 - (y + r - A - b)^2} - \sqrt{r^2 - (y + r - A)^2} \right) y^2 dy \quad (9)$$

Where A denotes the amplitude of the circular arc. The relationship between the amplitude A and the radius r is given by:

$$A_b = r - \sqrt{r^2 - \frac{p^2}{16}} \quad (10)$$

When calculating the area moment of inertia I_{SY} of the S-shaped wall about the Y-axis, the differential area can be expressed as:

$$dS_s = 2b dx \quad (11)$$

Based on Eq. (11), the area moment of inertia I_{SY} can be expressed as:

$$I_{SY} = \int_0^{\frac{p}{4}} 2bx^2 dx = \frac{bP^3}{96} \quad (12)$$

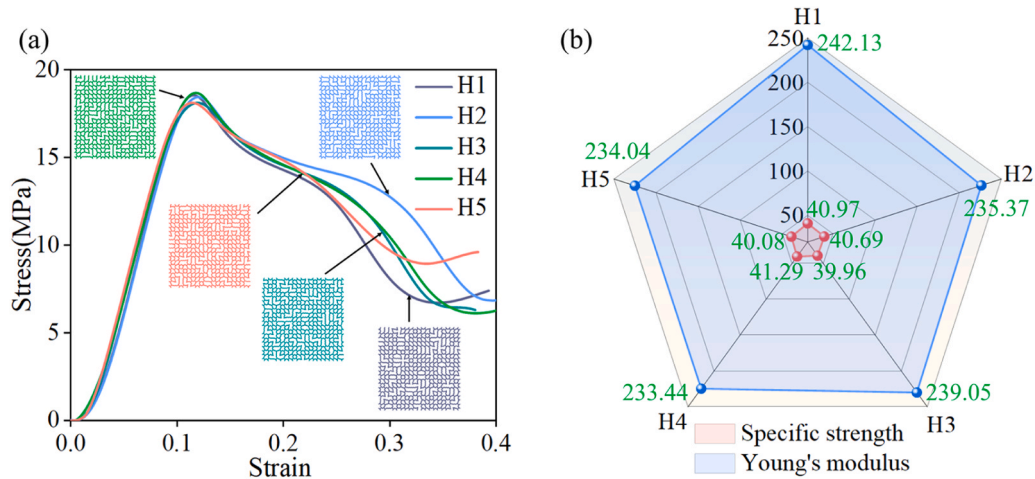


Fig. 5. Robustness of mechanical performances. (a) Stress-strain curves of five asymmetric disordered metamaterials generated with the same probability combination. (b) Radar chart of specific strength and Young's modulus for the five metamaterials.

The calculated moments of inertia are $I_{ZX} = Pb^3/24 = 0.104$ and $I_{ZY} = bP^3/96 = 0.163$ for the straight wall, indicating preferential buckling about the X-axis. For the symmetric S-wall, $I_{SX} = 0.7657$ and $I_{SY} = 0.163$, thus, symmetric curvature substantially increases resistance to X-axis bending, while the geometric width-thickness disparity suppresses macroscopic Y-axis buckling to a deflection tendency. This simplified Euler treatment is not extended to the asymmetric configuration because its nonuniform curvature shifts the centroid, and the original symmetry axes are no longer centroidal axes. The asymmetric geometry is therefore assessed qualitatively by FE simulations (Fig. 2) and quantitatively by compression experiments (Fig. 4). It should be emphasized that the Euler analysis and the post-buckling bearing interval describe two sequential stages of the structural response rather than the same constitutive regime. The Euler analysis provides an idealized interpretation of the geometry-dependent elastic buckling tendency prior to pronounced nonlinear deformation, whereas, after local buckling is activated, the subsequent bearing response is governed primarily by geometrically nonlinear deformation and load redistribution among the building blocks.

3.3. Experimental sample fabrication and performance testing

Disordered metamaterials with straight-wall, symmetric S-wall, and asymmetric S-wall configurations are fabricated using a Zhongrui 880 stereolithography printer and white photosensitive resin (Fig. 4a). The resin has a tensile strength of 41–58 MPa, flexural modulus of 2712–2791 MPa, and flexural strength of 69–75 MPa. After fabrication, specimens are ultrasonically cleaned in anhydrous ethanol for two 3-min cycles. For the generated disordered metamaterials, compression tests are conducted on them (The testing apparatus is shown in Appendix C). Quasi-static compression tests are conducted using a UTM5605X series microcomputer-controlled electronic universal testing machine, equipped with a high-precision 600 kN load cell. To ensure stable specimen alignment and containment throughout the loading process, a pair of custom compression platens machined from 45-steel is utilized. All uniaxial compression tests are performed at a constant displacement rate of 1 mm/min.

For the proposed disordered metamaterials, compression is applied along the longitudinal direction, i.e., normal to the stacked partition layers. Owing to their layered architecture, these structures are architecturally anisotropic, and the mechanical properties reported in this work therefore correspond specifically to this prescribed loading direction. Mechanical responses in the transverse directions are not evaluated in the present study. The compressive stress-strain responses reported throughout this work are expressed in terms of engineering stress and

engineering strain. The engineering stress is calculated as F/A_0 , where F is the measured compressive force and A_0 is the cross-sectional area of the specimen perpendicular to the loading direction. The engineering strain is calculated as δ/H_0 , where δ is the axial compression displacement, and H_0 is the initial specimen height along the loading direction. The geometric parameters of the tested specimens are summarized in Appendix J.

H-dominated disordered metamaterials generated with the probability combination (0.7, 0.1, 0.1, 0.1) are used to compare the three wall configurations. The relative densities of the straight, symmetric, and asymmetric specimens are 41.53%, 41.37%, and 41.26%, respectively. Their maximum difference is only 0.27 %age points, indicating that the three configurations are compared under nearly identical material-volume conditions (Appendix J). The measured σ_d values for the straight, symmetric, and asymmetric configurations are 13.63 MPa, 13.78 MPa, and 14.26 MPa, respectively, while the corresponding σ_g values are 14.52 MPa, 14.88 MPa, and 16.19 MPa. Thus, $\Delta\sigma_{LW}$ increases from 0.89 MPa for the straight wall to 1.10 MPa for the symmetric S-wall and 1.93 MPa for the asymmetric S-wall (Fig. 4b). The asymmetric architecture also achieves a specific strength of 35.67 ± 1.43 MPa·cm³/g and a Young's modulus of 199.22 ± 3.58 MPa (Fig. 4c), exceeding the other two configurations. These findings demonstrate that the asymmetric configurations can help enhance the strength performance of disordered metamaterials. The same enhancement trend is observed in " - " -shape, "L" -shape, and "Y" -shape building blocks dominated metamaterials (Appendix D and E).

Considering the random characteristics of disordered metamaterials, this work further verifies the statistical robustness of the mechanical strengthening effect of asymmetric configurations (Fig. 5a). Statistical robustness is evaluated using five independently generated asymmetric structures (H1–H5) with the same probability combination (0.7, 0.1, 0.1, 0.1). The relative densities of H1–H5 are 41.22%, 41.21%, 41.22%, 41.17%, and 41.25%, respectively, confirming that the statistical comparison is conducted among specimens with nearly identical material fractions (Appendix J). Their stress-strain curves and post-buckling bearing intervals show close agreement. The specific strengths are 40.97, 40.69, 39.96, 41.29, and 40.08 MPa·cm³/g, while the Young's moduli are 242.13, 235.37, 239.05, 233.44, and 234.04 MPa, giving coefficients of variation of only 1.40% and 1.56%, respectively (Fig. 5b). This consistency arises from statistically similar building-block and chamber distributions despite different macroscopic realizations (Appendix F). Benefiting from the strengthening effect of the asymmetric configuration in the post-buckling bearing interval, the bearing capacity of the disordered metamaterials reaches 140,000 times their self-weight, which is significantly superior to that of existing biomimetic

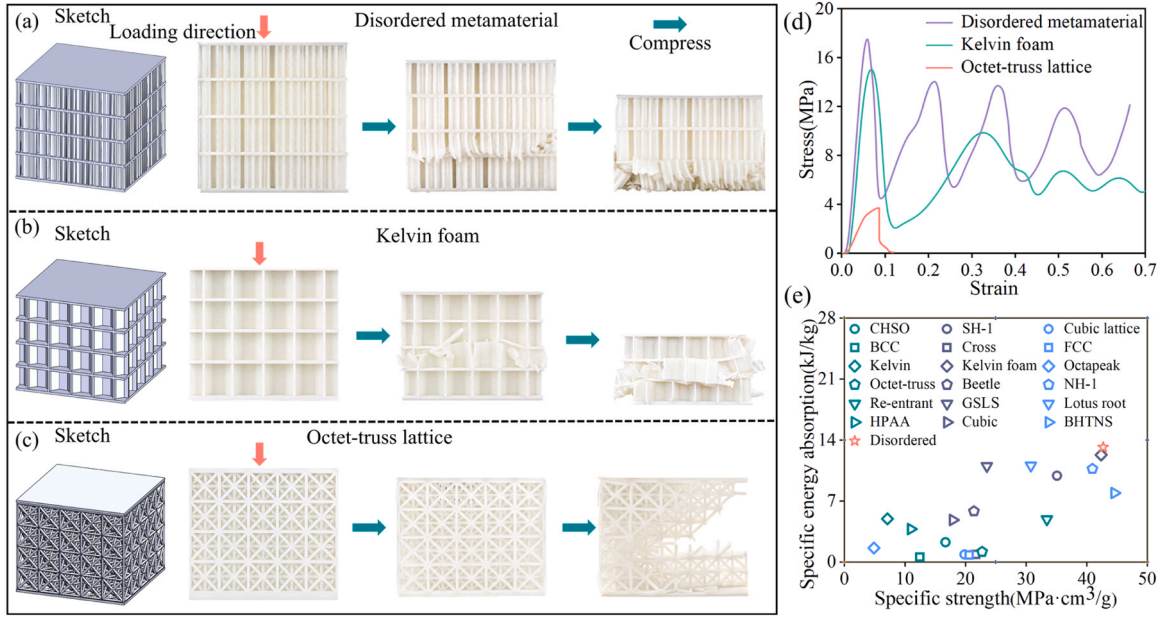


Fig. 6. Mechanical performances of multilayer disordered metamaterials. (a-c) Compression process of multilayer disordered metamaterials, Kelvin foams, and Octet-truss lattices. (d) Stress-strain curves for the three types of structures. (e) Ashby performance diagram. The data and corresponding material and testing information are summarized in [Appendix G](#).

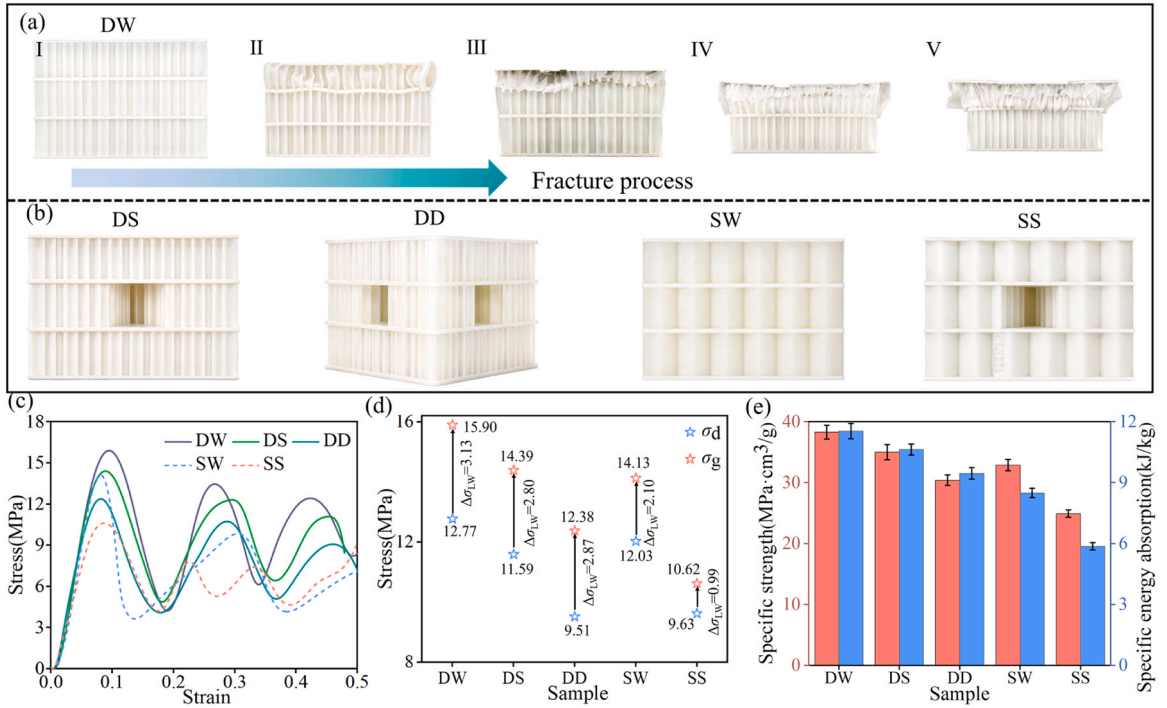


Fig. 7. Defect insensitivity of multilayer disordered metamaterials. (a) Intact multilayer disordered metamaterial, demonstrating its progressive collapse process under quasi-static compression. (b) Comparison of initial configurations, including multilayer disordered metamaterials with single/double defects and periodic honeycomb structures with intact/single defects. (c) Stress-strain curves for the five structures. (d) Quantification of the latency window for the five structures. (e) Specific strength and specific energy absorption for the five structures.

cuttlebone structures [17].

4. Performance advantages of multilayer disordered metamaterials

This work further demonstrates that a single-layered disordered metamaterial provides a single bearing stage, thereby limiting the

energy absorption potential. To overcome this limitation, multilayer disordered metamaterials comprising four layers are fabricated. Quasi-static compression tests are conducted, with Kelvin foams [17] and Octet-truss lattices [37,38] adopted as control groups (Fig. 6). Their relative densities are 37.30%, 31.78%, and 18.65%, respectively (Appendix J). It should be noted that the proposed multilayer disordered metamaterial is direction-dependent. Therefore, the comparison in

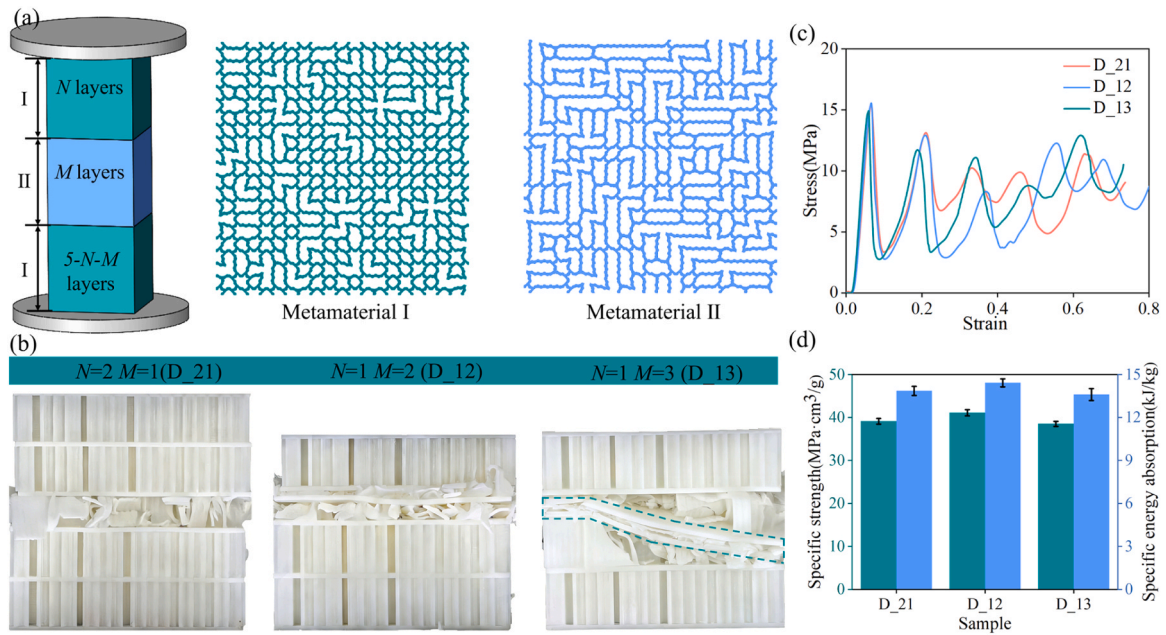


Fig. 8. Editability of failure modes for multilayer disordered metamaterials. (a) Schematic diagram of multilayer disordered metamaterial design. (b) Failure modes of three different multilayer disordered metamaterials under compression. (c) Stress-strain curves of the three disordered metamaterials. (d) Specific strength and specific energy absorption.

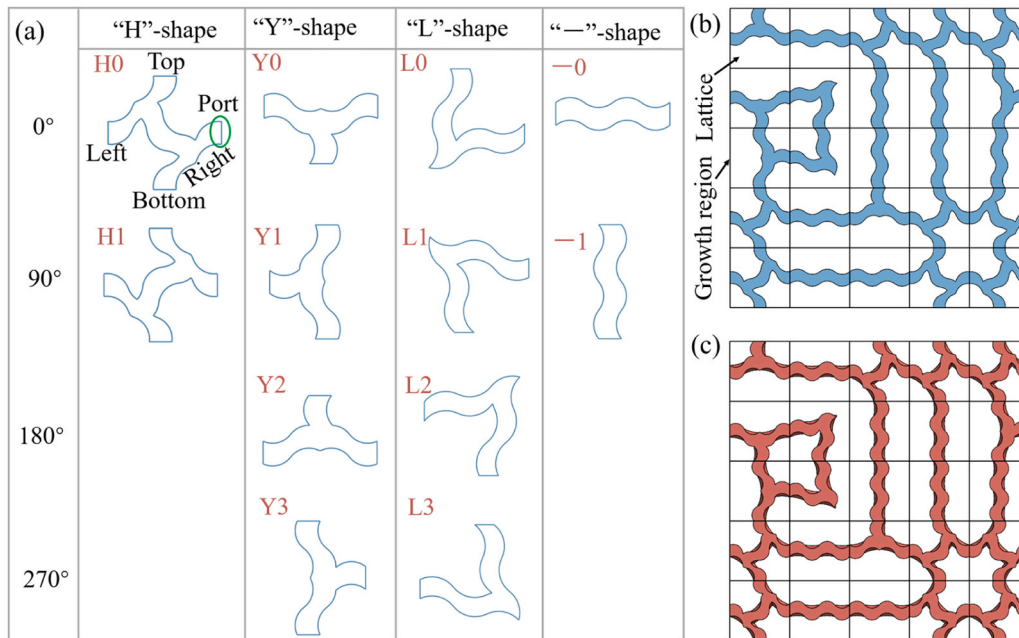


Fig. 9. Implementation process of the virtual growth strategy. (a) Building blocks. Comprising 4 types of basic building blocks and 8 types of building block variants. (b-c) Disordered metamaterials. Two disordered metamaterials composed of building blocks with symmetric and asymmetric configurations are presented, respectively.

Fig. 6 is restricted to the compressive responses measured along the prescribed loading directions shown in Fig. 6a-c.

It should be emphasized that the comparison in Fig. 6 is not intended as a strict topology- or dimensionality-matched comparison. The proposed metamaterial is constructed from planar disordered layers interconnected by partition layers, whereas the Octet-truss lattice are three-dimensional cellular architectures with different geometric and directional characteristics. In this study, the proposed multilayer disordered metamaterial, the Kelvin-foam benchmark, and the Octet-truss benchmark were all reconstructed, fabricated by the same printing process,

and tested under the same top-to-bottom quasi-static compression condition. Accordingly, the comparison is intended to evaluate their direction-specific compressive responses under a common experimental framework rather than to imply topological equivalence or direction-independent superiority. Specific strength and specific energy absorption are additionally used to reduce the direct influence of differences in material usage and apparent density.

As shown in Fig. 6a, the multilayer disordered metamaterial exhibits typical progressive failure characteristics during compression. The structures undergo local buckling successively along the layered

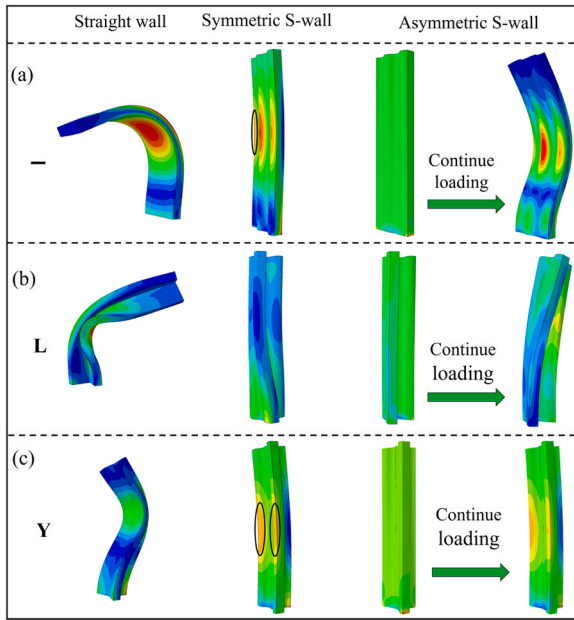


Fig. 10. Numerical deformation and buckling tendencies of three different building blocks. (a) Numerical buckling behavior of the “-”-shape building block. From left to right are the deformation diagrams of the straight wall, the symmetric S-shaped wall, and the asymmetric S-shaped wall under compression. The black ellipse highlights the region of stress asymmetry. (b-c) Numerical buckling behaviors of the “L”-shape and “Y”-shape building blocks.

interfaces, and the instability damage is released in stages, eventually forming a multi-stage stable collapse plateau. This phenomenon is clearly reflected by the corresponding stress-strain curves (Fig. 6d), where the post-buckling bearing interval is no longer a transient local effect of single-layer structures, but rather evolves into multi-peak progressive characteristics. The strength σ_g decreases in a stepwise manner without any sudden load drops, demonstrating excellent bearing stability and progressive energy dissipation capability. In contrast, although the Kelvin foam (Fig. 6b) exhibits layer-by-layer collapse, the interlayer deformation coupling is strong. This is reflected in the stress-strain curve by a faster decay of the strength σ_g and a limited width of the stable bearing plateau (Fig. 6d). Furthermore, sustained post-buckling bearing intervals are virtually absent in the Octet-truss lattice (Fig. 6c), which undergoes rapid, catastrophic global fracture under compression. The corresponding stress-strain curve features only a single peak, following the onset of global instability, the bearing capacity drops sharply, resulting in a low energy absorption capacity (Fig. 6d).

The essence of such performance differences lies in the fact that Kelvin foams are categorized as bending-dominated structures. Although instantaneous catastrophic failure can be prevented, their strength and modulus are inherently limited by the bending deformation mode. The octet-truss lattice is a tensile/compressive dominant structure that lacks an effective damage tolerance mechanism, rendering it

incapable of dissipating energy through local buckling. In contrast, the multilayer disordered metamaterials achieve controllability of post-buckling deformation and bearing behavior through the synergy of their layered structure and asymmetric configuration, thereby significantly enhancing the energy absorption capacity.

Fig. 6e benchmarks the proposed multilayer disordered metamaterial against 18 representative porous/lattice architectures reconstructed and experimentally evaluated in the present study. Importantly, Fig. 6e is constructed as a controlled within-study benchmark rather than as an Ashby diagram compiled directly from literature-reported mechanical-property data. All reference architectures were fabricated using the same photosensitive resin and stereolithography process and were tested under the same quasi-static compression protocol. This controlled framework reduces the confounding effects associated with differences in constituent material, manufacturing route, and testing protocol. Literature-reported mechanical data obtained using different material systems, manufacturing processes, characteristic scales, relative-density ranges, or loading conditions are therefore not directly incorporated into Fig. 6e. Within this controlled benchmark, the proposed structure achieves a specific strength of $42.70 \text{ MPa}\cdot\text{cm}^3/\text{g}$ and a specific energy absorption of 13.17 KJ/kg , placing it in the high-performance region of this controlled benchmark. Although its specific strength is slightly below that of the bamboo-mimetic honeycomb ($44.58 \text{ MPa}\cdot\text{cm}^3/\text{g}$), its specific energy absorption is 1.66 times higher, demonstrating a favorable balance between load-bearing capacity and energy absorption.

5. Defect insensitivity

The experimental results of the multilayer disordered metamaterials confirm that the synergistic enhancement of strength and energy-absorption capability can be achieved through the layered dissipation of the structure. However, whether the inevitable manufacturing defects or local damages in engineering applications will disrupt this mechanism is the core issue in verifying its engineering applicability. Inter-layer defects with identical dimensions and locations are introduced into three-layer disordered metamaterials and a periodic contrast structure in this work. The effects of these defects on the mechanical performance are compared (Fig. 7).

The intact multilayer structure (DW) exhibits sequential layerwise post-buckling collapse (Fig. 7a). Introducing single (DS) or double (DD) defects preserves this progressive mode without triggering penetrating shear bands or catastrophic global instability (Fig. 7b). In contrast [39], in the periodic spider-web honeycomb structures (SW is the intact structure and SS indicates the defective structure), the defects act directly as loci of stress concentration. The relative densities of DW, DS, DD, SW, and SS are 37.76%, 37.37%, 37.02%, 39.12%, and 38.81%, respectively (Appendix J). Under compression, they rapidly trigger global instability, with deformation propagating rapidly from the local defects to the entire structure (Appendix H). This distinct behavior is directly manifested in the stress-strain curves (Fig. 7c). Only mild decay of strength σ_g is observed for defective disordered metamaterials in comparison with the intact structure. Conversely, compared with the

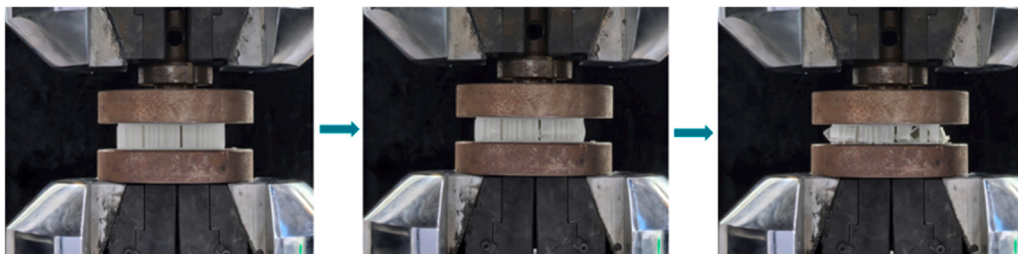


Fig. 11. Mechanical compression experiment.

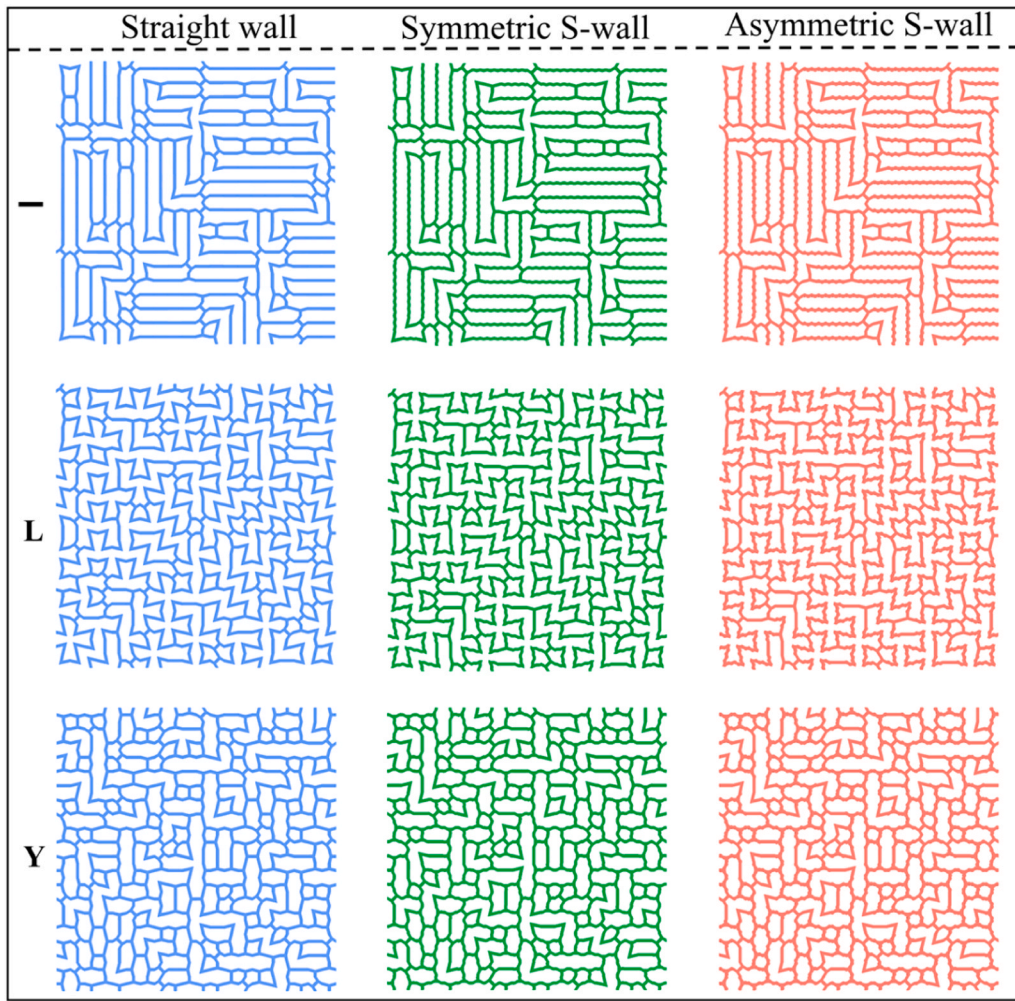


Fig. 12. Disordered metamaterial samples under different probability combinations. From left to right are the disordered metamaterials in the straight-wall, symmetric, and asymmetric configurations.

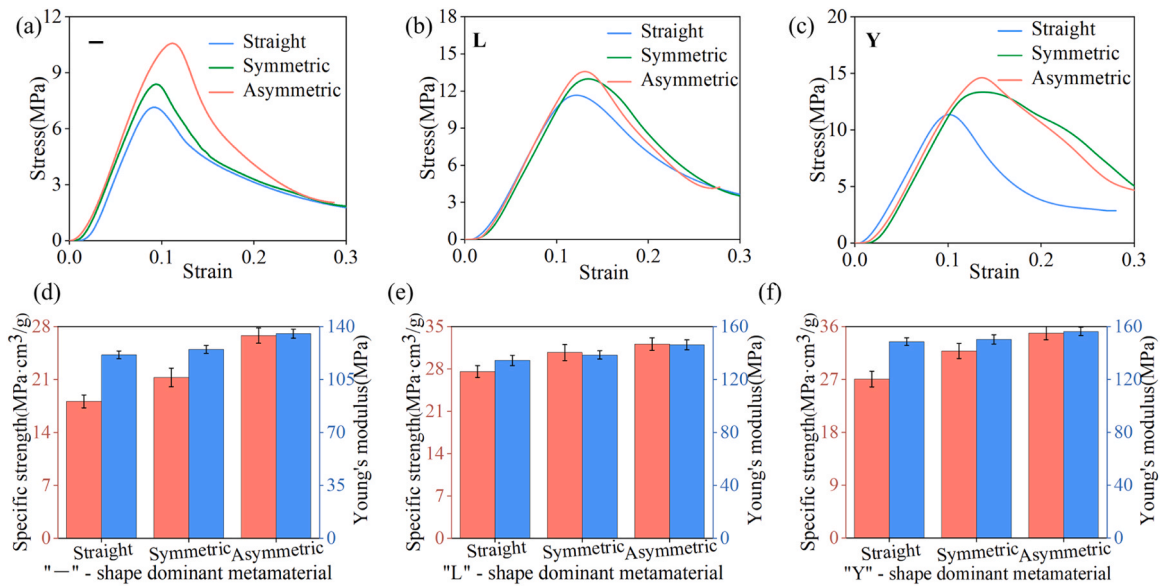


Fig. 13. Mechanical performances of three types of disordered metamaterials under different configurations. (a-c) Stress-strain curves of the three types of disordered metamaterials. For each type of metamaterial, the stress-strain curves of straight walls, symmetrical, and asymmetrical configurations are plotted. (d-f) Specific strength and Young's modulus of the three types of disordered metamaterials.

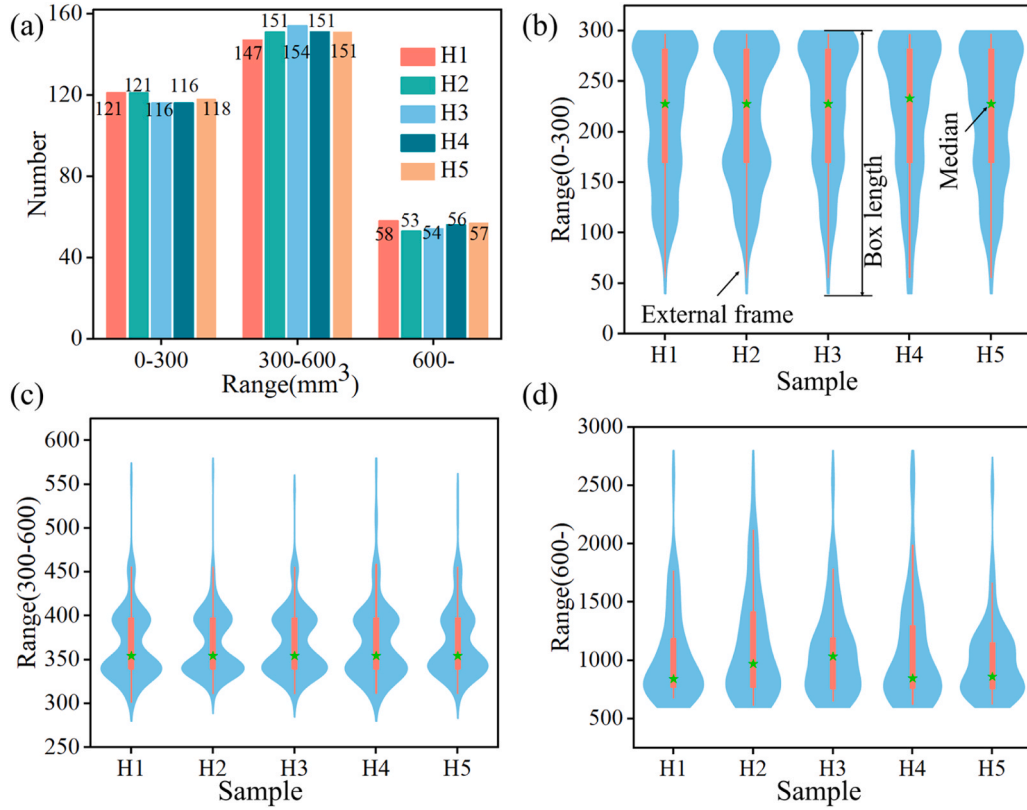


Fig. 14. Robustness of the chamber characteristics of disordered metamaterials. (a) Number of chambers across different volume ranges for five samples. (b) Violin plot for the 0–300 mm³ volume range. Includes 5 samples and marks the external frame, median, and box length. (c–d) Violin plots for the other two volume ranges.

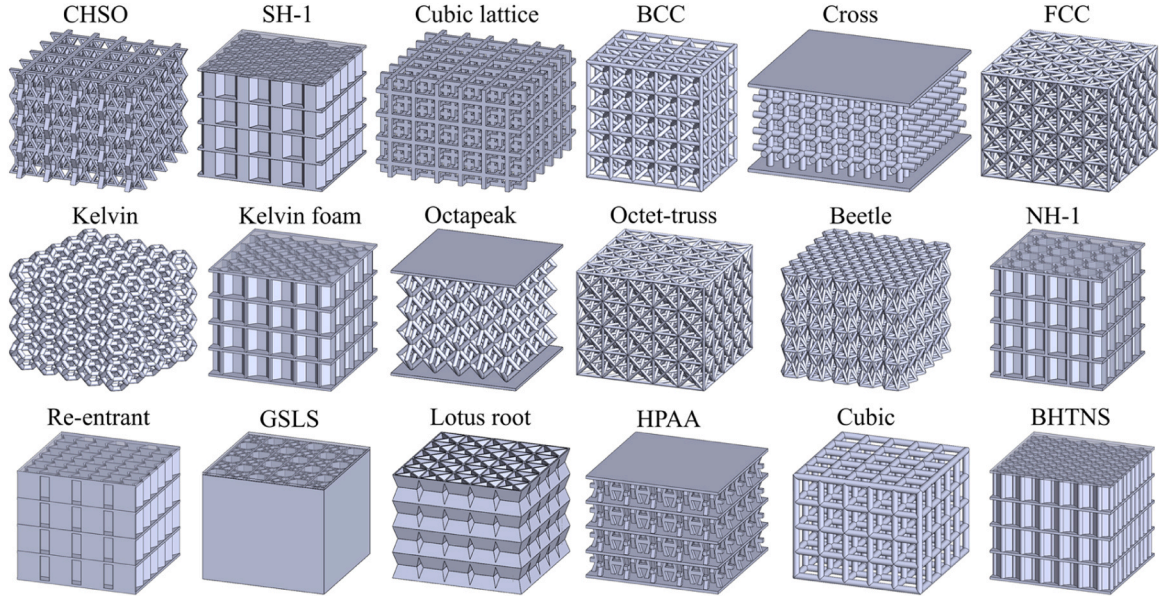


Fig. 15. 18 different periodic structures.

intact periodic structure, the defective periodic structure exhibits a precipitous decline in the strength σ_g , accompanied by a severe reduction in the stable plateau width and a marked degradation in overall mechanical performance.

To quantitatively characterize the degradative effect of defects on structural bearing capacity, this work presents a quantitative analysis of the initial post-buckling bearing interval for the five structures (Fig. 7d). The initial post-buckling intervals are 12.77–15.90 MPa for DW

($\Delta\sigma_{LW}=3.13$ MPa), 11.59–14.39 MPa for DS (2.80 MPa), and 9.51–12.38 MPa for DD (2.87 MPa). By comparison, the interval of the periodic reference decreases from 12.03 to 14.13 MPa for SW (2.10 MPa) to 9.63–10.62 MPa for SS (0.99 MPa). Thus, defects primarily shift the post-buckling regime of the disordered architecture toward lower stress while largely preserving its width, whereas the periodic reference exhibits substantial interval contraction.

The aforementioned advantages are ultimately reflected in the

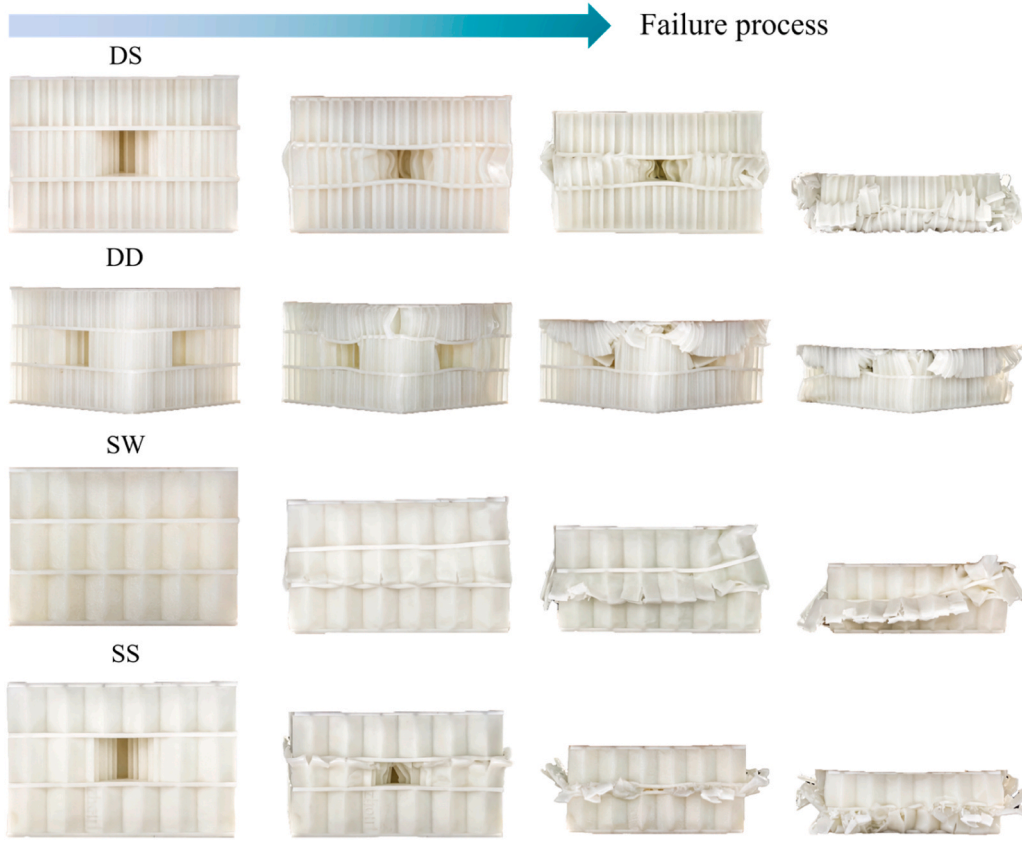


Fig. 16. Failure processes of multilayer disordered metamaterials and periodic structures. From top to bottom, the failure processes of single-defect disordered metamaterials, double-defect disordered metamaterials, defect-free spider-web honeycomb structures, and single-defect spider-web honeycomb structures are shown.

macroscopic mechanical performances (Fig. 7e). Compared to DW, the specific strength and specific energy absorption of DS decrease by 8.59% and 7.81%, respectively. For DD, these values decrease by 13.14% and 11.01% relative to DS, thereby demonstrating a progressive degradation trajectory. In contrast, the specific strength and specific energy absorption of SS exhibit sharp declines of 24.19% and 30.89% relative to SW, respectively, which manifests a significantly higher defect sensitivity. This disparity indicates that the superior mechanical performances of the multilayer disordered metamaterial are achieved not by the elimination of defects, but rather through the layered dissipation to prevent the simultaneous exhaustion of the global bearing capacity.

6. Editable failure modes

The regulatory ability of asymmetric configurations endows multilayer disordered metamaterials with excellent synergistic performance in strength and energy absorption, as well as defect insensitivity. This work further demonstrates that by tuning the post-buckling bearing intervals of metamaterials of individual layers, precise tailoring of failure modes can be achieved. Thus, the damage path can be precisely controlled in protective applications, protecting the critical functional regions. Multilayer structures assembled from two types of disordered metamaterials with distinct bearing capacities are fabricated to verify this design concept (Fig. 8a). Specifically, metamaterial I exhibits a high bearing capacity (probability combination of (0.7, 0.1, 0.1, 0.1)), while metamaterial II is characterized by a low bearing capacity (probability combination of (0.2, 0.2, 0.2, 0.4)). By adjusting the proportion of the layers in metamaterial II, three multilayer structures with a total of 5 layers, namely D₂₁, D₁₂, and D₁₃, are constructed. The relative densities of D₂₁, D₁₂, and D₁₃ are 36.20%, 34.95%, and 34.54%, respectively (Appendix J).

Compression results indicate that the metamaterial II preferentially triggers buckling. Consequently, damage propagates predominantly within this functional layer (Appendix I). Meanwhile, distinct failure modes are induced by interlayer metamaterial differences (Fig. 8b): D₂₁ and D₁₂ exhibit crush-band failure characteristics, whereas D₁₃ develops inclined penetrating shear bands (the green dashed line marks the location of the shear band). These variations in failure behavior are attributed to the interlayer confinement effect and the stress triaxiality mechanism. The intensity of the interlayer confinement is regulated by the geometric ratio K/M (defined as the ratio of the number of layers in the width direction to that in the thickness

direction) of the metamaterial II. The dimensionless stress triaxiality η is introduced to classify the failure regimes: crush failure correlates with elevated η values, whereas penetrating failure dominated by shear band is associated with low η values [12,40].

$$\eta = \frac{\frac{1}{3}(\sigma_x + \sigma_y + \sigma_z)}{\sqrt{\frac{1}{2}((\sigma_x - \sigma_y)^2 + (\sigma_y - \sigma_z)^2 + (\sigma_z - \sigma_x)^2)}} \quad (13)$$

Where σ_x and σ_y represent the lateral stresses along the x and y directions, respectively, while σ_z denotes the axial stress along the z direction. With fixed total structural layers and lateral layers, the K/M ratio is governed exclusively by the layer thickness parameter M of the metamaterial II. When the K/M ratio is large, the thickness of the metamaterial II accounts for a small proportion. This configuration enhances the lateral constraint exerted by metamaterial I, thereby inducing localized axial stress concentration, escalating the stress triaxiality, and ultimately culminating in crush-band failure. Conversely, a reduced K/M ratio relieves this interlayer confinement, which decreases the stress triaxiality and consequently triggers a transition to penetrating shear failure. Thus, η is used here as a mechanistic

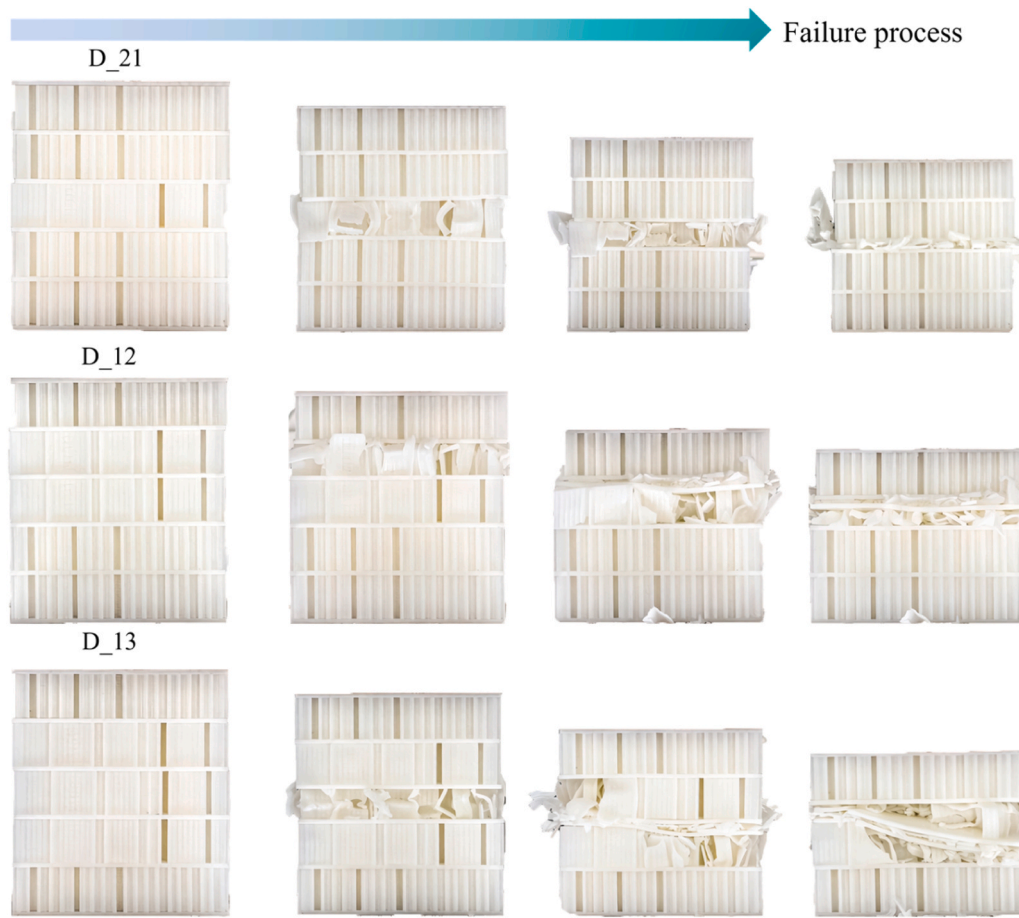


Fig. 17. Failure processes of multilayer structures. The failure processes of D_21, D_12, and D_13 are shown from top to bottom.

descriptor to interpret the experimentally observed failure-mode transition rather than as a quantitatively measured field variable.

Fig. 8c illustrates the stress-strain curves for D_21, D_12, and D_13, which exhibit distinct stepwise fluctuations. Fig. 8d encapsulates the corresponding statistical summarization of their mechanical performances. The quantitative results indicate that the specific strengths of D_21, D_12, and D_13 are $39.09 \pm 0.65 \text{ MPa}\cdot\text{cm}^3/\text{g}$, $41.08 \pm 0.73 \text{ MPa}\cdot\text{cm}^3/\text{g}$, and $38.49 \pm 0.58 \text{ MPa}\cdot\text{cm}^3/\text{g}$, respectively, with corresponding specific energy absorption values of $13.86 \pm 0.32 \text{ KJ/kg}$, $14.42 \pm 0.28 \text{ KJ/kg}$, and $13.60 \pm 0.42 \text{ KJ/kg}$. Notably, the D_12 metamaterial, which achieves layered dissipation through steady-state crushing, exhibits the optimal comprehensive performance. These findings demonstrate that by appropriately controlling the proportion of metamaterial layers with low bearing capacity, the energy dissipation advantages of the post-buckling bearing interval can be fully utilized. Conversely, an excessive fraction triggers shear instability, thereby degrading overall mechanical performance.

7. Conclusion

This work proposes an asymmetric post-buckling reinforcement strategy to address the strength-energy absorption trade-off in disordered metamaterials. Asymmetric configurations delay the development of buckling-induced deformation and shift the stable post-buckling bearing regime toward higher stress levels, thereby enhancing structural load-bearing capacity. Extending this mechanism to multilayer architectures produces progressive layerwise collapse, improving energy absorption while preserving substantial mechanical performance in the presence of defects. The macroscopic failure mode can further be tailored between crush-dominated and penetrating shear responses by

adjusting the proportion of layers with different bearing capacities. These findings provide critical theoretical insights and design guidelines for developing next-generation advanced protective metamaterials characterized by high strength, high energy-absorption capacity, defect robustness, and editable failure modes.

CRediT authorship contribution statement

Yong Liu: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Ye Zhou:** Visualization. **Kai Wei:** Supervision. **Gary P.T. Choi:** Writing – review & editing, Writing – original draft, Funding acquisition. **Baizhan Xia:** Writing – review & editing, Writing – original draft, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgment

This work was supported by the National Natural Science Foundation of China (Grant Nos. 52475254 and 12072108), the Natural Science Foundation of Hunan Province for Young Scientists Fund (Category A, including continuation funding projects) (Grant No. 2026JJ20001), CUHK Vice-Chancellor Early Career Professorship Research Startup

Fund, and the Project of State Key Laboratory of Advanced Design and Manufacturing for Vehicle Body.

Appendix A. Virtual growth strategy

The virtual growth strategy is predicated on four fundamental components: building block, splicing rule, probability combination, and growth region. Two-dimensional schematic diagrams of the four types of basic building blocks are presented in Fig. 9, designated as H0, Y0, L0, and - 0, respectively, according to their structural characteristics. These building blocks possess distinct numbers of ports, comprising four, three, two, and two independent ports, respectively. The distribution characteristics of port orientations for each type of building block are described as follows: the four ports of building block H0 face top, bottom, left, and right, respectively; the three ports of building block Y0 are distributed at the bottom, left, and right of the structure; the ports of building block L0 face top and right; and the ports of building block - 0 are oriented horizontally.

Crucially, multiple structural variants can be derived from each type of basic building block via clockwise rotation. Building blocks H1 and - 1 are generated by rotating the basic building blocks H0 and - 0 by 90° clockwise, respectively. Rotating the basic building block Y0 clockwise by 90°, 180°, and 270° sequentially yields three structural variants: Y1, Y2, and Y3. Similarly, three structural variants, namely L1, L2, and L3, can be acquired when basic building block L0 is rotated clockwise at the same angular intervals. The basic building blocks and their corresponding structural variants are collectively defined as “*”-shape building blocks, where the symbol “*” stands for H, Y, L, and -. It is worth noting that as the basic building blocks rotate clockwise, the orientation of their ports must also be adjusted accordingly. In addition, the various building blocks examined in this work exhibit differences in wall morphology, ranging from straight walls to symmetrical and asymmetrical walls. However, in terms of overall structural classification, all of the above wall morphologies are uniformly classified under the “*”-shape building block category.

The overall assembly process for the aforementioned building blocks operates within a planar grid framework. Strict splicing rules are established for connecting building blocks to ensure compatibility when combining different types of building blocks. Two adjacent building blocks can only form a valid connection if they possess complementary ports; otherwise, the structural continuity is inhibited. Specifically, the structural alignment conforms to the following constraints: building blocks with a right-side port are restricted to interfacing exclusively with building blocks with a left-side port, whereas building blocks with a top port must interface with those possessing a bottom port. The assembly integrity is independent of the structural morphologies of the building blocks, as the geometric requirements for port alignment are universally satisfied across all configurations. The assembly effects of building blocks with symmetric and asymmetric configurations are successively illustrated in Fig. 9b and c.

Based on the four types of building blocks defined above, probability combinations are introduced to quantitatively control the occurrence frequency of each type of building block in disordered metamaterials. Specifically, if the probability combination is set to (a, b, c, d) , the theoretical probabilities of the “H”-shape, “Y”-shape, “L”-shape, and “-”-shape building blocks are a, b, c , and d , respectively. These four parameters strictly satisfy a normalization constraint, expressed as $a + b + c + d = 1$. For example, the probability combination of $(0.36, 0.20, 0.08, 0.36)$ is applied in Fig. 9b and c. In addition, spatial constraints are dictated by the growth region, which defines the topological boundary dimensions and spatial distribution limits of the disordered metamaterials. Examples of growth regions consisting of 25 lattices are provided in Fig. 9b and c. Once the four basic components are specified, the corresponding disordered metamaterials are systematically generated.

Appendix B. Building block simulation

Numerical simulations of the buckling evolution are performed on three building blocks, including “-”-shape, “L”-shape, and “Y”-shape configurations (Fig. 10). For the “-”-shape building block (Fig. 10a), pronounced X-axis buckling occurs in the straight-wall configuration under compression, exhibiting the largest deformation amplitude. The overall deformation of the symmetric configuration is remarkably suppressed, the buckling mode shifts to coupled X-Y axis buckling, thereby enhancing structural stability. Conversely, the asymmetric configuration exhibits negligible deformation at the equivalent load level, the

asymmetric configuration exhibits substantially smaller deformation under the same applied load. Buckling is eventually triggered when continuous loads are applied to the asymmetric configuration.

This phenomenon is consistently observed in both the “L”-shape and “Y”-shape building blocks (Fig. 10 b and c). The straight-wall configurations exhibit pronounced X-axis deformation, whereas the symmetric configurations show reduced deformation accompanied by coupled X-Y deflection tendencies. The asymmetric configurations exhibit substantially smaller deformation under the same external loads, with pronounced buckling-induced deformation appearing only after the load is further increased. These numerical results are used to compare relative deformation and buckling tendencies under identical idealized conditions; no quantitative critical buckling load or failure threshold is extracted from these simulations.

Appendix C. Compression experimental apparatus

The whole deformation process of disordered metamaterials with asymmetric configurations under quasi-static uniaxial compression is visually demonstrated in Fig. 11. From left to right, the sequential stages encompass the initial load-bearing stage, initial buckling stage, and post-instability collapse stage. Integral rigid load-bearing performance is maintained by the structure at the initial load-bearing stage. As the load increases, individual building blocks are the first to buckle, entering the initial buckling stage. Once the applied load exceeds the critical threshold for global instability, the post-buckling bearing interval is exhausted, triggering catastrophic macroscale collapse.

Appendix D. Disordered metamaterial structures

To verify the universality of the mechanical regulation effect induced by asymmetric configurations in different disordered metamaterial systems, disordered metamaterials dominated by the “-”-shape, “L”-shape, and “Y”-shape building blocks are further constructed based on three probability combinations of $(0.1, 0.1, 0.1, 0.7)$, $(0.1, 0.1, 0.7, 0.1)$, and $(0.1, 0.7, 0.1, 0.1)$. For each probability combination, disordered metamaterial samples with straight-wall, symmetric, and asymmetric configurations are generated, ensuring a complete set of configuration comparison systems for each probability combination (Fig. 12). The single-variable control principle is strictly followed throughout the tests. Differentiated regulation is only implemented on the curvature parameters of the upper and lower planes of dominant building blocks, while the straight-wall configuration is

uniformly adopted for the remaining non-dominant building blocks.

Appendix E. Mechanical performances of disordered metamaterials

The quasi-static compression tests are performed on metamaterials dominated by the “-”-shape, “L”-shape, and “Y”-shape building blocks. Taking the stress-strain curves of metamaterials dominated by the “-”-shape building blocks as an example, the characteristic onset stress σ_d of straight-wall, symmetric, and asymmetric configurations is measured as 6.01 MPa, 7.19 MPa, and 8.84 MPa, while the stress σ_g is obtained as 7.15 MPa, 8.38 MPa, and 10.57 MPa, and the corresponding post-buckling bearing interval width $\Delta\sigma_{LW}$ is 1.14 MPa, 1.19 MPa, and 1.73 MPa, respectively. These results demonstrate that the asymmetric configurations simultaneously elevate the load-bearing capacity and expand the post-buckling bearing interval width. This regulatory trend is consistently replicated across the disordered metamaterials dominated by “L”-shape and “Y”-shape building blocks (Fig. 13a-c).

The mechanical performances of the three configurations are quantified (Fig. 13d-f). The introduction of symmetric and asymmetric configurations induces a monotonic increase in both specific strength and Young's modulus across the metamaterials dominated by the “-”-shape, “L”-shape, and “Y”-shape building blocks. For instance, the metamaterials dominated by the “-”-shape building blocks featuring the asymmetric configuration exhibit a specific strength of $26.81 \pm 1.01 \text{ MPa}\cdot\text{cm}^3/\text{g}$ and a Young's modulus of $135.32 \pm 2.99 \text{ MPa}$, significantly outperforming their straight-wall and symmetric configurations. This phenomenon is stably reproduced in disordered metamaterials dominated by the “L”-shape and “Y”-shape building blocks.

Appendix F. Mechanisms of Robustness

The robustness of the mechanical performance of the disordered metamaterials can be attributed to the statistical consistency of their internal chamber units. To reveal the intrinsic relationship between topological randomness and performance stability, five independent samples (H1–H5) are generated under the probability combination (0.7, 0.1, 0.1, 0.1).

Table 1
Number of chambers of disordered metamaterials

Variable	H1	H2	H3	H4	H5
Number	326	325	324	323	326

The microstructural evolution is quantitatively evaluated using three distinct metrics: the total number of chambers, the number of chambers in different volume intervals, and the chamber volume distribution. Statistical results show that the total number of chambers in the five sets of samples is 326, 325, 324, 323, and 326, respectively (Table 1). The overall values are highly consistent and do not exhibit significant fluctuations due to the random arrangement of building blocks. Significance tests are further conducted on the chamber volume distribution, and a p-value of 0.989 ($p > 0.05$) is obtained. Confirming that, under the same probability combination, there are no significant differences in chamber volume among different disordered metamaterials.

To visualize the distribution characteristics of chamber volumes, the chamber volumes are divided into three distinct ranges: 0–300 mm³, 300–600 mm³, and greater than 600 mm³. The corresponding chamber number within each range is subsequently quantified (Fig. 14a). The results show that the number of chambers across the three volume ranges remains remarkably uniform for all five samples, with no significant differences. Violin plots are employed to delineate the specific volume distribution characteristics within these discrete ranges (Fig. 14b-d). The data dispersion degree is represented by the box length, the data central

tendency is reflected by the median, and the probability density distribution of data is described by the external frame. The results show that across the three volume ranges, the box length, median, and external frame of each sample are highly consistent, which proves that the dispersion degree, central tendency, and probability distribution pattern of chamber volumes are kept consistent. In summary, random differences in the macroscopic morphologies of disordered metamaterials are induced by the virtual growth strategy. However, high statistical consistency in the quantity, size, and spatial distribution of chambers is ensured under the constraint of probability combinations, and good robustness is thus presented in the overall mechanical performances of disordered metamaterials.

Appendix G. Periodic structures

18 types of typical periodic porous/lattice structures (Fig. 15) are selected as reference benchmarks [12,17,39,41–51]. The corresponding material systems, relative densities, and compression-test conditions are summarized in Table 2.

Table 2
Data on the structures used in the Ashby diagram

Structure	Material	Relative density	Specific strength	Specific energy absorption	Test conditions
CHSO	Resin	0.186	16.68 MPa·cm ³ /g	2.26 kJ/kg	Quasi-static, 1 mm/min
SH-1	Resin	0.367	35.08 MPa·cm ³ /g	9.91 kJ/kg	Quasi-static, 1 mm/min
Cubic lattice	Resin	0.169	19.83 MPa·cm ³ /g	0.87 kJ/kg	Quasi-static, 1 mm/min
BCC	Resin	0.207	12.46 MPa·cm ³ /g	0.57 kJ/kg	Quasi-static, 1 mm/min
Cross	Resin	0.281	21.68 MPa·cm ³ /g	0.88 kJ/kg	Quasi-static, 1 mm/min
FCC	Resin	0.125	20.59 MPa·cm ³ /g	0.79 kJ/kg	Quasi-static, 1 mm/min
Kelvin	Resin	0.213	7.12 MPa·cm ³ /g	4.95 kJ/kg	Quasi-static, 1 mm/min
Kelvin foam	Resin	0.322	42.38 MPa·cm ³ /g	12.29 kJ/kg	Quasi-static, 1 mm/min
Octapeak	Resin	0.143	4.89 MPa·cm ³ /g	1.61 kJ/kg	Quasi-static, 1 mm/min

(continued on next page)

Table 2 (continued)

Structure	Material	Relative density	Specific strength	Specific energy absorption	Test conditions
Octet-truss	Resin	0.149	22.72 MPa-cm131/g	1.18 kJ/kg	Quasi-static, 1 mm/min
Beetle	Resin	0.141	21.38 MPa-cm131/g	5.82 kJ/kg	Quasi-static, 1 mm/min
NH-1	Resin	0.307	40.93 MPa-cm131/g	10.69 kJ/kg	Quasi-static, 1 mm/min
Re-entrant	Resin	0.296	33.42 MPa-cm131/g	4.91 kJ/kg	Quasi-static, 1 mm/min
GSLs	Resin	0.441	23.51 MPa-cm131/g	11.01 kJ/kg	Quasi-static, 1 mm/min
Lotus root	Resin	0.293	30.77 MPa-cm131/g	11.07 kJ/kg	Quasi-static, 1 mm/min
HPAA	Resin	0.291	10.97 MPa-cm131/g	3.78 kJ/kg	Quasi-static, 1 mm/min
Cubic	Resin	0.169	17.92 MPa-cm131/g	4.81 kJ/kg	Quasi-static, 1 mm/min
BHTNS	Resin	0.362	44.58 MPa-cm131/g	7.91 kJ/kg	Quasi-static, 1 mm/min

Appendix H. Progressive failure evolution in the defective state

The progressive failure evolution of defective and defect-free multilayer disordered and periodic metamaterials under quasi-static compression is visually presented in Fig. 16.

Appendix I. Progressive failure evolution of the multilayer structures

Fig. 17 presents the progressive collapse behavior of composite multilayer structures assembled from two types of disordered metamaterials with distinct post-buckling bearing performance. For the D_21 and D_12 samples, steady-state crushing failure occurred along the thickness direction during loading. In contrast, for the D_13 sample, during the loading process, exhibits a distinct oblique penetrating-shear failure mode during loading.

Appendix J. Geometric and dimensional parameters of experimental specimens

Table 3

Geometric and dimensional parameters of all experimentally tested specimens

Name	Wall thickness	Curvature(r_{11} , r_d)(mm)	Relative density	Overall dimensions(mm ³)
H Straight	1 mm	(0, 0)	41.53%	100 × 100 × 24
H Symmetric	1 mm	(1.0, 1.0)	41.37%	100 × 100 × 24
H Asymmetric	1 mm	(0.8, 2.6)	41.26%	100 × 100 × 24
H1	1 mm	(0.8, 2.6)	41.22%	100 × 100 × 24
H2	1 mm	(0.8, 2.6)	41.21%	100 × 100 × 24
H3	1 mm	(0.8, 2.6)	41.22%	100 × 100 × 24
H4	1 mm	(0.8, 2.6)	41.17%	100 × 100 × 24
H5	1 mm	(0.8, 2.6)	41.25%	100 × 100 × 24
multilayer			37.30%	100 × 100 × 90
Kelvin			31.78%	104.3 × 104.3 × 90
Octet			18.85%	101.4 × 101.4 × 85.4
DW			37.76%	100 × 100 × 68
DS			37.37%	100 × 100 × 68
DD			37.02%	100 × 100 × 68
SW			39.12%	98.9 × 104.8 × 68
SS			38.81%	98.9 × 104.8 × 68
D_21			36.20%	100 × 100 × 112
D_12			34.95%	100 × 100 × 112
D_13			34.54%	100 × 100 × 112

Data Availability

Data will be made available on request.

References

- [1] Z. Li, S. Li, Y. Zhang, R. Zhang, G. Zhang, Y. Li, Multi-stage deformation enhanced combined metamaterial based on buckling beam and anti-tetra-chiral structure for extended elastic range and high energy absorption, *Smart Mater. Struct.* 35 (2026) 055011.
- [2] P. Wu, S. Li, Z. Li, W. Xia, Y. Li, Modular QZS metamaterials with enhanced load adaptability for low-frequency vibration isolation, *Smart Mater. Struct.* 34 (2025) 055017.
- [3] X. Ju, S. Li, Y. Zhang, P. Wu, Y. Li, Design of multi-stable metamaterial cell with improved and programmable energy trapping ability based on frame reinforced curved beams, *Thin-Walled Struct.* 202 (2024) 112120.
- [4] Y. Zhao, L. Wang, X. Zhai, J. Han, W.W.S. Ma, J. Ding, Y. Gu, X.-M. Fu, Near-Isotropic, Extreme-Stiffness, Continuous 3D Mechanical Metamaterial Sequences Using Implicit Neural Representation, *Adv. Sci.* 12 (2025) 2410428.
- [5] J. Yi, R. Lyu, Y. Li, C. Wan, K. Zhang, Stability-Enhanced Variable Stiffness Metamaterial with Controllable Force-Transferring Path, *Adv. Funct. Mater.* 35 (2025) 2413789.
- [6] W.W.S. Ma, L. Zhang, J. Ding, S. Qu, M.Y. Wang, X. Song, M.W. Fu, Rib-Reinforced Ultralight and Ultra-Strong Shell Lattices, *Adv. Sci.* 13 (2026) e18357.
- [7] W.W.S. Ma, H. Yang, Y. Zhao, X. Li, J. Ding, S. Qu, Q. Liu, Z. Hu, R. Li, Q. Tao, H. Mo, W. Zhai, X. Song, Multi-Physical Lattice Metamaterials Enabled by Additive Manufacturing: Design Principles, Interaction Mechanisms, and Multifunctional Applications, *Adv. Sci.* 12 (2025) 2405835.
- [8] Z. Chai, Z. Zong, H. Yong, X. Ke, J. Zhu, H. Ding, C.F. Guo, Z. Wu, Tailoring Stress-Strain Curves of Flexible Snapping Mechanical Metamaterial for On-Demand Mechanical Responses via Data-Driven Inverse Design, *Adv. Mater.* 36 (2024) 2404369.
- [9] D.K.J. Lim, C.Q. Lai, Ultrahigh Stiffness and Energy Absorption Properties of Isotropic Metallic Closed Cell Microlattices, *Small* 22 (2026) e73694.

- [10] G.Y. Lim, R.J.X. Kuek, J. Teo, I.P. Seetoh, C.Q. Lai, Mechanical properties of additively manufactured kraft paper lattices and paper-epoxy interpenetrating phase composites for polymer foam replacement, *Addit. Manuf.* 77 (2023) 103816.
- [11] C.Q. Lai, G.Y. Lim, K.J. Tai, K.J.D. Lim, L. Yu, P.K. Kanaujia, P.I. Seetoh, Exceptional energy absorption characteristics and compressive resilience of functional carbon foams scalably and sustainably derived from additively manufactured kraft paper, *Addit. Manuf.* 58 (2022) 102992.
- [12] Y. Tian, X. Zhang, B. Hou, A. Jarlöv, C. Du, K. Zhou, Programmable heterogeneous lamellar lattice architecture for dual mechanical protection, *Proc. Natl. Acad. Sci. U. S. A.* 121 (2024) e2407362121.
- [13] Y. Liu, B. Xia, K. Liu, Y. Zhou, K. Wei, Robustness and diversity of disordered structures on sound absorption and deformation resistance, *J. Mech. Phys. Solids* 190 (2024) 105751.
- [14] S. Luan, E. Chen, J. John, S. Gaitanos, A data-driven framework for structure-property correlation in ordered and disordered cellular metamaterials, *Sci. Adv.* 9 (2023) eadi1453.
- [15] D.R. Reid, N. Pashine, J.M. Wozniak, H.M. Jaeger, A.J. Liu, S.R. Nagel, J.J. De Pablo, Auxetic metamaterials from disordered networks, *Proc. Natl. Acad. Sci. U. S. A.* 115 (2018).
- [16] T. Magrini, C. Fox, A. Wihardja, A. Kolli, C. Daraio, Control of Mechanical and Fracture Properties in Two-phase Materials Reinforced by Continuous, Irregular Networks, *Adv. Mater.* 36 (2024) 2305198.
- [17] A. Mao, N. Zhao, Y. Liang, H. Bai, Mechanically Efficient Cellular Materials Inspired by Cuttlebone, *Adv. Mater.* 33 (2021) 2007348.
- [18] G. Giménez-Ribes, M. Motaghian, E. Van Der Linden, M. Habibi, Crumpled structures as robust disordered mechanical metamaterials, *Mater. & Des.* 232 (2023) 112159.
- [19] Y. Jia, K. Liu, X.S. Zhang, Modulate stress distribution with bio-inspired irregular architected materials towards optimal tissue support, *Nat. Commun.* 15 (2024) 4072.
- [20] M.A. Reyes-Martinez, E.J. Barron, D. Hwang, C.L. Soles, M.D. Bartlett, E.P. Chan, Topology as a limiting factor for mechanical properties in disordered networks, *Cell. Rep. Phys. Sci.* 5 (2024) 101848.
- [21] Y. Liu, B. Xia, Y. Zhou, K. Wei, Prediction and Reinforcement of Fracture-Prone Regions in Disordered Mechanical Metamaterials, *Adv. Mater.* 38 (2026) e08361.
- [22] A.S. Bhuwal, Y. Pang, I. Ashcroft, W. Sun, T. Liu, Discovery of quasi-disordered truss metamaterials inspired by natural cellular materials, *J. Mech. Phys. Solids* 175 (2023) 105294.
- [23] M.I.N. Rosa, K. Karapiperis, K. Radi, E. Pesciulli, D.M. Kochmann, Enhanced Deformability Through Distributed Buckling in Stiff Quasicrystalline Architected Materials, *Adv. Mater.* 37 (2025) 2505125.
- [24] W. Liu, B. Ennis, C. Coulais, Tuning the buckling sequences of metamaterials using plasticity, *J. Mech. Phys. Solids* 196 (2025) 106019.
- [25] W. Liu, S. Janbaz, D. Dykstra, B. Ennis, C. Coulais, Harnessing plasticity in sequential metamaterials for ideal shock absorption, *Nature* 634 (2024) 842–847.
- [26] A. Rafsanjani, K. Bertoldi, Buckling-Induced Kirigami, *Phys. Rev. Lett.* 118 (2017) 084301.
- [27] S. Emam, W. Lacarbonara, A review on buckling and postbuckling of thin elastic beams, *Eur. J. Mech. - A/Solids* 92 (2022) 104449.
- [28] J. Xu, Z. Xie, H. Yue, Y. Lu, F. Yang, A triboelectric multifunctional sensor based on the controlled buckling structure for motion monitoring and bionic tactile of soft robots, *Nano Energy* 104 (2022) 107845.
- [29] Y. Zhu, Z. Chen, Y. Zhu, M. Gresil, Y. Tang, Bio-inspired perturbed hierarchical mechanical metamaterial for energy absorption, *Int. J. Mech. Sci.* 307 (2025) 110847.
- [30] J. Chen, Y. Li, X. Kang, W. Yao, Inverse design of growth-inspired disordered metamaterials with programmable nonlinear force deflection responses, *Thin-Walled Struct.* 220 (2026) 114418.
- [31] Z. Shi, P. Jiang, X. Zhu, S. Li, W. Wang, T. Zhao, R. He, Y. Li, Unraveling the Power of Disorder: A Bioinspired Cuttlebone Structure With Superior Strength, Energy Absorption and Isotropy, *Adv. Sci.* 13 (2026) e75605.
- [32] X. Li, Z. Li, The Cuttlebone Blueprint for Multifunctional Metamaterials: Design Taxonomy, Functional Decoupling, and Future Horizons, *Adv. Funct. Mater.* 36 (2026) e30551.
- [33] H.-B. Yang, Y.-X. Lu, X. Yue, Z.-X. Liu, W.-B. Sun, W.-P. Zheng, Q.-F. Guan, S.-H. Yu, Multiscale integral synchronous assembly of cuttlebone-inspired structural materials by pre-designed hydrogels, *Nat. Commun.* 16 (2025) 62.
- [34] L. Yuan, D. Gu, X. Liu, K. Shi, K. Lin, H. Liu, H. Zhang, D. Dai, J. Sun, W. Chen, J. Wang, Design and additive manufacturing of bionic hybrid structure inspired by cuttlebone to achieve superior mechanical properties and shape memory function, *Int. J. Extrem. Manuf.* 6 (2024) 055001.
- [35] T. Yang, Z. Jia, H. Chen, Z. Deng, W. Liu, L. Chen, L. Li, Mechanical design of the highly porous cuttlebone: A bioceramic hard buoyancy tank for cuttlefish, *Proc. Natl. Acad. Sci. U. S. A.* 117 (2020) 23450–23459.
- [36] A. Köllner, L. Gardner, M.A. Wadde, A new approach to the stability design of Ramberg-Osgood material struts, *Structures* 56 (2023) 104844.
- [37] P. Zhang, P. Yu, R. Zhang, X. Chen, H. Tan, Grid octet truss lattice materials for energy absorption, *Int. J. Mech. Sci.* 259 (2023) 108616.
- [38] L. Dong, A. Neils, K. Yu, H. Wadley, Octet truss lattices fabrication via a layer-by-layer stacking manufacturing approach: Mechanical properties of the Al6061-T6 lattices, *Compos. Commun.* 60 (2025) 102653.
- [39] Y. Li, C. Shen, Q. Wu, J. Gao, H. Meng, T.J. Lu, Design and Characterization of Spiderweb-Inspired CF/Nylon Composite Honeycombs for Enhanced Energy Absorption, *Appl. Compos. Mater.* 33 (2026) 29.
- [40] G.R. Johnson, W.H. Cook, Fracture characteristics of three metals subjected to various strains, strain rates, temperatures and pressures, *Eng. Fract. Mech.* 21 (1985) 31–48.
- [41] M. He, Y. Li, J. Yin, Q. Sun, W. Xiong, S. Li, L. Yang, L. Hao, Compressive performance and fracture mechanism of bio-inspired heterogeneous glass sponge lattice structures manufactured by selective laser melting, *Mater. & Des.* 214 (2022) 110396.
- [42] D. Hu, Y. Wang, B. Song, L. Dang, Z. Zhang, Energy-absorption characteristics of a bionic honeycomb tubular nested structure inspired by bamboo under axial crushing, *Composites Part B Engineering* 162 (2019) 21–32.
- [43] A. Ingrole, A. Hao, R. Liang, Design and modeling of auxetic and hybrid honeycomb structures for in-plane property enhancement, *Mater. & Des.* 117 (2017) 72–83.
- [44] N. Li, S. Pang, S. Chen, Y. Liu, W. Aiyiti, Z. Chen, Design and application of hybrid lattice metamaterial structures with high energy absorption and compressive resistance, *J. Mater. Res. Technol.* 33 (2024) 7100–7112.
- [45] X. Li, X. Yu, W. Zhai, Additively Manufactured Deformation-Recoverable and Broadband Sound-Absorbing Microlattice Inspired by the Concept of Traditional Perforated Panels, *Adv. Mater.* 33 (2021) 2104552.
- [46] H.-B. Lin, H.-T. Liu, Load carrying capacity analysis and gradient design of new 3D zero Poisson's ratio structures, *Mater. Today Commun.* 36 (2023) 106915.
- [47] M. Nasim, U. Galvanetto, Mechanical characterisation of additively manufactured PA12 lattice structures under quasi-static compression, *Mater. Today Commun.* 29 (2021) 102902.
- [48] D.-B. Pham, S.-C. Huang, A novel bio-inspired lattice metamaterial for energy absorption and vibration mitigation, *J. Mech. Sci. Technol.* 38 (2024) 2725–2739.
- [49] Q. Wang, Z. Li, Y. Zhang, S. Cui, Z. Yang, Z. Lu, Ultra-low density architected metamaterial with superior mechanical properties and energy absorption capability, *Composites Part B Engineering* 202 (2020) 108379.
- [50] X. Wang, R. Qin, X. Zhang, B. Chen, Quasi-static and dynamic behavior of additively manufactured metamaterial structures with layered-hybrid topologies, *Thin-Walled Struct.* 183 (2023) 110434.
- [51] X. Zheng, W. Smith, J. Jackson, B. Moran, H. Cui, D. Chen, J. Ye, N. Fang, N. Rodriguez, T. Weisgraber, C.M. Spadaccini, Multiscale metallic metamaterials, *Nat. Mater.* 15 (2016) 1100–1106.