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A Review of 3D-Printed Auxetic Honeycomb Structures

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Abstract: Auxetic honeycomb structures, characterized by their unique lateral expansion behavior, have shown great potential in energy absorption and structural protection applications. With the rapid development of additive manufacturing technologies, the high-precision fabrication of complex honeycomb structures has become feasible, significantly promoting research in this field. This paper presents a comprehensive review of recent advances in 3D-printed auxetic honeycomb structures. First, the fundamental principles of additive manufacturing and its advantages in fabricating complex honeycomb geometries are introduced. Subsequently, the geometric configurations and deformation mechanisms of typical auxetic honeycomb structures are systematically summarized, with emphasis on dominant mechanisms such as cell rotation, bending, and hinging. On this basis, recent progress in structural design optimization, mechanical performance regulation, and engineering applications is reviewed. Finally, the existing challenges, including the lack of systematic design methodologies, unclear process–structure–property relationships, and insufficient understanding of in-service performance, are discussed, and future research directions are outlined. This review aims to provide a comprehensive reference for the design and application of 3D-printed auxetic honeycomb structures.

Keywords: 3D printing; Auxetic structures; Honeycomb structures.

1. Introduction

Additive manufacturing (AM), commonly known as 3D printing, is an advanced manufacturing technology that has developed rapidly in recent years[1]. Its fundamental principle is based on digital three-dimensional models, in which materials are deposited layer by layer to fabricate physical structures, thereby overcoming the inherent limitations of traditional subtractive manufacturing and mold-based forming processes in terms of geometric complexity, toolpath constraints, and material utilization efficiency[2]. As a highly flexible and programmable manufacturing approach, 3D printing technologies have become increasingly mature, encompassing several major process routes, including fused deposition modeling (FDM)[3], selective laser sintering/melting (SLS/SLM)[4], stereolithography (SLA)[5], digital light processing (DLP)[6], and electron beam melting (EBM)[7]. These processes, based on distinct forming mechanisms such as photopolymerization, melting, sintering, or material jetting, are compatible with a wide range of material systems, including polymers, metals, ceramics, and composites. Each process exhibits specific advantages in terms of fabrication accuracy, mechanical performance, build efficiency, and material adaptability. As illustrated in Figure 1. The application of 3D printing technology in various fields, with the continuous advancement of process technologies, 3D printing has evolved from rapid prototyping to the direct manufacturing of functional components, leading to a significant expansion of its application domains. For instance, in the aerospace field, metal powder bed fusion technologies are widely employed to produce lightweight and topology-optimized components[8]. In the biomedical field, photopolymerization-based processes enable the fabrication of personalized implants, bone scaffolds, and tissue engineering structures[9]. In automotive engineering and protective structure design, polymer-based additive manufacturing is extensively used for rapid structural iteration and performance validation[10]. Overall, 3D printing enables the direct transformation of digital models into physical entities, facilitating the integration of design, simulation, optimization, and manufacturing processes. It is particularly advantageous for the fabrication of complex porous structures, mechanical metamaterials, functionally graded materials, and multi-material systems, and has become a key enabling technology for structural innovation and performance enhancement[11], [12].Among the numerous novel structural systems based on complex structural design, auxetic structures have attracted considerable attention due to their unique mechanical behavior. The Poisson's ratio is an important mechanical parameter that describes the relationship between transverse strain and axial strain during structural deformation. For most conventional engineering structures, when subjected to axial tensile loading, the structure usually contracts in the transverse direction, resulting in a positive Poisson's ratio. However, in certain special structures or structural systems, the transverse dimension expands rather than contracts when the structure is stretched axially. This unusual deformation behavior is known as the negative Poisson's ratio effect[5].Due to this distinctive deformation characteristic, auxetic structures generally exhibit a series of superior mechanical properties, such as higher shear modulus, excellent energy absorption capability, improved indentation resistance, and enhanced impact resistance. Consequently, they possess significant application potential in protective structures, energy-absorbing systems, and smart structures[6], [7].

Benefiting from its unique layer-by-layer deposition mechanism, additive manufacturing exhibits significant advantages over traditional manufacturing methods in multiple aspects. First, it offers exceptional geometric design freedom, free from the constraints of molds or cutting tools, enabling the fabrication of complex architectures such as porous unit cells, internal channel networks, functionally graded structures, and multiscale mechanical metamaterials without increasing manufacturing complexity. This capability effectively decouples structural design from conventional manufacturing limitations[13]. Second, additive manufacturing inherently supports a high degree of customization and flexible production. As the entire process is driven by digital models, different structural configurations can be readily generated by simply modifying modeling parameters, making it particularly advantageous for small-batch customization and experimental structure development[14]. In addition, additive manufacturing enables rapid prototyping, significantly shortening the iteration cycle from structural design and finite element analysis to physical validation, thereby improving product development efficiency[15]. During the fabrication process, materials are deposited on demand, which reduces material waste and enhances material utilization efficiency, aligning well with the principles of green manufacturing[16]. More importantly, additive manufacturing demonstrates strong synergy with digital design tools, such as computer-aided design (CAD), computer-aided engineering (CAE), and optimization algorithms, allowing for a highly integrated workflow encompassing design, analysis, and fabrication of complex structures[17]. These features make additive manufacturing an ideal approach for constructing honeycomb structures, lattice structures, and various programmable energy-absorbing metamaterials.

Figure 1. The application of 3D printing technology in various fields.

With additive manufacturing providing a solid technological foundation for the rapid fabrication of complex structures, honeycomb structures have been widely applied in numerous fields due to their porous architecture, lightweight characteristics, and high specific energy absorption capacity[18], including aerospace[19], automotive engineering[20], biomedical devices[21], load-bearing systems[22], and energy absorbers[23]. Honeycomb structures were originally inspired by the classical hexagonal honeycomb model. Owing to their excellent in-plane mechanical properties, they have long been utilized in lightweight load-bearing applications[24] and energy absorption systems[25]. With the advancement of manufacturing technologies, honeycomb structures have evolved from conventional hexagonal configurations to a variety of geometries, such as re-entrant[26], star-shaped[27], and double-arrow-shaped structures[28]. This geometric diversification enables researchers to tailor key mechanical properties—including elastic modulus[29], Poisson's ratio[30], buckling behavior[31], and energy absorption performance[32]—through unit cell design, thereby achieving enhanced and multifunctional mechanical performance.

Despite the significant progress achieved in recent years in the study of 3D-printed auxetic honeycomb structures, several challenges remain to be further addressed, particularly in terms of structural design methodologies, optimization of manufacturing process parameters, and mechanical performance regulation. Therefore, it is necessary to systematically review and synthesize the existing research findings. In this context, this paper presents a comprehensive review of recent advances in 3D-printed auxetic honeycomb structures. First, the fundamental principles of additive manufacturing and its application characteristics in the fabrication of complex honeycomb structures are introduced. Subsequently, the geometric configurations and deformation mechanisms of typical auxetic honeycomb structures are summarized. On this basis, recent progress in structural design, performance optimization, and engineering applications of auxetic honeycomb structures is highlighted. Finally, the key challenges in current research are discussed, and future development directions are outlined, with the aim of providing useful references for further studies in this field.

2. Research status and main technologies

2.1. 3D Printing Technologies

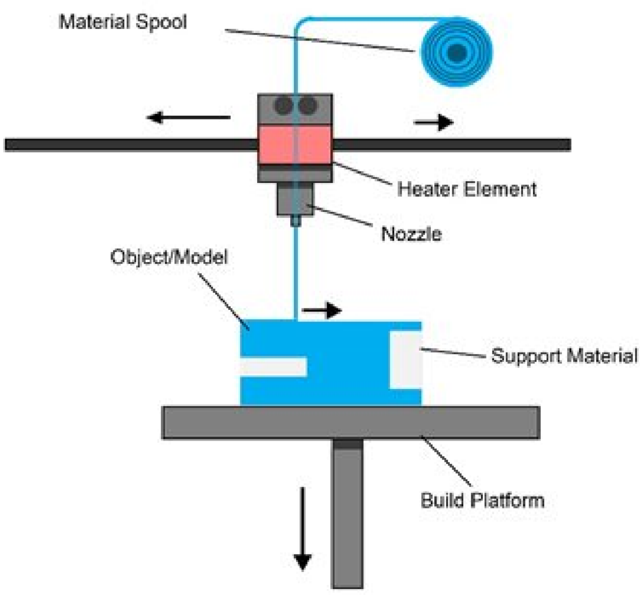

Figure 2. Schematic diagram of 3D printing technology principles.

Additive manufacturing, commonly referred to as 3D printing, is a fabrication technology that constructs three-dimensional physical objects based on digital geometric models through a layer-by-layer material deposition process[33]. Its fundamental concept involves discretizing a continuous three-dimensional structure into a finite number of thin layers along the build direction, which are then fabricated sequentially according to a predefined manufacturing path to ultimately achieve the desired geometry, as illustrated in Figure 2. Schematic diagram of 3D printing technology principles. Unlike traditional subtractive manufacturing or mold-based forming methods, additive manufacturing does not rely on bulk material removal or dedicated tooling. Instead, structural fabrication is realized through precise control of material deposition locations, deposition paths, and build sequences. Owing to this layer-wise accumulation mechanism, the fabrication of complex geometries is no longer strictly constrained by conventional manufacturing limitations. The achievable structural complexity is primarily governed by the capability of geometric representation and the resolution of the manufacturing process, thereby enabling the reliable and controllable fabrication of structures with intricate internal features and significant topological variations.

The additive manufacturing process typically begins with the creation of a three-dimensional geometric model, which can be generated using computer-aided design (CAD) software or obtained through parametric modeling, mathematical function descriptions, or scanning-based reconstruction techniques. However, although the 3D model serves as the initial input for fabrication, it cannot be directly interpreted by printing equipment. Instead, it must undergo a series of geometric processing and build planning steps to be converted into executable manufacturing instructions[34], as illustrated in Figure 3. Continuous surfaces or solid geometries are first approximated into discrete boundary representations to facilitate numerical processing and toolpath generation. Subsequently, the geometric model is sliced along a predefined build direction into a series of layers with finite thickness, each corresponding to an individual fabrication unit. These cross-sectional data not only define the geometric contours of each layer but also implicitly determine the material deposition strategy and build sequence, forming the basis for layer-by-layer manufacturing. Layer thickness plays a critical role in this process, as it directly governs the trade-off between geometric accuracy and manufacturing efficiency[35]. A smaller layer thickness enables more accurate reconstruction of curved surfaces and fine features, thereby improving geometric fidelity, but significantly increases the number of layers and prolongs the overall build time. Conversely, a larger layer thickness enhances manufacturing efficiency but tends to introduce pronounced staircase effects in inclined surfaces or complex geometries, thereby reducing surface quality and dimensional accuracy. Therefore, the geometric construction process in additive manufacturing is essentially a comprehensive problem involving discretization approximation, parameter trade-offs, and build strategy selection. After slicing and toolpath planning, the process proceeds to the physical fabrication stage, where the printer deposits material layer by layer in space according to the generated instructions to gradually construct the final structure. Although different additive manufacturing technologies vary significantly in terms of material forms, energy input modes, and solidification mechanisms, their fabrication processes generally follow a common paradigm of “controlled positioning – localized formation – layer-wise stacking.” Taking fused deposition-based processes as an example, the material is heated from a solid state to a viscofluid state, extruded through a nozzle, and deposited onto the substrate or the previously formed layer, followed by solidification upon cooling to form a stable structure. During this process, factors such as material rheological behavior, continuity of deposition paths, cooling rate, and interlayer thermal interactions collectively determine the interlayer bonding quality and final fabrication accuracy. Since the final structure is formed by stacking multiple discrete layers, its geometry and mechanical response often exhibit pronounced anisotropy. Consequently, the printing direction, build sequence, and process parameters play a crucial role in determining the overall structural performance.

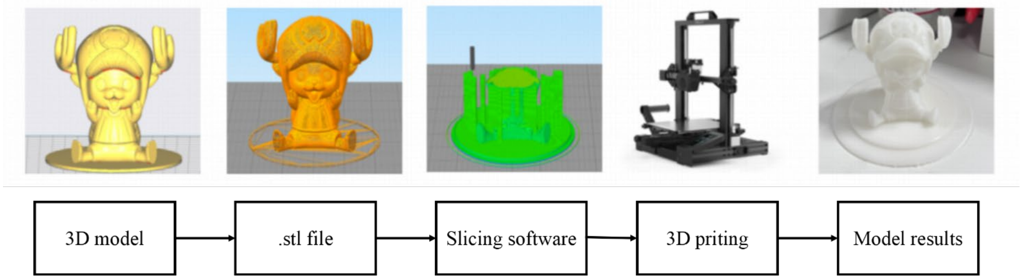

Figure 3. 3D printing process.

With the introduction of the layer-by-layer fabrication mechanism, interlayer interface characteristics have gradually become one of the key factors influencing the overall mechanical performance and failure behavior of additively manufactured structures[36]. Since adjacent layers are not formed continuously but are deposited sequentially with a certain time interval, the interfacial bonding quality is governed by multiple factors, including the thermal state at the moment of deposition, molecular diffusion behavior of the material, and the build sequence. When interlayer bonding is insufficient, structures are prone to delamination or crack propagation along the interfaces under external loading, a phenomenon that is particularly pronounced in thin-walled components and periodic structures. Therefore, in theoretical analyses and numerical modeling, interlayer interfaces are often regarded as potential weak regions that must be carefully considered during geometric design and process parameter selection. Meanwhile, the discrete nature of layer-wise fabrication inevitably leads to the generation and accumulation of geometric errors. Approximation errors introduced during slicing and toolpath planning, simplifications in deposition trajectories, and shrinkage-induced deformation during material cooling and solidification all contribute to deviations between the as-built structure and the ideal digital model. Such discrepancies are more pronounced in curved geometries, slender components, and periodic honeycomb cells, and, if not properly controlled, may significantly affect mechanical response and deformation stability. Therefore, during the modeling and design stages, it is often necessary to employ strategies such as parameter compensation, curve smoothing, and geometric correction to proactively mitigate potential manufacturing-induced errors, thereby improving the consistency and predictability of the fabricated structures.

Overall, additive manufacturing is not a simple one-to-one transformation from a digital model to a physical entity, but rather a continuous fabrication process composed of multiple interconnected stages, including geometric discretization, generation of manufacturing instructions, material deposition, and interlayer interface evolution. In this process, geometric modeling results must undergo discretization and toolpath planning before they can be interpreted by the manufacturing system, while the layer-by-layer deposition and solidification of materials introduce additional physical constraints and mechanisms of error evolution. It is precisely this strong coupling among geometric representation, numerical discretization, and physical fabrication that enables additive manufacturing to realize complex structural geometries. At the same time, it imposes higher requirements on structural design and parametric modeling. Furthermore, this integrated framework provides a critical technological foundation for subsequent studies on the geometric configuration design, parameter regulation, and mechanical performance of complex honeycomb structures.

2.2. Typical Auxetic Honeycomb Structures and Deformation Mechanisms

Typical auxetic unit cell structures currently include re-entrant hexagonal structures, star-shaped structures, double-arrow shaped structures, and chiral structures[37], as illustrated in Figure 4. The earliest auxetic foam fabricated by Roderic Lakes featured a microstructural unit cell based on the re-entrant hexagonal geometry. Subsequently, Gibson et al.[38] systematically investigated the deformation mechanisms responsible for the auxetic behavior of re-entrant hexagonal unit cells. As shown in the figure, under in-plane tensile loading, the deformation of the re-entrant hexagonal structure is characterized by the bending of inclined cell ribs. Driven by hinge-like joints, the vertical cell ribs aligned with the loading direction undergo coordinated lateral translation, resulting in an overall transverse expansion of the structure and thus exhibiting a negative Poisson's ratio effect. Evans et al.[39] further demonstrated that, for auxetic materials with re-entrant geometrical features, the primary origin of the negative Poisson's ratio lies in the inwardly inclined cell ribs. During deformation, the combined effects of angular variation between interconnected ribs, axial deformation, and bending deformation collectively contribute to the auxetic response. The star-shaped structure was first proposed and extensively studied by N. Theocaris et al.[40] in 1997 Using finite element analysis based on homogenization theory, it was shown that fiber-reinforced composites with star-shaped or re-entrant polygonal cross-sections can exhibit a negative effective Poisson's ratio. Chiral structures were first introduced by Wojciech Wojciechowski et al.[41] in 1989 and subsequently applied to material fabrication, leading to auxetic foams with Poisson's ratios as low as −0.9. Compared with previously reported structures, chiral configurations exhibit improved structural stability, and their auxetic behavior is manifested in two orthogonal in-plane directions. Later, D. Prall et al.[42] conducted systematic studies on chiral structures, proposing a constitutive model to characterize their mechanical behavior under large deformation. Experimental results demonstrated that the auxetic effect of chiral structures becomes more pronounced as deformation increases.

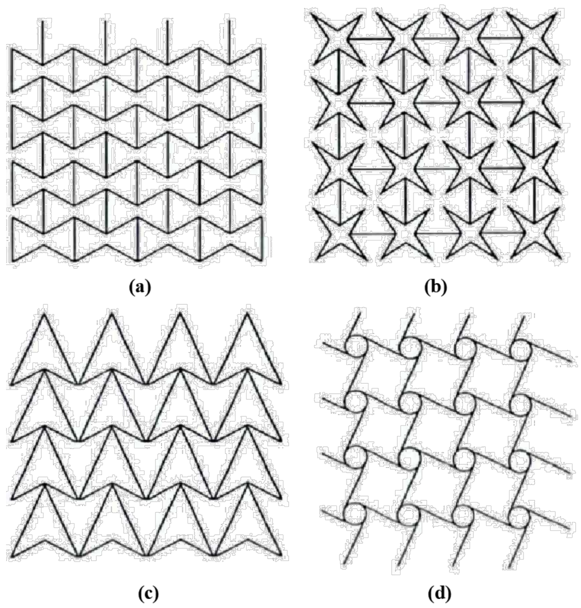

Figure 4. Typical negative auxetic structures. (a) Re-entrant structures; (b) Star-shaped structures; (c) double-arrow shaped structures; (d) chiral structures.

In addition to the aforementioned cell rib bending mechanism and the three-stage fibril stretching theory, other theoretical frameworks have been proposed to systematically explain the underlying mechanisms of auxetic behavior in various materials. Griffin et al.[43] designed and investigated auxetic structures composed of liquid crystalline polymers at the molecular level. Their results indicated that the negative Poisson's ratio effect in such materials is primarily attributed to the reorientation of molecular structures. Under tensile loading, the polymer backbone is stretched, while the rod-like molecular units, initially aligned approximately parallel to the backbone, rotate by about 90° to become perpendicular to it. This molecular reconfiguration leads to transverse expansion of the material. Alderson et al.[44] proposed and elaborated the rotating unit (lattice rotation) mechanism to explain the auxetic behavior observed in certain crystalline materials. Their studies revealed that the internal structure of such materials consists of square units connected at their vertices, forming a lattice-like microstructure, as illustrated in Figure 5. Under tensile loading, these units undergo rotation, resulting in an overall volumetric expansion of the material. The rotating unit mechanism also accounts for auxetic effects in some inorganic crystalline materials, in which the Poisson's ratio can reach values as low as −1.

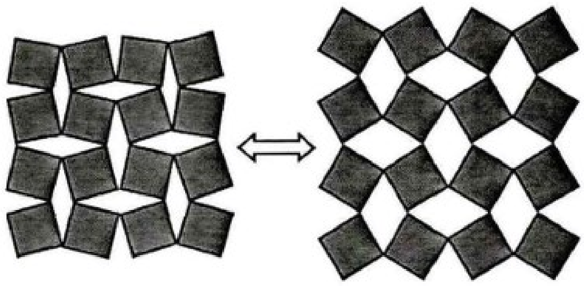

Figure 5. Rotational deformation model of auxetic lattices.

2.3. Recent Advances in Auxetic Honeycomb Structures

Honeycomb metamaterials, as a class of engineered structures with programmable geometries, tunable mechanical properties, and multifunctional responses, have attracted extensive attention from researchers worldwide in recent years. The fundamental concept lies in tailoring the topology or implementing multiscale design of honeycomb unit cells, enabling structures to exhibit unconventional mechanical behaviors that are rarely observed in traditional materials, such as negative Poisson's ratio, high specific energy absorption, stable deformation modes, anisotropic responses, and multi-stage collapse characteristics. Lakes[9] first proposed achieving a macroscopic negative Poisson's ratio through unit cell geometry design, laying the theoretical foundation for the development of honeycomb metamaterials. Subsequently, Gibson[45] systematically investigated the equivalent mechanical models of honeycomb and foam structures, providing an important methodological framework for analyzing and predicting metamaterial behavior. With increasing performance demands, Ajdari et al.[46] explored various auxetic honeycomb configurations based on the control of geometric deformation pathways, further revealing the influence mechanisms of unit cell geometry on overall stiffness, Poisson's ratio, and buckling modes.

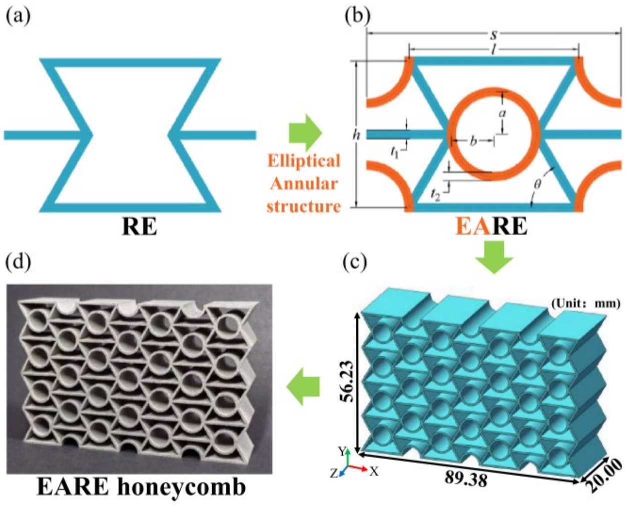

Figure 6. Improved design of re-entrant honeycomb structures.

Driven by the progressive development of this theoretical framework, researchers have begun to propose a variety of novel honeycomb porous structures from the perspective of unit cell geometric modification, aiming to further enhance overall mechanical performance. Lu et al.[47] introduced a slender rib element into the conventional re-entrant honeycomb structure, which not only significantly improved the Young's modulus but also enabled tunable Poisson's ratio. Fu et al.[48], [49] embedded rhombic units into the NRHH structure, thereby enhancing buckling strength and in-plane stiffness while maintaining desirable auxetic behavior. Inspired by the "concentric wall" microstructure of coconut trees, Jiang et al.[50] designed a concentric auxetic re-entrant honeycomb (CARH), in which the cooperative support of multiple concentric walls effectively improves structural stability, demonstrating excellent impact resistance and crushing load efficiency. Zhang et al.[51] extended this bio-inspired design paradigm to other natural models by introducing concave arc elements to develop C-shaped and S-shaped re-entrant honeycomb (RH) metamaterials, achieving tunable stiffness and more uniform deformation responses. To further optimize load transfer paths, Baran and Öztürk[52] incorporated inclined wall designs into classical re-entrant honeycombs, effectively enhancing global stiffness. Meanwhile, Zhang et al.[53] proposed a re-entrant arc honeycomb (RAH), where curved profiles enable a more uniform distribution of compressive loads, resulting in more continuous auxetic deformation behavior under low-velocity impact. In addition, Tatler et al.[54] embedded circular walls at the center of the unit cell to construct an MRC structure, thereby improving energy absorption capacity under nonlinear compression. Building upon this, Zhu et al.[55] proposed a novel elliptical annular re-entrant honeycomb (EARE). By introducing an elliptical ring support configuration, the structure not only preserves the auxetic effect but also further enhances stiffness and energy absorption capacity, effectively alleviating the inherent trade-off between stiffness and deformation in conventional re-entrant honeycombs, as illustrated in Figure 6. Subsequently, Chen and Wang[56] employed hollow circular ring designs to improve the specific Young's modulus, shear modulus, and structural anisotropy. Following these studies, Zhang et al.[57] further introduced wedge-shaped elements into conventional unit cells, achieving simultaneous improvements in stiffness and auxetic performance, highlighting the critical role of unit cell geometric optimization in performance regulation. Moreover, Mo et al.[58] proposed a novel hierarchical auxetic star-shaped honeycomb structure (HASS). By embedding internal star-shaped support modules into traditional star units, the structure exhibits significantly enhanced energy absorption capacity and deformation stability. Furthermore, a theoretical model for predicting plateau stress was established, demonstrating the considerable potential of hierarchical geometric design in improving honeycomb structural performance.

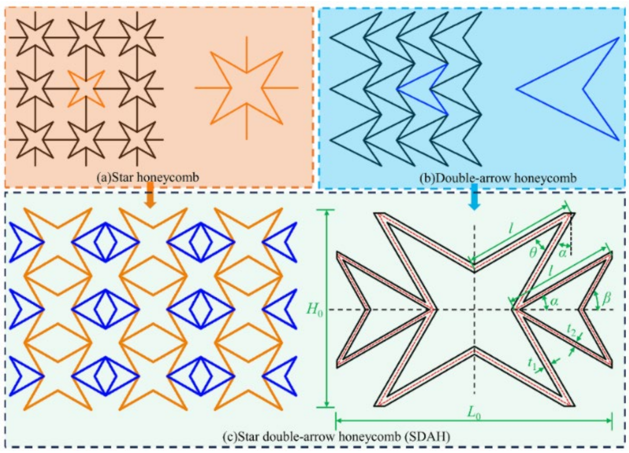

Figure 7. Star-shaped hybrid honeycomb structure design.

To further improve structural stability during loading, some studies have focused on regulating deformation mechanisms and buckling pathways. Qi et al.[59]-[60][61] proposed a re-entrant circular honeycomb (REC), in which double-arc cell walls are introduced to induce a characteristic "X"-shaped multiscale deformation mode. This structure exhibits excellent energy absorption performance under both quasi-static and dynamic loading conditions. Building upon this concept of deformation mechanism regulation, An et al.[62] developed a bidirectional re-entrant honeycomb (BRH) by integrating quadrilateral and hexagonal units. Through structural hybridization, multiple deformation pathways and staged crushing control are achieved, effectively enhancing impact resistance. Chen et al.[63] introduced curved insertion walls at the connection regions, enabling efficient energy absorption under combined tensile–bending loading conditions. Based on this, Zhou et al.[64] proposed a layered substructure combined-wall honeycomb (RCW), where hierarchical layering improves the overall compressive strength and impact stability. Furthermore, Kahraman and Genel[65] combined auxetic units with octagonal cells to construct a multi-cell hybrid structure (AuxOcta), significantly enhancing bending stiffness and energy absorption capacity. This demonstrates the multiscale synergistic effect between unit-cell design and overall structural response. In addition, Li et al.[66] proposed a hybrid structure (SDAH) that integrates the geometric features of star-shaped and double-arrow honeycombs. By innovating the unit connection configuration, independent regulation of dual plateau stresses is achieved, significantly improving energy absorption capability and compression stability, as illustrated in Figure 7.

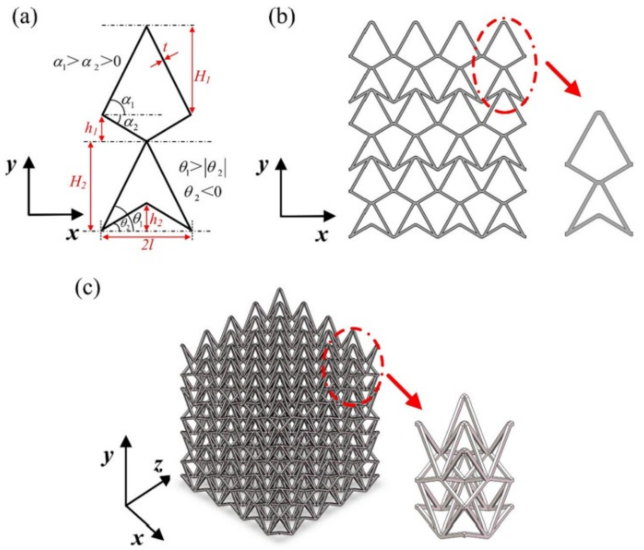

Figure 8. 3D hybrid double-arrow structure design.

With increasing performance demands, the design of honeycomb structures has gradually evolved from unit-level innovations to multi-unit collaborative configurations. By combining different types of unit cells, more complex collapse mechanisms and more efficient energy absorption capabilities can be achieved. As illustrated in Figure 8, Guo et al.[67] proposed a three-dimensional hybrid double-arrow structure (3D HAD), in which geometric coupling enables tunable Poisson's ratio characteristics while maintaining excellent mechanical stability under both tensile and compressive loading. Zhang et al.[68] constructed a VSHCS structure by integrating vertical supports with hexagonal units, achieving a pronounced dual-plateau energy absorption response during compression. To address the variation in structural response under different impact velocities, Wang et al.[69] designed a re-entrant star-shaped honeycomb (RSH), enabling dynamic switching of deformation modes at different loading rates, thereby enhancing adaptability under multi-condition impacts. In terms of energy absorption path regulation, Dong et al.[70] developed an SREAM structure based on thickness gradients and catenary profiles, effectively suppressing unstable buckling and improving energy absorption efficiency. Furthermore, Zou et al.[71], [72] proposed both arch-rib reinforced and gradient-enhanced re-entrant honeycomb (RRH) structures, which exhibit desirable dual-plateau energy absorption mechanisms. These structures achieve multi-stage compressive responses by activating cell walls or ribs at different deformation stages. Wei et al.[73][74] proposed a star–triangle auxetic honeycomb (STH) and systematically investigated its mechanical responses under different loading directions, revealing pronounced directional sensitivity and distinct dual-plateau stress characteristics. Building upon this, a hybrid gradient design strategy was further introduced, in which thickness distributions were assigned to different types of cell walls, providing an effective approach for tuning structural performance under multi-loading conditions. Additionally, Lv et al.[75] incorporated friction-based energy dissipation mechanisms into auxetic metamaterials, enabling reversible energy dissipation within the elastic regime and thereby expanding their application potential under cyclic loading conditions.

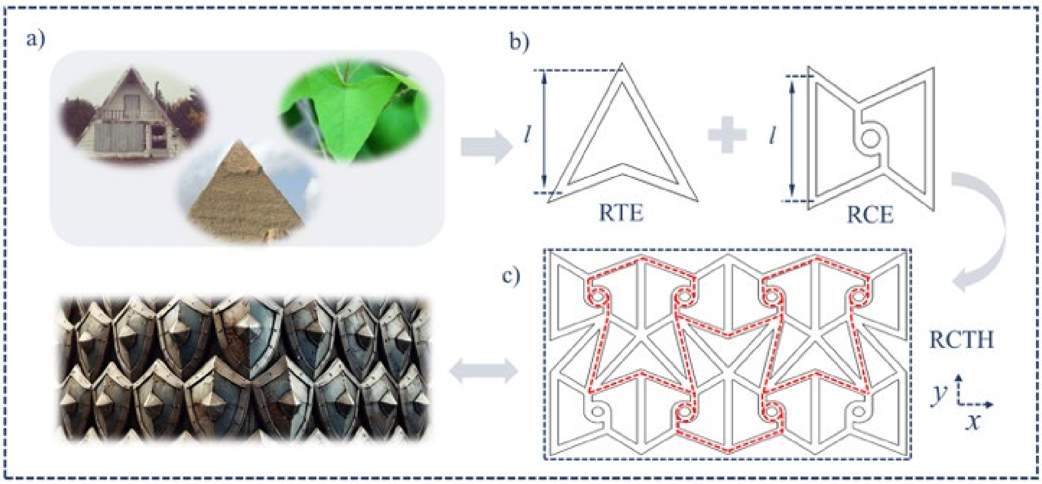

Figure 9. Chiral hybrid honeycomb structure design.

To ensure deformation stability, Széles et al.[76] introduced a double re-entrant honeycomb structure, which effectively suppresses buckling failure while maintaining a continuous auxetic response. Meanwhile, Lyu et al.[77] developed a structure capable of switching between positive and negative Poisson's ratios under both tensile and compressive loading, demonstrating high adaptability, particularly for applications in flexible connections and intelligent responsive systems. Hosseini et al.[78] systematically optimized auxetic honeycomb structures across multiple scales, including angle grading, thickness gradients, and local reinforcement. The resulting structures exhibit excellent energy dissipation capacity under bending and impact loads. Yu et al.[79] introduced concave arc elements into re-entrant honeycombs (RH) and proposed a three-dimensional sinusoidal–parallel–hybrid honeycomb (SPHH). Through structural integration and Poisson's ratio switching regulation, the design achieves more uniform stress distribution and significantly enhanced energy absorption performance under low-velocity impact. Chen et al.[80] proposed a chiral auxetic honeycomb (RCH) with strong orthotropic anisotropy. Its superior performance under small deformation was validated through theoretical, experimental, and numerical approaches. Based on this structure, a tubular scaffold featuring axial stability and radial contractibility was further designed, demonstrating promising applications in the biomedical field. Bian et al.[81] developed a novel honeycomb structure with embedded chiral units (ECH). By introducing localized rotational mechanisms, the structure exhibits significantly enhanced energy absorption capacity and a more stable plastic plateau during compression, offering a new pathway for the design of embedded composite honeycombs. Xu et al.[82] designed a novel gradient auxetic honeycomb sandwich beam (RCTH) by combining chiral and triangular units and applying gradient design along both horizontal and vertical directions. This configuration significantly improves energy absorption performance and flexural resistance under three-point bending, as shown in Figure 9. In summary, the collapse mode of honeycomb metamaterials plays a crucial role in determining their energy absorption performance, while geometric connection configurations, unit morphology transitions, and local buckling pathways dominate their deformation stability.

3. Summary

In summary, with the rapid development of additive manufacturing technologies, 3D printing has provided new technological pathways for the design and fabrication of auxetic honeycomb structures. First, in terms of additive manufacturing techniques, various fabrication processes are now capable of achieving high-precision manufacturing of complex re-entrant geometries, thereby laying a solid foundation for the construction of multiscale and topologically complex honeycomb structures. Second, regarding structural design and deformation mechanisms, typical auxetic honeycomb structures (such as re-entrant and chiral configurations, as well as their modified variants) have evolved into relatively well-established geometric design systems. Their auxetic behavior primarily originates from synergistic deformation mechanisms, including unit rotation, bending, and hinging. Third, in terms of research progress, through parameter optimization, structural modification, and multi-material design, auxetic honeycomb structures have demonstrated significant advantages in energy absorption, impact resistance, and functional integration, showing great potential in applications such as aerospace, biomedical engineering, and protective structures.

Nevertheless, several key challenges remain to be addressed in current studies of 3D-printed auxetic honeycomb structures: (1) structural design methodologies are still largely experience-driven, lacking systematic and generalized topological design theories and optimization frameworks; (2) the influence mechanisms of additive manufacturing process parameters on structural quality and mechanical performance remain insufficiently understood, particularly in terms of scale effects and defect control; (3) existing studies mainly focus on quasi-static mechanical behavior, while investigations into dynamic loading, fatigue behavior, and multi-field coupled responses are relatively limited; (4) at the engineering application level, challenges such as high manufacturing cost, structural reliability, and the lack of standardized evaluation systems still persist.

Future research on 3D-printed auxetic honeycomb structures may focus on the following directions. First, by integrating topology optimization and machine learning approaches, a new paradigm of structure design combining data-driven methods with physical mechanisms can be developed to enable intelligent design of high-performance structures. Second, in-depth investigation of the material–structure–process coupling mechanisms in additive manufacturing is needed to improve fabrication accuracy and performance consistency. Third, the development of multi-material and functionally graded designs can facilitate the integration of multiple functionalities (e.g., energy absorption, thermal insulation, and vibration damping). In addition, further studies on impact dynamics and adaptability under extreme environments are essential to promote their application in advanced engineering systems. Finally, establishing unified testing and evaluation standards will be crucial for accelerating their engineering implementation and industrialization.

Overall, 3D-printed auxetic honeycomb structures are currently at a critical stage transitioning from fundamental research to engineering applications. With the continuous integration of design methodologies, manufacturing technologies, and application demands, they are expected to exhibit broad prospects in the field of advanced structural materials.

Conflicts of interest

The authors declare that they have no conflict of interest.

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