

Architectural Design and 3D Printing-based Fabrication of Auxetic Metamaterials

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Abstract. Auxetic metamaterials with lateral expansion under tension and lateral contraction under compression have garnered growing interest for lightweight load-bearing components, protective energy absorbers, conformal structures, and integrated structural-functional systems. Inspired by the idea that architecture dictates mechanical performance, the basic concept of the negative Poisson's ratio effect, dominant deformation mechanisms, and important mechanical characteristics of auxetic metamaterials are summarized. Representative architectures such as re-entrant honeycombs, chiral structures, and origami/kirigami-inspired systems are compared regarding deformation mechanism, mechanical advantages, limitations, and potential applications. Special focus has been given to the emerging three-dimensional petal-like auxetic structures, covering their geometric design rationale, multi-stage compressive deformation, stress plateau formation, and reinforcing effect of continuous fiber composites. Finally, the suitability of prominent additive manufacturing techniques (fused deposition modeling, stereolithography, selective laser sintering, direct ink writing, continuous fiber composite forming, and metal additive manufacturing) is reviewed; the influence of printing defects, process parameters, material choice, and manufacturing constraints on structural performance is analyzed. Coordination between three-dimensional architecture, gradient layout, composite reinforcement, and manufacturing-aware design represents a crucial aspect of future developments. However, practical application is limited due to multi-cell coupling, size effects, anisotropy, defect sensitivity, and lack of long-term reliability validation.

Keywords: Auxetic metamaterials, Negative Poisson's ratio, Three-dimensional petal-like structures, Energy absorption

1. Introduction

Mechanical metamaterials represent an emergent class of architected materials where their macroscopic mechanical responses are dominated by artificial designs of unit cell geometry and multiscale arrangement. In contrast to traditional materials which rely mostly on chemical compositions, phases constitution, or matrix behaviors, mechanical metamaterials exhibit unusual responses based on spatial topology, strut connectivity, folding pathways, and pore distributions. The architecture-based design strategy can realize rare properties found in nature like a negative

Poisson's ratio behavior, ultralow density with high stiffness, programmable deformation, and multistable mechanical responses [1, 2].

One of the most representative types of mechanical metamaterial is auxetic metamaterials which expands in lateral direction under stretching while contracting in lateral direction under compression with a transverse deformation opposite to that of conventional materials. The counterintuitive behavior improves their conformability on curved surfaces, shear resistance, indentation resistance, and impact energy absorption. Auxetic metamaterials thus show great potential applications such as lightweight aerospace sandwich cores, protective cushioning system, flexible device, biomedical scaffold, and morphing structure [3, 4].

Advances in finite element analysis, parametric modeling, and additive manufacturing have led to the emergence of auxetic metamaterials ranging from 2D honeycomb unit cells to 3D lattices, origami-and kirigami-inspired systems, composite-reinforced architectures, and graded multi-cell structures [5]. This review presents an overview of the architectural evolution, mechanical mechanism, and manufacturing technology of auxetic metamaterials, highlighting their performance differences between representative architectures as well as discussing the design features of novel three-dimensional petal-like auxetic structures. Current challenges associated with theoretical modeling, forming quality, and engineering validation are identified to guide further structural optimization and practical implementation [6].

2. Fundamental concepts and mechanical characteristics of negative Poisson's ratio materials

2.1. Definition and physical meaning of Poisson's ratio

The Poisson's ratio measures the relation between the transverse strain and the axial strain when subjected to axial loading. It can be written for an isotropic linear elastic material as:

$$\nu = -\varepsilon_t / \varepsilon_l \quad (1)$$

Most natural materials exhibit positive Poisson's ratios (they contract laterally with tension and expand laterally with compression). Negative-Poisson's-ratio materials show $\nu < 0$ so that they expand laterally with uniaxial tension and contract laterally with compression. Auxetic metamaterials are usually not based upon a negative Poisson's ratio within their constitutive material. Rather, the macroscopic auxetic behavior arises from geometric reconfiguration of artificial unit cells like rotation, bending, folding, or buckling under external loading [7]. Therefore, Poisson's ratio in auxetic metamaterials is not only an elastic property but also a crucial indicator of architecture design, deformation mode, and structural tunability.

2.2. Mechanical advantages of auxetic materials

Auxetic materials have unique laterally coupled deformations that are beneficial for improving local indentation resistance and protection under compression as lateral contraction pushes the deformed region towards the loading center; negative Poisson's ratio effect is often correlated with higher effective shear modulus leading to better shear resistance and in-plane stability [7].

In porous auxetic structures, compression generally results in cell rotation, local contact, progressive crushing, and densification resulting in a long and relatively stable stress plateau, thus enhancing energy absorption per unit mass. Flexible/conformable structures benefit from lateral

expansion for improved contact stability on complex curved surfaces. Performance of auxetic metamaterials strongly depends upon unit-cell size, relative density, joint stiffness, matrix material, and manufacturing imperfections. An effective optimization needs integration between architecture, mechanics, and processing constraints.

3. Representative architectures of auxetic metamaterials and their mechanical features

3.1. Re-entrant honeycomb structures

Re-entrant honeycombs are one of the most classic auxetics. The unit cells contain vertical struts with inward-inclined ribs. When axially loaded, these inclined ribs bend and rotate changing the re-entrant angle so that both transverse and axial dimensions change in the same direction. Such an architecture has a simple structure, obvious deformation mechanism, and suitable for analytical model and finite element simulations. Poisson's ratio and stiffness could be adjusted through varying strut length, re-entrant angle, wall thickness, and relative density [8].

However, the load bearing capacity of re-entrant honeycombs depends on the bending of slender struts; under large compression or impact loading, local buckling, strut fracture, and stress concentration at joint will happen easily. Re-entrant honeycombs are good candidates for theoretical analysis and low-load flexible structures but usually need hierarchy design, local reinforcement, filling strategy, or material hybridization for high strength energy absorption applications.

3.2. Chiral structures

Typical chiral structures contain circular nodes, central rings, or polygonal nodes linked together via tangential ligaments. Chiral structure's auxetic behavior arises from node rotation and ligament bending. In comparison to re-entrant architectures, they deform smoothly and show lateral expansion/contraction without prominent inward corners. The chiral honeycomb designed by Prall and Lakes showed how one could achieve an effective Poisson's ratio near -1 using node rotation [9].

These structures have advantages in flexible devices, recoverable cushioning systems, and morphing mechanisms. But their initial stiffness/load bearing capacity is often compromised due to slender ligaments. Thin ligaments allow for large deformation at the cost of strength while thick ligaments limit node rotation and weaken auxetic effect. Designing chiral structures involves balancing between rotational freedom, ligament strength, and overall stability.

3.3. Origami- and kirigami-inspired structures

Auxetic origami/kirigami inspired structures have emerged quickly as programmable mechanical systems. Origami structures rely on specified crease pattern and panel geometry to program their folding pathway. Miura-ori units show negative Poisson's ratio behavior when stretched in plane and could be stacked into 3D cellular systems [10]. Kirigami structures incorporate periodic cuts that cause local opening/rotation/out-of-plane buckling resulting in large deformation with programmable shape transformation in a thin sheet [11].

These architectures offer high design freedom and strong deployability, making them ideal for large deformation, recoverability, multistability, and shape morphing. However, they suffer from sensitivity towards crease/cut accuracy, fatigue life, and local damage evolution. Crease cracking,

panel buckling, and stress concentration at cut tip are still significant barriers for engineering applications in thin-walled systems.

3.4. Comparative assessment of representative architectures

The re-entrant honeycombs, chirality, and origami/kirigami inspired designs constitute three main strategies of realizing auxetic behaviors via strut bending, node rotation and folding/cut programming, respectively. The deformation mechanism, advantages/limitations, and typical applications of these systems are summarized in Table 1.

While traditional two-dimensional architectures exhibit strong auxetic response but are restricted by their spatial stability, multidirectional load bearing ability, and impact energy absorption; three-dimensional auxetic architectures were designed to maintain the benefits of anomalous deformation with increased load transfer pathways, improved structural stability, and enhanced manufacturability.

Table 1. Comparison of representative auxetic metamaterial architectures

Architecture	Dominant deformation mechanism	Mechanical advantages	Main limitations	Typical applications
Re-entrant honeycomb	Inclined-strut bending and re-entrant angle rotation	Clear mechanism; easy parameterization; pronounced auxetic response	Strut buckling, joint stress concentration, and limited load-bearing capacity	Theoretical modeling, lightweight sandwich cores, and low-load cushioning
Chiral structure	Node rotation and ligament bending	Smooth deformation, good recoverability, and high rotational freedom	Low initial stiffness and ligament-dominated weakness	Flexible devices, morphing structures, and recoverable energy absorbers
Origami/kirigami-inspired structure	Crease rotation, cut opening, and/or out-of-plane buckling	High programmability; suitable for deployable, large-deformation, and multistable functions	Sensitive to crease/cut fatigue, manufacturing accuracy, and local stress concentration	Deployable aerospace structures, intelligent structures, and soft robotics

4. Advances in three-dimensional auxetic metamaterial architectures

4.1. Motivation for three-dimensional design

Although two-dimensional auxetic unit cells are easy to analyze and fabricate, real-world engineering structures often experience complicated spatial loads such as axial compression, out-of-plane bending, shear, impact, or multidirectional coupled loading. Engineering structures made by only two-dimensional unit-cell arrays could be prone to out-of-plane instabilities, simple load transfer pathways, and strong boundary effects.

The introduction of three-dimension design provides multidirectional struts, rotating unit cells, spatial pores, and hierarchical connections that enhance the force chain transmission and improve stability against complex loading [12, 13]; in addition, three-dimensional unit cells also allow

incorporating gradient parameters, local density variation, and material partitioning into achieving directional energy absorption, guiding deformations, and integrating functions. Rapid development of additive manufacturing significantly reduces the fabrication barriers for complex open-cell architectures, which drives the transformation of auxetic metamaterials from 2D proof-of-concepts towards 3D engineering prototypes [14].

4.2. Three-dimensional petal-like auxetic structures

4.2.1. Geometric design rationale

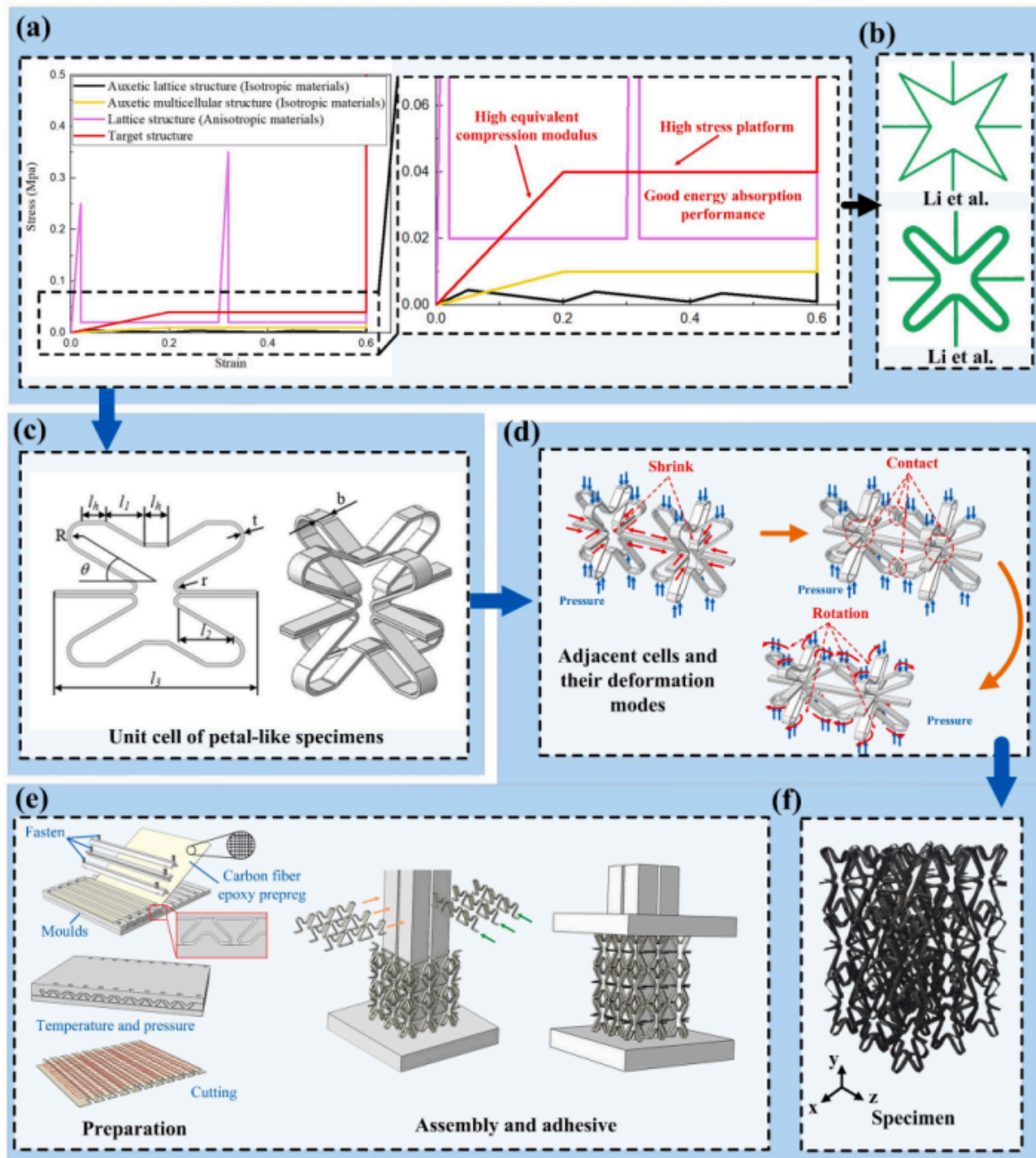


Figure 1. Design strategy, multi-stage deformation, and fabrication route of the three-dimensional petal-like auxetic structure [13]

Three-dimensional petal-like auxetic structures have emerged as a typical architecture. These structures are generally obtained by extending two-dimensional re-entrant petal-like units into three-dimensional open cells via spatial rotation, interlayer connection and multi-cell assembly. The design idea is mainly based on three aspects: first, the re-entrant petal-like unit supplies both contraction and rotational degrees of freedom necessary for auxetic behavior; secondly, introducing circular arcs instead of sharp corners reduces stress concentration and delays brittle failure; third, providing platform bonding segments or connection regions increases the assembly area between composite strips and improves the stability of load transfer [15].

The continuous carbon-fiber-reinforced composite petal-like structure was found to increase strength, stiffness and energy absorption without increasing its density [15]. The design is shown in Figure 1, which connects the desired mechanical response to geometry evolution and specimen fabrication. In Figure 1 (a), the stress-strain responses for porous structures made by different materials/architectures are compared; it can be seen that the target design needs to realize high equivalent compressive modulus, stable high-stress plateau as well as strong energy absorption at once. In Figure 1 (b), the evolution from star-shaped and petal-like parent units is shown, whereas Figure 1 (c) demonstrates some important geometric parameters (re-entrant segments, arc transitions, strip thickness, platform connections, and cell sizes). Figure 1 (d) emphasizes the expected sequence of deformations: shrinkage, contact, and rotation. Figure 1 (e) depicts how to prepare, cut, assemble, and bond the continuous fiber composite strips, and Figure 1 (f) displays the final multi-cell three-dimensional specimen.

4.2.2. Multi-stage deformation mechanism

Compression response of three-dimensional petal-like structures relies on multiple stages rather than one simple linear bending process. Initially, the petal-like units compress towards the cell center while both the transverse dimension shrinks under axial compression leading to a unique auxetic response [16]. When strain increases, neighboring petals start contacting each other; this alters their local stress state and leads them to enter a nonlinear transition stage [17].

Then, local connection regions and circular arc segments rotate, bend and suffer progressive damage resulting in a rather stable stress plateau. In contrast to traditional composite thin-walled structures that could show a sudden cliff-like load drop upon brittle failure, due to the presence of circular transitions and multiple contact paths within petal-like structures, loads can redistribute after local damage; thus, the compression response shifts from abrupt collapse to progressive crushing. When the pores get compacted, the densification stage is entered, where stress rises quickly with strain. Thus, the deformation process consists of: (i) linear elastic stage, (ii) reversible nonlinear transition stage, (iii) stress plateau stage, (iv) densification stage.

4.2.3. Mechanical performance

In contrast to re-entrant honeycombs, double arrow structures or traditional chiral structures, three-dimensional petal-like structures combine re-entrant petal-like geometry, space multi cell connectivity, circular arc transition as well as continuous fiber composite reinforcement for generating auxetic behaviors that are not purely based on geometric rotation. The conventional two-dimensional architecture usually lacks stiffness under compression since its deformation relies mostly on strut bending whereas a composite reinforced structure can suffer from sudden load loss caused by brittle fracture.

With multi-stage contact and rotation, petal-like structure can achieve more continuous load transfer after local damage while maintaining a relatively steady plateau stress. Some related works showed that continuous carbon fiber-reinforced polymer (CFRP) uniform and gradient petal-like structures still preserve their auxetic behavior in large deformation with good energy absorption capability under both quasi-static compression and low velocity impact [18], which is an example for auxetic metamaterial design moving from single geometry regulation towards coordination between architecture, material, manufacturing and mechanical responses.

5. 3D printing and additive manufacturing of auxetic metamaterials

5.1. Comparison and applicability of mainstream fabrication processes

The ability to fabricate complex pores, curved transitions, and multi-cell arrays directly makes additive manufacturing a crucial tool for rapidly designing and validating auxetic metamaterials. The variation between different processes is significant with respect to material compatibility, forming accuracy, mechanical performance, cost, and scalability. Table 2 compares some typical fabrication routes—fused deposition modeling (FDM), stereolithography (SLA), selective laser sintering (SLS), direct ink writing (DIW)—along with their appropriate applications [19].

Table 2. Comparison of representative fabrication processes for auxetic metamaterials

Process	Typical materials	Main advantages	Main limitations	Suitable applications
FDM/FFF	polylactic acid (PLA), acrylonitrile butadiene styrene (ABS), polyethylene terephthalate glycol (PETG), thermoplastic polyurethane (TPU), and short-fiber-reinforced filaments	Low cost, accessible equipment, and suitability for rapid prototyping and large open-cell structures	Weak interlayer bonding, rough surfaces, and pronounced anisotropy	Teaching/research prototypes and low-cost flexible cellular structures
SLA/DLP	Photopolymer resins, elastomeric resins, and ceramic-filled resins	High resolution and suitability for fine unit cells and complex curved features	Limited toughness and heat resistance; post-curing affects final properties	Small-scale high-precision auxetic structures
SLS/MJF	Nylon, TPU powders, and composite powders	Little support requirement and suitability for complex open-cell lattices	Powder removal from internal pores and relatively high surface roughness	Complex three-dimensional lattices and flexible cushioning structures
DIW	Elastomeric inks, hydrogels, ceramic slurries, and composite inks	Good material versatility and programmable deposition paths	Limited printing speed, rheology dependence, and possible shape instability	Soft auxetic devices, biomedical scaffolds, and functional gradient structures
Continuous fiber composite forming	Continuous carbon-/glass-fiber-reinforced polymers and prepreps	High specific strength and stiffness; suitable for high-performance energy absorption	Complex path planning, interlaminar bonding, and joint-region design	Lightweight protective components and load-bearing composite structures

Table 2. (continued)

Metal additive manufacturing	Titanium alloys, aluminum alloys, stainless steels, and other metals	High strength, thermal resistance, and suitability for harsh environments	High cost, residual stress, and demanding post-processing	Aerospace, high-temperature, and structural lattice applications
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5.2. Printing defects and optimization strategies

Auxetic unit cells usually feature slender struts, thin walls, re-entrant corners, overhanging parts, and complex internal pores. The printing defects will have a significant impact on their performances. Typical defects of FDM/FFF specimens: weak interlayer bonding, nonuniform filament deposition, over-extrusion at corners, burrs along pore edges, dimension deviation for slender struts, and direction-dependent anisotropy. Typical defects of SLA/DLP structures: over-curing, residual resin, brittleness, and post-curing shrinkage. Powder residue, high surface roughness, and difficulty in trapping powder removal from internal pores are key issues with SLS/MJF structures. Fiber turning radius, path continuity, interlaminar delamination, and bonding strength at joints are crucial factors for continuous fiber composite structures [19].

The above defects may be alleviated through design, slicing, and post-processing steps: avoid overly thin walls and sharp internal corner designs; add fillets/transition segments/local thickening for critical connections during design. Consider dimensional compensation based on printer resolution. Orienting the main load bearing path of the printed part as close to a continuous deposition path/in-plane direction is important when slicing. Optimize printing speed in fine feature areas, nozzle temperature, layer height, infill ratio, and cooling condition. Post-process by removing supports, secondary curing, heat treatment, surface polishing, and impregnation reinforcement will help improve the quality of specimens. In designing petal-like composites, consider integrating platform bonding segments, arc transitions, and fiber trajectory to minimize local failure risk.

5.3. Manufacturing challenges

While 3D printing has significantly reduced the fabrication threshold of complex auxetic architectures, there remain some issues that impede engineering translation: first, printed structures show obvious size effects; as unit cell sizes decrease, surface roughness, dimension deviations and pore defects have a greater impact on mechanical performance. Secondly, additively manufactured parts are intrinsically anisotropic with real moduli, strengths and fracture behaviors differing greatly from ideal homogeneous models.

Furthermore, a joint effect of boundary conditions, cell-to-cell coupling, defect distribution, and contact friction governs the failure of multi-cell structures; thus, unit-cell level theories are not sufficient in predicting global responses. Lastly, most works concentrate only on quasi-static compression whereas fatigue behavior, impact resistance, thermo-hygro aging and long-term service reliability need further investigation. It is necessary to establish defect-aware design methods and standardized testing protocols to bridge the gap between laboratory-scale prototypes and engineering applications [20].

6. Conclusion and outlook

6.1. Conclusion

From simple 2D unit cell designs to complex 3D architectures and rapid advancement in fabrication technologies through additive manufacturing, the negative Poisson's ratio effect is due to the cooperation between rotations, bendings, foldings, or bucklings of unit-cell geometry upon external loading that causes anomalous transverse deformations.

Re-entrant honeycombs, chiral structures, and origami/kirigami-inspired systems are typical auxetics that rely on strut rotation, node rotation, and folding/cut programming, respectively. They vary significantly with respect to their structural complexity, load-bearing capacity, deformation stability, and manufacturing difficulty. The novel three-dimensional petal-like auxetic structures combine re-entrant geometry, multi-cell spatial connectivity, arc transitions, and continuous fiber composite reinforcement which can synergistically improve its auxetic behavior, load-bearing capacity, and energy absorption. While 3D printing offers a facile way to rapidly fabricate complex auxetic architectures, the printing direction, interlayer bonding, dimension errors, and local defects have significant effects on the measured mechanical response.

6.2. Outlook

Auxetic metamaterials are transitioning from architectural concept designs towards performance-optimized and manufacturing-aware optimizations. A future effort is needed in establishing a closed loop between design, fabrication, testing, and applications. Firstly, multi-cell coupling and multiscale theoretical models need to be strengthened, with incorporation of unit cell parameters, array configurations, boundary conditions, and contact behaviors within unified predictive frameworks. Secondly, combining machine learning, topology optimization, and finite element simulation for multi-objective design enables simultaneous optimization of Poisson's ratio, stiffness, strength, energy absorption efficiency, and mass.

Third, manufacturing-aware architectural designs need to be improved such as considering printing orientation, minimum wall thickness, support accessibility, and post-processing feasibility at the very beginning of design. Fourth, continuous fiber composites, multi-material printing, and 4D printing can offer auxetic metamaterials with enhanced specific strength, programmable response, and environmental adaptability. Lastly, application-oriented studies on impact, fatigue, thermo-hygro aging, and long-term reliability in realistic service conditions shall be conducted.

References

- [1] Lakes, R. (1987). Foam structures with a negative Poisson's ratio. *Science*, 235(4792), 1038–1040.
- [2] Evans, K. E., & Alderson, A. (2000). Auxetic materials: Functional materials and structures from lateral thinking. *Advanced Materials*, 12(9), 617–628.
- [3] Greaves, G. N., Greer, A. L., Lakes, R. S., & Rouxel, T. (2011). Poisson's ratio and modern materials. *Nature Materials*, 10(11), 823–837.
- [4] Bertoldi, K., Vitelli, V., Christensen, J., & van Hecke, M. (2017). Flexible mechanical metamaterials. *Nature Reviews Materials*, 2(11), 17066.
- [5] Ren, X., Das, R., Tran, P., Ngo, T. D., & Xie, Y. M. (2018). Auxetic metamaterials and structures: A review. *Smart Materials and Structures*, 27(2), 023001.
- [6] Gibson, L. J., & Ashby, M. F. (1997). *Cellular solids: Structure and properties* (2nd ed.). Cambridge: Cambridge University Press. <https://doi.org/10.1017/CBO9781139878326.004>

- [7] Grima, J. N., & Evans, K. E. (2000). Auxetic behavior from rotating squares. *Journal of Materials Science Letters*, 19, 1563–1565.
- [8] Grima, J. N., Alderson, A., & Evans, K. E. (2005). Auxetic behaviour from rotating rigid units. *Physica Status Solidi B*, 242(3), 561–575.
- [9] Prall, D., & Lakes, R. S. (1997). Properties of a chiral honeycomb with a Poisson's ratio of -1. *International Journal of Mechanical Sciences*, 39(3), 305–314.
- [10] Schenk, M., & Guest, S. D. (2013). Geometry of Miura-folded metamaterials. *Proceedings of the National Academy of Sciences*, 110(9), 3276–3281.
- [11] Rafsanjani, A., & Bertoldi, K. (2017). Buckling-induced kirigami. *Physical Review Letters*, 118(8), 084301.
- [12] Babae, S., Shim, J., Weaver, J. C., Patel, N., & Bertoldi, K. (2013). 3D soft metamaterials with negative Poisson's ratio. *Advanced Materials*, 25(36), 5044–5049.
- [13] Overvelde, J. T. B., Weaver, J. C., Hoberman, C., & Bertoldi, K. (2017). Rational design of reconfigurable prismatic architected materials. *Nature*, 541(7637), 347–352.
- [14] Frenzel, T., Kadic, M., & Wegener, M. (2017). Three-dimensional mechanical metamaterials with a twist. *Science*, 358(6366), 1072–1074.
- [15] Li, Z. Y., Zhang, W. M., Wang, W. J., et al. (2024). New 3D petal-like structures with lightweight, high strength, high energy absorption, and auxetic characteristics. *Thin-Walled Structures*, 205, 112483.
- [16] Lu, C., Hsieh, M., Huang, Z., et al. (2022). Architectural design and additive manufacturing of mechanical metamaterials: A review. *Engineering*, 17, 44–63.
- [17] Xue, X., Lin, C., Wu, F., Li, Z., & Liao, J. (2023). Lattice structures with negative Poisson's ratio: A review. *Materials Today Communications*, 34, 105132.
- [18] Li, Z. Y., Wang, W. J., Li, H. Z., Yang, J. S., Zhang, W. M., Wang, X. T., Xiong, J., & Hu, H. (2025). Mechanical properties of novel uniform/gradient auxetic structures made of CFRP composites. *Polymer Composites*, 46(12), 10824–10841.
- [19] Jiang, D., Thissen, H., Hughes, T. C., et al. (2024). Advances in additive manufacturing of auxetic structures for biomedical applications. *Materials Today Communications*, 40, 110045.
- [20] Siniauskaya, V., Wang, H., Liu, Y., Chen, Y., Zhuravkov, M., & Lyu, Y. (2024). A review on the auxetic mechanical metamaterials and their applications in the field of applied engineering. *Frontiers in Materials*, 11, 1453905.