

# The structure design and application of metamaterials with negative Poisson's ratio

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Received: 5 November 2025 / Accepted: 21 November 2025

**Abstract.** Metamaterials with negative Poisson's ratio, also called auxetic metamaterials, are artificially engineered structures or materials that possess extraordinary auxetic effect, high shear modulus, excellent impact resistance, and remarkable energy absorption capability. They have been widely applied in aerospace, transportation equipment, mechanical automation, and biomedical engineering. The unique properties of metamaterials are generally determined by the geometry and arrangement of their unit cells. However, due to the structural complexity and microscale dimensions of these cells, traditional manufacturing methods often fail to meet precision requirements, which has significantly restricted research progress in this field. In recent years, with the continuous advancement and maturation of additive manufacturing technology, it has become possible to fabricate complex and delicate microstructures, providing new opportunities for the development and practical application of auxetic materials. This paper focuses on the deformation mechanisms, mechanical properties, and structural characteristics of auxetic metamaterials. It provides an in-depth summary of the physical models of auxetic unit cells, such as re-entrant polygon and rotating rigid unit structures, and explores their wide applicability. Finally, the challenges and future prospects of auxetic metamaterials are summarized, aiming to provide valuable insights and references for the further development and practical applications of auxetic metamaterials and structures.

**Keywords:** Auxetic metamaterials / negative Poisson's ratio / structure design / deformation mechanism / 3D printing

## 1 Introduction

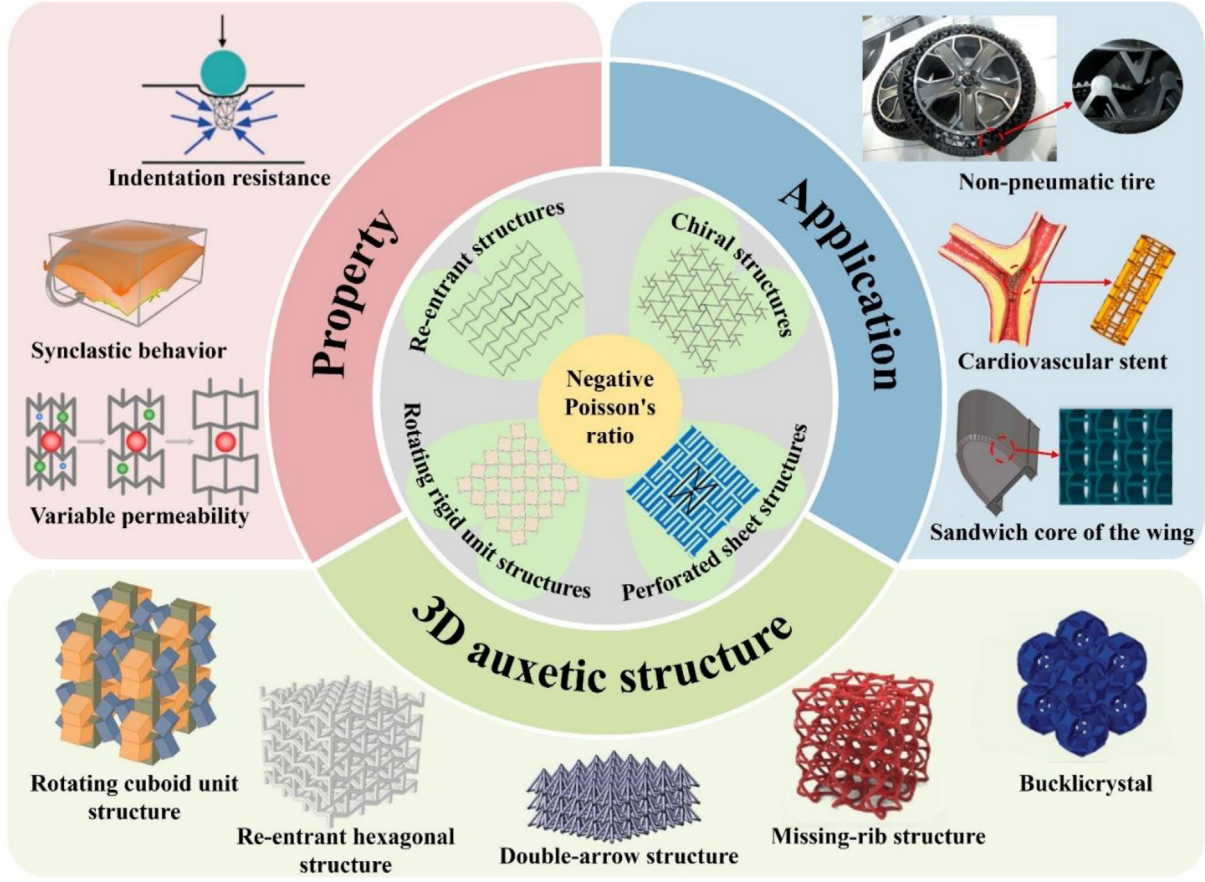
Metamaterials are artificially engineered materials that exhibit extraordinary physical properties not found in natural substances, such as optical metamaterials [1], acoustic metamaterials [2], thermodynamic metamaterials [3], and mechanical metamaterials [4]. In the study of mechanical metamaterials, there exists an anomalous phenomenon known as the negative Poisson's ratio (NPR). Early examples of NPR materials were mainly found in certain naturally occurring inorganic materials with special molecular structures, such as pyrite, arsenic, cadmium single crystals [5], natural silicates [6], and  $\alpha$ -cristobalite [7], as well as in biological materials with

fibrous or porous microstructures, such as animal skin [8], cancellous bone structures [9], and human Achilles tendons [10].

Since Lakes experimentally fabricated NPR materials, numerous artificial materials and structures exhibiting the auxetic effect have been developed. As shown in Figure 1, auxetic metamaterials can be classified according to their deformation mechanisms into re-entrant polygonal structures, rotating rigid unit structures, chiral structures, perforated sheet structures, and others [11]. Due to their NPR characteristics, auxetic metamaterials exhibit excellent mechanical properties, such as high shear modulus, synclastic behavior, and energy absorption. These properties form the basis for their applications in aerospace, transportation, and other fields. Owing to the anisotropy of two-dimensional auxetic metamaterials and their limitation of exhibiting the auxetic effect only in a single direction, their application in practical engineering remains difficult. Currently, research is gradually shifting from

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**Fig. 1.** The structure, property and applications of auxetic metamaterials. The four innermost leaves represent the four basic 2D auxetic structures of auxetic metamaterials [16,17]. The outer ring is divided into three parts, illustrating the 3D auxetic structures [18–22], properties [11,23,24], and applications in aerospace [25], vehicle [26], and biomedical [27] fields.

two-dimensional (2D) to three-dimensional (3D) auxetic structures, which are geometrically and mechanically more complex. Traditional subtractive manufacturing techniques cannot fabricate these complex 3D structures in a single process and often require multiple post-processing steps, resulting in low efficiency and high costs. In contrast, 3D printing technology offers significant advantages, including the ability to fabricate geometrically complex parts that are difficult to produce by conventional methods, high material utilization, near-net-shape forming, and relatively low fabrication costs. As a result, 3D printing has become the preferred processing method for manufacturing metamaterials. 3D printing is a technology that fabricates 3D solid models by slicing a digital 3D model into layers using specialized software, followed by layer-by-layer deposition of materials such as powders, filaments, or liquids according to the planned toolpath. In the field of 3D printing, a variety of forming processes have been developed. The main 3D printing techniques used for fabricating negative Poisson's ratio (NPR) metamaterials include Fused Deposition Modeling [12], Stereolithography [13], Powder Bed Fusion [14], and Directed Energy Deposition [15]. The deep integration of 3D printing technology and metamaterials is expected to further

promote the development and application of metamaterials across various fields.

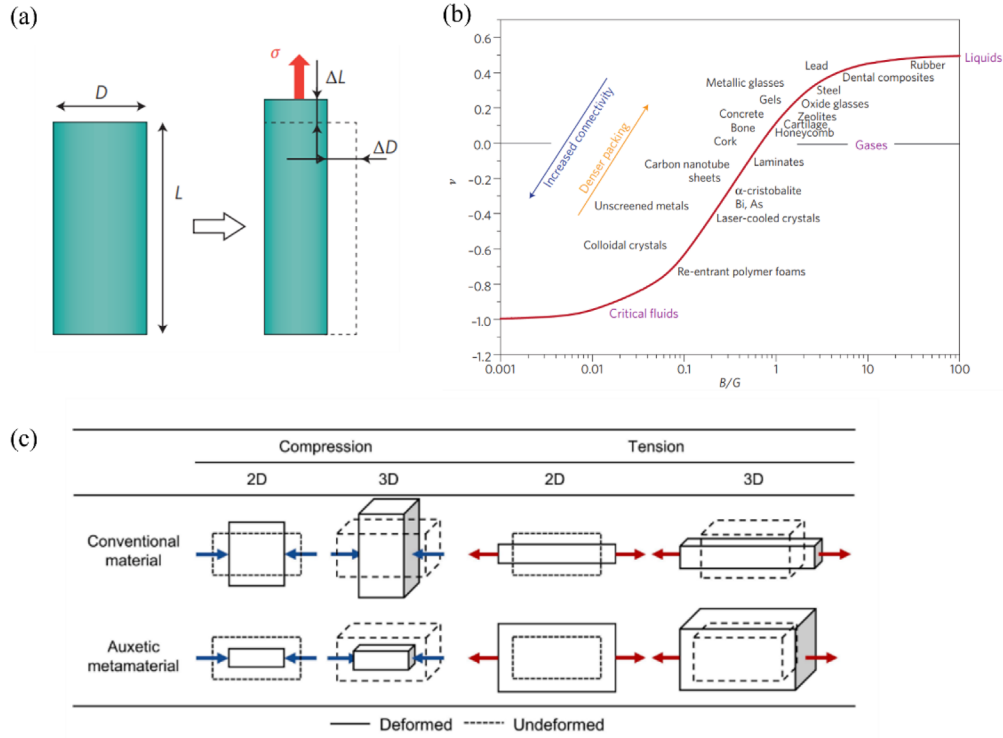
This review provides a comprehensive summary of the types, mechanisms, and properties of NPR materials and structures, highlights the current challenges, and offers valuable references for future research in this field.

## 2 Extraordinary property of auxetic metamaterials

The Poisson's ratio  $\nu$  is defined as the ratio of the transverse normal strain to the longitudinal normal strain when a material is subjected to uniaxial tension or compression. It is expressed by the following formula:

$$\nu = -\frac{\varepsilon_x}{\varepsilon_y} \quad (1)$$

where  $\varepsilon_x$  is the transverse strain perpendicular to the applied load and  $\varepsilon_y$  is the longitudinal strain in the loading direction. Here,  $\varepsilon_x = \Delta D/D$  and  $\varepsilon_y = \Delta L/L$ , where  $\Delta D$  and  $\Delta L$  are the changes in transverse and longitudinal dimensions, while  $D$  and  $L$  refer to the initial dimensions



**Fig. 2.** Poisson's ratio: physical significance, distribution in isotropic materials, and deformation illustration. (a) Schematic diagram of Poisson's ratio definition [28]. (b) Distribution of Poisson's ratio across various isotropic materials plotted as a function of the bulk-to-shear modulus ratio  $B/G$ . The theoretical range for homogeneous isotropic materials is  $-1 \leq \nu \leq 0.5$  [28]. (c) Schematic illustration of the deformation behavior of conventional materials and auxetic metamaterials under compression and tension, presented in both 2D and 3D forms [4].

in the respective directions (See Fig. 2a). For isotropic materials, the Poisson's ratio  $\nu$  can be expressed by the following formula:

$$\nu = \frac{3B/G - 2}{6B/G + 2} \quad (2)$$

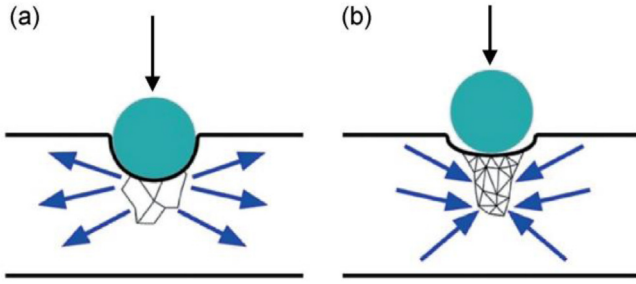
where  $B$  is the bulk modulus, which is related to volumetric changes, and  $G$  is the shear modulus, which is associated with shape changes. According to this formula, the Poisson's ratio of a homogeneous isotropic material falls within the range  $-1 \leq \nu \leq 0.5$  when  $0 \leq B/G < \infty$  [28]. Based on the function of  $B/G$ , Greaves et al. [28] plotted data for various isotropic materials (See Fig. 2b). From the figure, it can be observed that liquids and rubber have Poisson's ratios close to 0.5, while gases have a Poisson's ratio of approximately 0. Most natural materials exhibit Poisson's ratios within the range of  $[0, 0.5]$ . In contrast, artificially synthesized materials, such as re-entrant polymer foams and colloidal crystals, possess negative Poisson's ratios. For anisotropic materials, the range of Poisson's ratio is even broader, theoretically extending from  $-\infty < \nu < \infty$ . When a material is stretched laterally, it usually contracts longitudinally, and when compressed, it expands longitudinally, a phenomenon known as the positive Poisson's effect (See Fig. 2c). This behavior is

typical of most conventional materials. In contrast, materials with an NPR exhibit the opposite behavior: they expand longitudinally when stretched laterally and contract when compressed, showing a unique auxetic effect (See Fig. 2c). This unusual deformation mechanism endows auxetic materials with many superior properties, giving them broad application prospects in various fields.

## 2.1 Shear resistance

In the field of materials science and engineering, the mechanical properties of a material are among the key indicators for material selection and application. Shear resistance refers to a material's ability to resist deformation under the action of shear forces. For many engineering applications, such as aerospace, automotive industry, civil engineering, and protective equipment, a material's shear performance is crucial. Auxetic metamaterials, due to their unique internal structures and deformation mechanisms, exhibit significant advantages in terms of shear resistance. For isotropic materials, the relationships among Young's modulus  $E$ , bulk modulus  $B$ , shear modulus  $G$ , and Poisson's ratio  $\nu$  are given by:

$$B = \frac{E}{3(1 - 2\nu)} \quad (3)$$



**Fig. 3.** Deformation mechanisms under impact loading [11]. (a) Positive Poisson's ratio and (b) negative Poisson's ratio.

$$G = \frac{E}{2(1 + \nu)} \quad (4)$$

$$G = \frac{3B(1 - 2\nu)}{2(1 + \nu)} \quad (5)$$

with  $B > 0$  and  $G > 0$ . When  $\nu < 0$ ,  $G$  becomes relatively large, indicating that the material's shear resistance increases significantly as the Poisson's ratio changes from positive to negative. By contrast, the Young's modulus of ordinary materials is two to three times larger than the shear modulus. NPR materials may offer advantages in terms of damage resistance, in view of modification of stress concentration factors for in homogeneities [29]. Choi et al. [30] conducted experiments and analyses on copper metal foams and found that the fracture toughness of auxetic copper foams is higher than that of conventional foams. Moreover, the fracture toughness increases with the permanent volumetric compression ratio. The study indicates that although the Young's modulus of re-entrant foams is relatively low, the fracture toughness of re-entrant foams with a negative Poisson's ratio is greater than that of conventional foams.

## 2.2 Indentation resistance

Auxetic metamaterials exhibit significantly greater indentation resistance than conventional materials. Lakes et al. [31] investigated the indentation behavior of conventional and newly designed re-entrant metal foams with negative Poisson's ratio using holographic interferometry. For materials with the same initial relative density, re-entrant foams demonstrated higher yield strength and lower stiffness compared with conventional foams.

For conventional materials with a positive Poisson's ratio, when subjected to longitudinal impact loading, the material is compressed and tends to expand laterally at the impact region, resulting in a decrease in local density and a larger deformation (See Fig. 3a). In contrast, auxetic metamaterials behave oppositely. When subjected to longitudinal impact loading, the material contracts laterally, causing an increase in local density and a reduction in deformation (See Fig. 3b). Therefore, auxetic metamaterials exhibit superior indentation resistance and impact energy absorption performance. According to

classical elasticity theory, the indentation resistance of a material is closely related to its hardness ( $H$ ), which can be expressed as:

$$H \propto \left( \frac{E}{1 - \nu^2} \right)^\gamma \quad (6)$$

where  $\gamma$  is the sensitivity index, which equals 1 under uniform loading and  $2/3$  under concentrated loading. When the Poisson's ratio  $\nu$  is positive ( $0 \leq \nu \leq 0.5$ ), the indentation resistance varies slightly. However, for isotropic materials with  $-1 \leq \nu \leq 0$ , the indentation resistance can increase significantly [32]. The superior indentation resistance of auxetic metamaterials has been widely applied in ballistic protection, polymers, metallic foams, and fiber-reinforced composites.

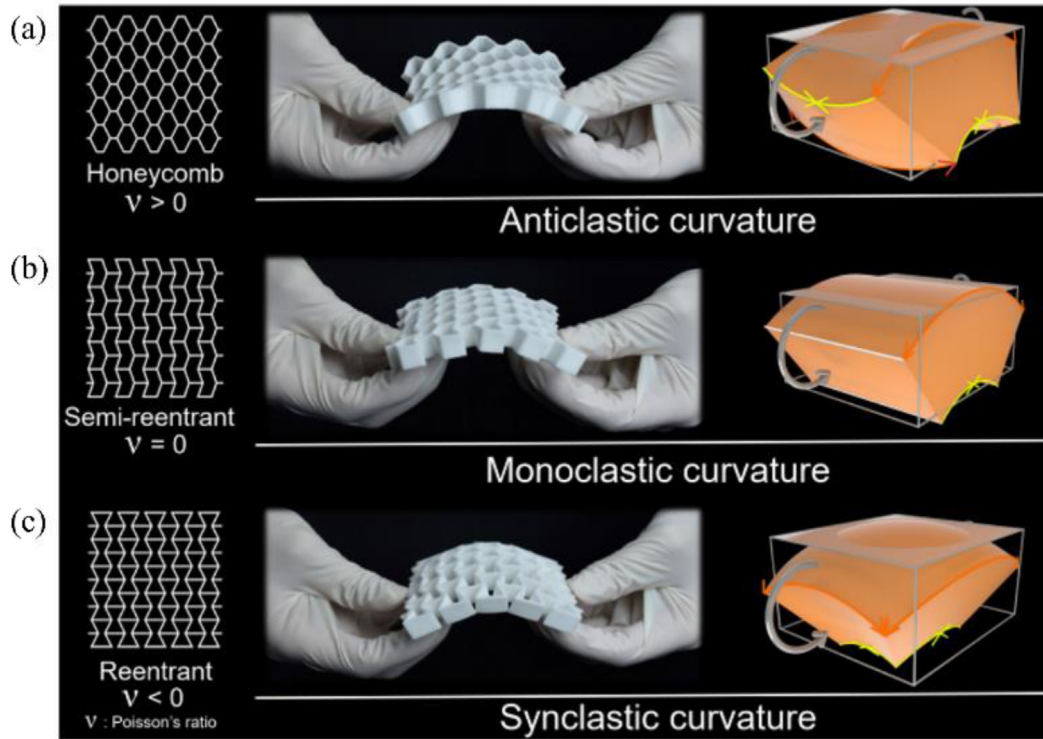
## 2.3 Synclastic behavior

When an out-of-plane bending moment is applied to a material, transverse curvature is generated. Conventional materials exhibit a saddle-shaped deformation, where the transverse curvature is opposite to the direction of the principal bending curvature, as shown in (See Fig. 4a) [23]. When the Poisson's ratio is zero, elastic curvature appears only in a single direction, while no deformation occurs in the orthogonal direction, resulting in an arch-shaped deformation, as illustrated in (See Fig. 4b) [23]. In contrast, materials with a negative Poisson's ratio form a synclastic surface, where the transverse curvature is consistent with the principal curvature direction, as shown in (See Fig. 4c) [23]. This arch-like deformation characteristic is referred to as surface synclasticity. Such a unique behavior allows auxetic materials to conform closely to same-direction curved surfaces, such as hulls, vehicle bodies, aircraft wing panels, and human joint areas. Furthermore, for plates or beams subjected only to bending moments, the formation of an arch-shaped deformation can effectively reduce damage. Therefore, auxetic materials have broad application prospects in the fields of aerospace, marine engineering, and biomedical devices.

The internal angle of re-entrant (RE) corners serves as a critical design parameter for RE polygons, significantly influencing the surface synclasticity of individual unit cells. Chow et al. [33] demonstrated through theoretical calculations and finite element analysis two conventional auxetic structures: RE hexagonal cells (See Fig. 5a) and double-arrowhead cells. They investigated the effect of internal angle variation on out-of-plane bending, estimating the minimum and maximum curvatures using Heron's formula (See Fig. 5b) and calculating the total curvature. Finite element simulations were performed to compare the geometric deformation of RE hexagonal cells and conventional honeycomb cells under identical bending moments (See Fig. 5c). As the internal angle increases, the total curvature gradually decreases, and the deformation transitions from a synclastic surface to an anticlastic surface (See Figs. 5d–5f).

In practical applications, the influence of a single RE unit cell is limited. When a large number of RE unit cells are interconnected, interactions among them lead to a more





**Fig. 4.** Deformation modes of materials under out-of-plane bending moments for different Poisson's ratios [23]. (a) Positive Poisson's ratio, (b) zero Poisson's ratio and (c) negative Poisson's ratio.

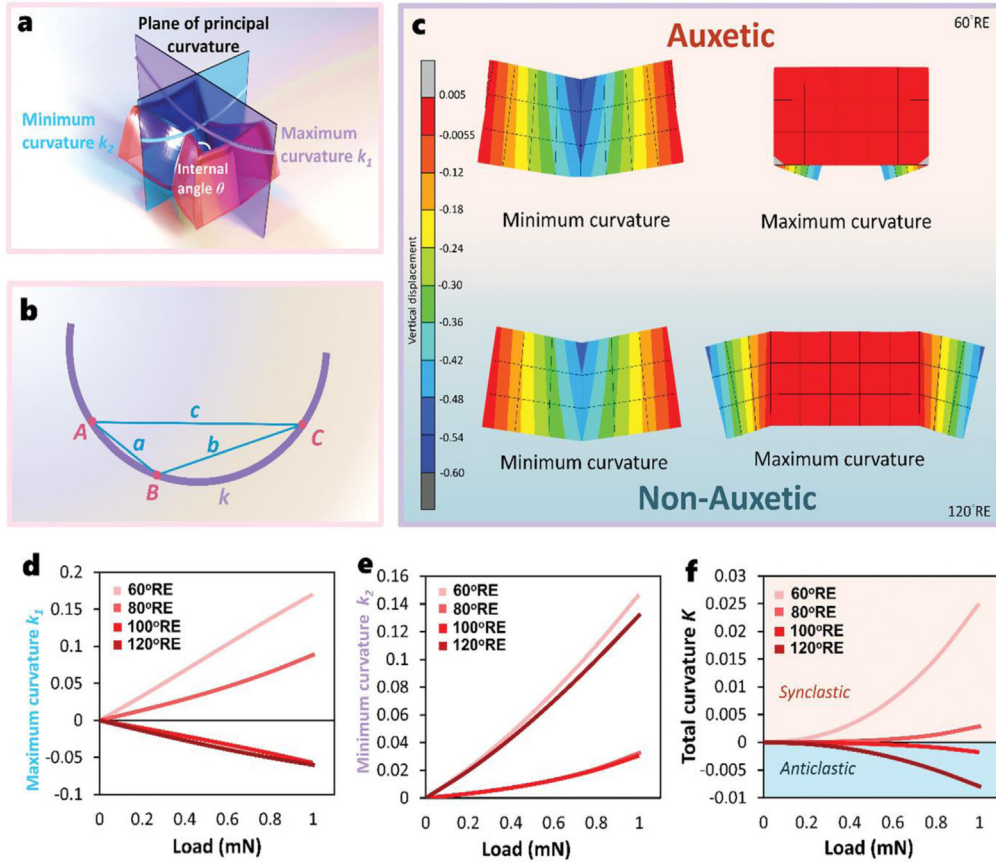
pronounced surface synclasticity. Jiang et al. [23] further conducted experimental and numerical studies on the curvature behavior of auxetic and non-auxetic materials. Using finite element simulations, the structural performance was evaluated with respect to engineering and ergonomic applications. The results indicate that auxetic metamaterials are more easily formed into dome-shaped surfaces compared with non-auxetic materials, although some RE structures exhibit insufficient stiffness after forming. Among different designs, RE polygonal structures demonstrate the best conformity. In practical applications, the choice of structure should be based on the surface characteristics of the object, loading conditions, and specific requirements. This study provides valuable guidance for the application of auxetic metamaterials in engineering and ergonomics.

## 2.4 Energy absorption

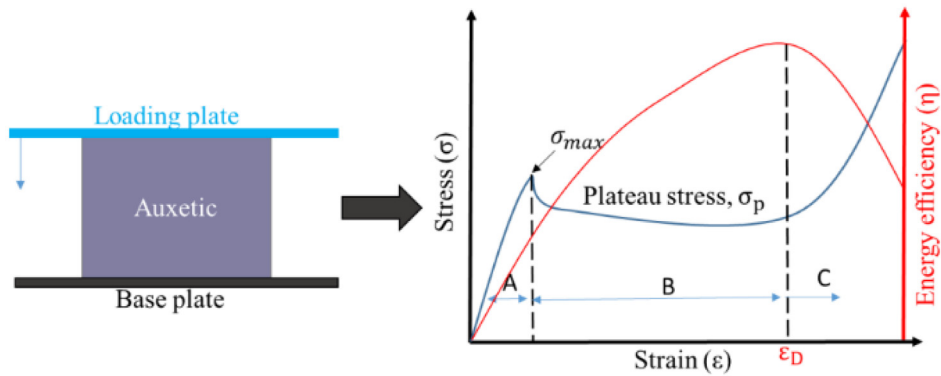
Energy absorption performance is a critical indicator for evaluating a structure's resistance to impact and vibration damping. Enhancing energy absorption not only improves the structure's impact resistance but also helps absorb and dissipate vibrational energy. This makes NPR metamaterials highly promising for protective engineering applications. Lakes [31], while investigating the indentation performance of NPR copper foams, proposed a formula for maximum impact energy under the condition of not exceeding the allowable stress. The study showed that the energy absorption calculated during dynamic impacts was significantly higher for NPR foams compared to

conventional foams. Subsequently, Rad et al. [34] conducted experimental and numerical simulations to study the energy absorption characteristics of various 3D honeycomb NPR structures under quasi-static and dynamic loads. Compared to conventional unit cells, NPR unit cells exhibited superior energy absorption properties. This research provides valuable design insights for engineers intending to use NPR metamaterials in impact-resistant applications, such as explosive-resistant armor, vehicle bumper energy-absorbing boxes, impact shields, and protective helmets [35].

The energy absorption in NPR structures primarily results from the deformation mechanism of the cell walls and the subsequent formation of plastic hinges within the cell walls [35]. As a result, the energy absorption capability of NPR structures varies depending on the structure of the unit cells. Moreover, NPR structures have higher porosity and lighter structural mass, which contribute to their superior energy absorption properties. Figure 6 illustrates the typical stress-strain curve of a multi-cellular structure. Generally, multi-cellular structures experience three distinct phases under uniaxial compressive loading: the elastic phase (A), the stress plateau phase (B), and the densification phase (C). The area under the stress-strain curve represents the energy absorbed by the porous structure. At the onset of densification, the cell walls within the multi-cellular structure begin to interact, causing the stress level to rise rapidly. Therefore, the start of densification is considered the limit of actual energy absorption [35]. Furthermore, for multi-stage honeycomb materials, the energy absorption characteristics are



**Fig. 5.** Illustration and simulation of RE hexagonal cell deformation under bending moments, and the effect of the re-entrant angle on curvature variation [33]. (a) Illustration of the bent RE unit cell with planes along the principal curvature directions. (b) Curvature estimation based on Heron's formula. (c) Simulation of geometrical change between 60°RE and 120°RE sample under 1 mN load. (d)–(f) Effects of internal angle on maximum curvature, minimum curvature and internal angle to the synclastic or anticlastic curvature behavior of samples.



**Fig. 6.** Compression illustration and stress-strain curve of multi-cellular structure [35].

influenced by the number of stages. As the number of stages  $n$  increases, the energy absorption performance improves accordingly [11].

## 2.5 Variable permeability

Most NPR structures are porous, and under tension and compression, the pores can expand and contract, which also leads to changes in the particle size of the permeable substances (See Fig. 7). This variation mechanism offers the potential for NPR materials in filtration applications,

as it can prevent clogging of the filter pores by impurity particles and improve filtration efficiency. Alderson et al. [36] conducted comparative tests using small glass beads to evaluate the performance of re-entrant hexagonal honeycomb filters and conventional hexagonal honeycomb filters. The results showed that during the decontamination and pollution processes of the filters, the re-entrant membranes exhibited superior performance in reducing membrane pressure, providing both theoretical and experimental support for the development of efficient filtration technologies.

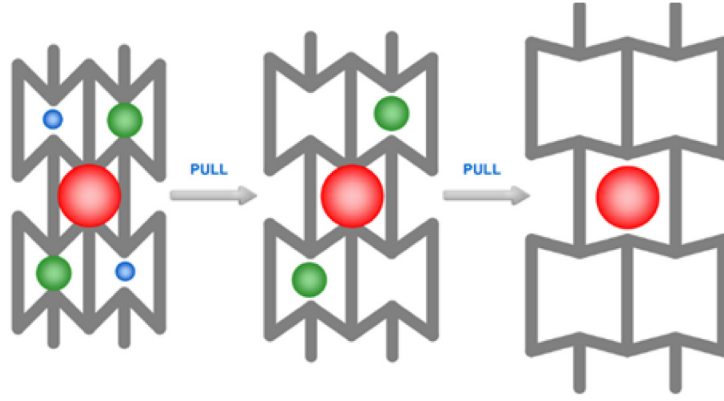


Fig. 7. Schematic of variable permeability [24].

### 3 Structure design of auxetic metamaterials

Since Lakes developed isotropic NPR foams, the rapid development of 3D printing technology has revolutionized the manufacturing of lattice mechanical metamaterials, enabling the realization of complex structural designs. Research has gradually expanded from one-dimensional to multi-dimensional, from natural to artificial, from single-material to multi-material composites, and from theoretical studies to practical applications. Researchers have designed various unit cell structures and used experiments, theoretical calculations, and simulation analyses to explain their deformation mechanisms and mechanical properties. This paper primarily focuses on the structural forms of re-entrant polygonal structures, rotating rigid unit structures, chiral structures, and perforated sheet structures, discussing their deformation mechanisms and performance, while also reviewing other NPR structures.

#### 3.1 Re-entrant polygonal structures

Most common 2D re-entrant structures are variants of honeycomb multi-cell configurations, including re-entrant hexagonal honeycombs, double-arrow models, and star-shaped honeycombs, as well as derived optimized structures such as composite structure models [37], double-U models [38], and petal-shaped models [39]. Due to their unique geometry, the re-entrant regions tend to expand outward under tensile loading, facilitating the formation of auxetic behavior. However, not all re-entrant structures exhibit a negative Poisson's ratio. The following section introduces several classic re-entrant polygonal structures.

As a classic multi-cell structure, conventional honeycombs have been extensively studied, providing a substantial theoretical foundation for re-entrant polygonal honeycomb structures. This foundation has facilitated the rapid development of 2D NPR metamaterials. Gibson et al. [40] analyzed the mechanical properties of 2D honeycomb materials (See Fig. 8a), investigating experimentally and theoretically how their elastic and plastic behaviors depend on cell wall properties, cell geometry, and density. Subsequently, Lakes [41] studied the relevant microscopic structural features that give rise to a negative

Poisson's ratio, providing important guidance for understanding the mechanical behavior of honeycomb materials and for related structural design. Meanwhile, the re-entrant hexagonal honeycomb structure was proposed. Under lateral tensile loading, the re-entrant regions expand longitudinally, exhibiting auxetic behavior, whereas under compression, the re-entrant regions collapse inward, shortening the longitudinal length and demonstrating NPR characteristics (See Fig. 8b). Since the connections between nodes can be regarded as isotropic elastic beams with uniform cross-sections, the axial, torsional, shear, and bending stiffnesses are no longer independent but can be determined by the beams' geometric and elastic parameters. Conversely, these parameters, together with the angles between beams, define the characteristics of planar NPR structures. This provides a theoretical basis for subsequent modeling. Masters et al. [42] developed a theoretical model for predicting honeycomb elastic constants by combining the bending model [40], tensile model [43], and hinged model [42] into a general framework. Berinskii et al. [44] performed homogenization of planar honeycomb structures, simplifying the model, and derived expressions for the Poisson's ratio and Young's modulus along the loading direction as follows [16]:

Poisson's ratio:

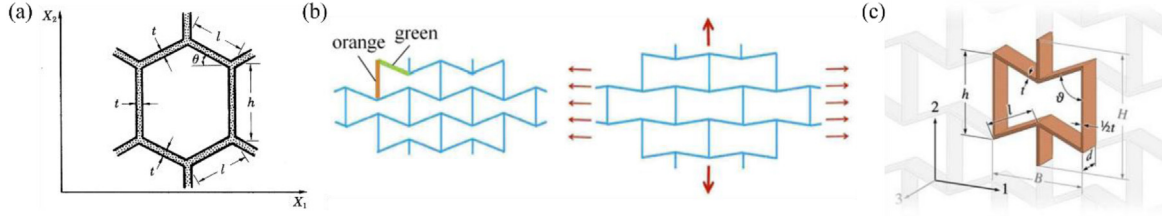
$$\nu_{12} = \frac{B}{H} \cdot \frac{2[1 - (\frac{2t\sin\theta}{B})^2] \sin\theta \cos\theta}{1 + (\frac{2t\sin\theta}{B})^2 [1 - (\frac{2t\sin\theta}{B})^2] \cos 2\theta} \quad (7)$$

Young's modulus:

$$E_1 = \frac{2BE_s (\frac{2t\sin\theta}{B})^3}{H \{1 + (\frac{2t\sin\theta}{B})^2 + [1 - (\frac{2t\sin\theta}{B})^2] \cos 2\theta\}} \quad (8)$$

where  $E_s$  is the Young's modulus of the beam,  $B$  is the cell width,  $H$  is the cell height,  $t$  is the thickness of the short cell wall, and  $\theta$  is the angle between the long and short cell walls (See Fig. 8c).

Due to the relatively low strength and limited load-bearing efficiency of such 2D re-entrant hexagonal honeycomb structures, some researchers have sought to enhance their structural performance by adding ribs or



**Fig. 8.** Re-entrant hexagonal honeycomb structures. (a) Unit cell model of 2D honeycomb material [40], (b) deformation of re-entrant hexagonal honeycomb structure [11] and (c) unit cell model of re-entrant hexagonal structure [16].

employing composite materials. For instance, Li et al. [45] introduced symmetrically arranged ribs of various shapes within the unit cells, which not only improved the structural strength but also enhanced the energy absorption capacity. Quan et al. [46] fabricated re-entrant hexagonal honeycomb structures of continuous fiber-reinforced thermoplastic composites using 3D printing technology. Compared with the structures made of traditional polylactic acid materials, the structural stiffness and energy absorption capacity were significantly improved.

Topology optimization, a common method for optimizing the topology of structures, allows for model simplification and lightweight design without compromising structural mechanical performance. Larsen et al. [47] designed a double-arrow structure using topology optimization, whose deformation mechanism is similar to that of re-entrant hexagonal structures. Both rely on the rotation between adjacent beams to achieve the NPR deformation effect (See Fig. 9a). The auxetic behavior depends on the lengths of the long and short beams and the angles between them. Compared to the re-entrant hexagonal structure, the double-arrow structure is simpler and easier to fabricate, more suitable for large deformations, and capable of producing a larger NPR, offering higher stiffness and stability [48]. Later, Guo et al. [38] optimized this model, replacing the zigzag shape with a smoother curve (See Fig. 9b), resulting in a double-U shaped auxetic honeycomb structure with tunable NPR and equivalent stiffness. This modification not only reduces stress concentration in the elastic region at the arrow hinge but also exhibits stronger NPR behavior during large deformations. For the mechanical properties of the double-arrow structure, Gao et al. [49] considered the interaction between adjacent unit cells and predicted the equivalent elastic mechanical properties in the Z-axis direction, based on the coordinate reduction homogenization theory. The obtained expressions for Young's modulus and Poisson's ratio are as follows:

$$E_z = \frac{12E_s I}{b l^3} \alpha(\theta_1, \theta_2) \quad (9)$$

$$\nu_{xz} = -\cot \theta_1 \cot \theta_2 \quad (10)$$

where  $E_s$  represents the Young's modulus of the structural material,  $I$  is the moment of inertia of the short and long beams,  $\theta_1$  and  $\theta_2$  are the angles between the short and long sides and the Z-axis direction,  $l$  is the half-width of the unit

cell structure in the X-axis direction, and  $b$  is the thickness in the out-of-plane direction (See Fig. 9c). The moment of inertia  $I$  is given by:

$$I = \frac{b t^3}{12}. \quad (11)$$

The function  $\alpha(\theta_1, \theta_2)$  is defined as

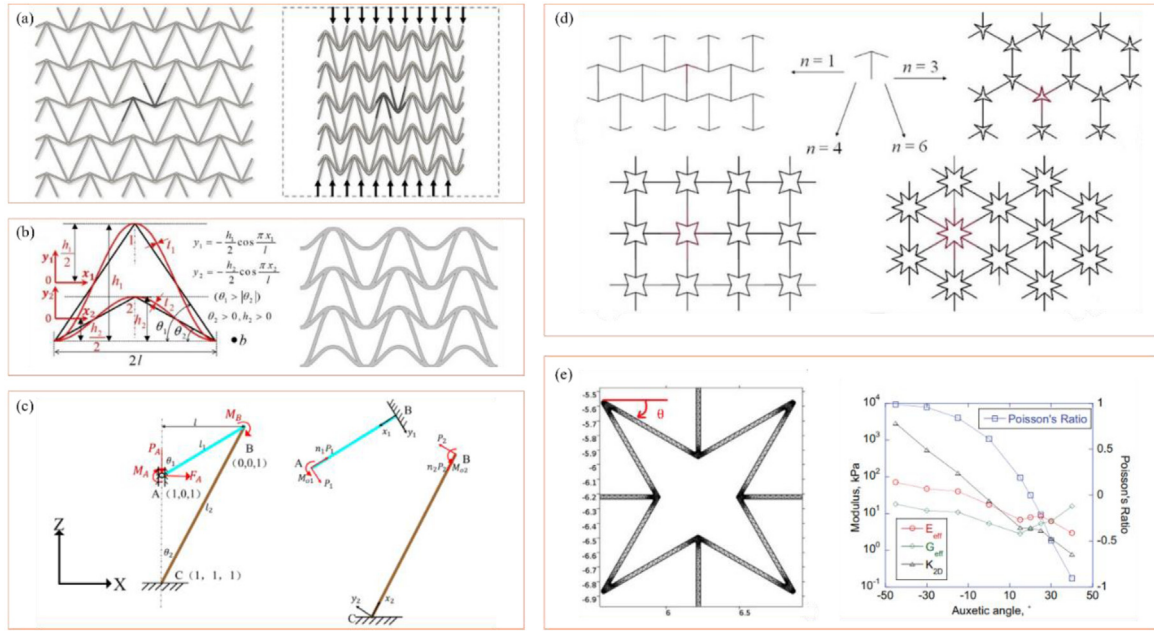
$$\alpha(\theta_1, \theta_2) = \frac{(\cot^2 \theta_1 \csc \theta_1 + \cot^2 \theta_2 \csc \theta_2) \sin(\theta_1 - \theta_2)}{(\cot \theta_1 - \cot \theta_2)^2}. \quad (12)$$

Then, Finite Element Analysis (FEA) was also employed to verify the accuracy of the mathematical model.

Due to the anisotropy of the double-arrow structure, its mechanical properties vary significantly in different directions, limiting its general applicability in practical engineering. In contrast, star-shaped structures can achieve isotropic deformation and mechanical properties, such as the 3rd-order and 6th-order star-shaped structures. Grima et al. [50] investigated multi-order star-shaped structures using Empirical Modelling with Unusual Deformable Atoms. The star-shaped structures can be regarded as being composed of arrow-shaped building blocks connected at the arrow "heads" to form star-shaped unit cells, resulting in 1st-, 3rd-, 4th-, and 6th-order star-shaped structures (See Fig. 9d). The magnitude of the Poisson's ratio is influenced by the hinge stiffness of the connecting members within the structure. Wang et al. [51] conducted a study on 2D star-shaped structures using finite element numerical methods. When the auxetic angle  $\theta$  is less than  $20^\circ$ , the structure generally does not exhibit a negative Poisson's ratio, and the auxetic angle also affects the effective pure shear modulus of the structure (See Fig. 9e). Subsequently, Ai and Gao [52] proposed a novel analytical model based on Cartan's second theorem to predict the effective Young's modulus and Poisson's ratio of 2D periodic star-shaped structures with orthogonal symmetry exhibiting a negative Poisson's ratio.

In addition, different concave structures can be arranged and combined according to specific patterns to create new NPR concave configurations. Zhao et al. [37] designed three types of Nine-Grid Combination Multi-Cell Structures composed of concave hexagonal and star-shaped units (See Fig. 10a) and performed finite element simulations (See Fig. 10b). Among them, the H-type combination exhibits the most pronounced NPR effect, as





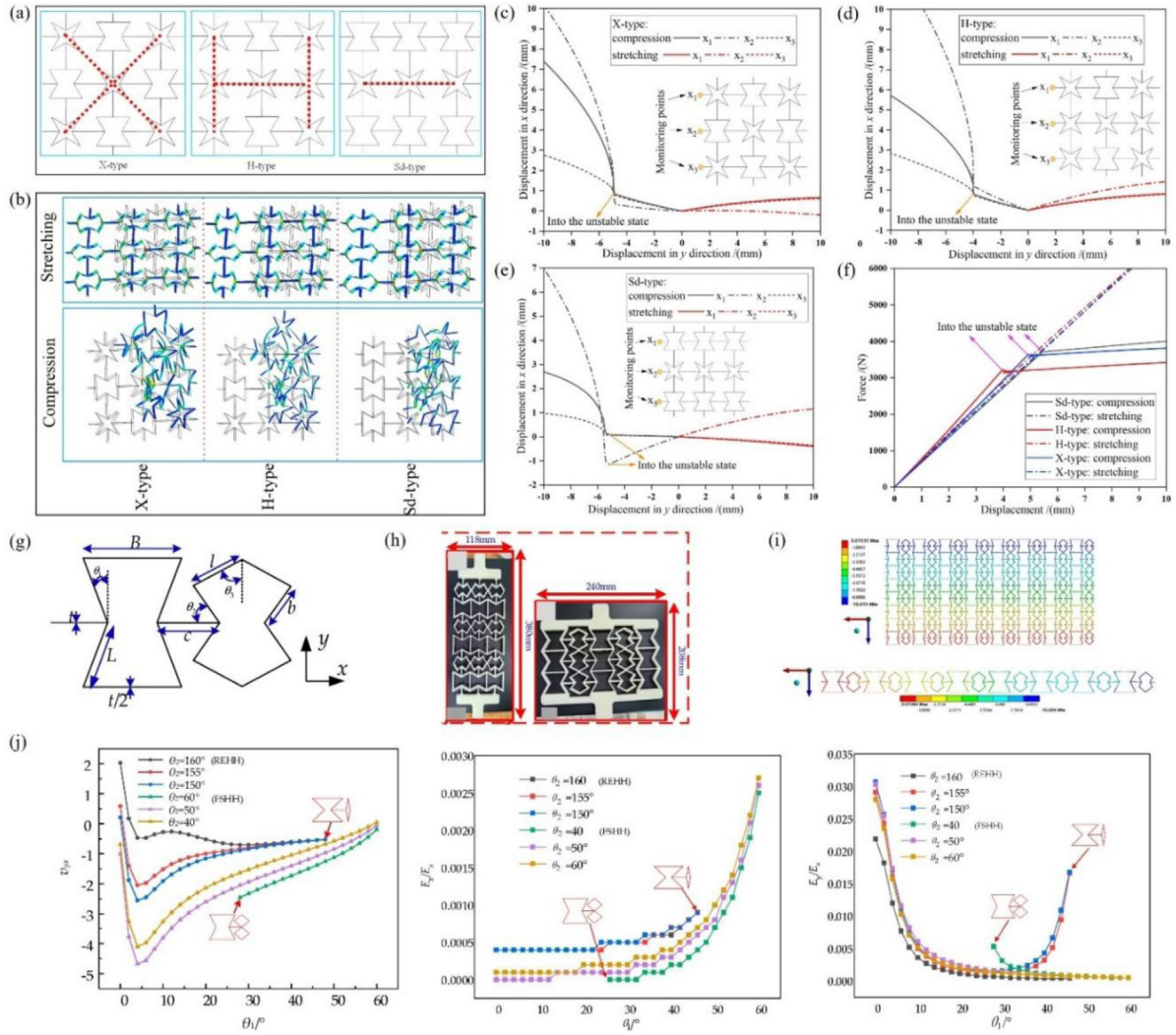
**Fig. 9.** Double-arrow and star-shaped structures. (a) Illustration of the double-arrow structure before and after uniaxial compression deformation [16]. (b) Double-U auxetic honeycomb structure [38]. (c) Schematic of the planar double-arrow unit cell under load along the Z-axis [37]. (d) Star-shaped structures with  $n = 1, 3, 4$ , and  $6$  [50]. (e) The definition of the auxetic angle, and the effective Young's modulus, shear modulus, 2D bulk modulus, and Poisson's ratio of numerical models with different auxetic angles [51].

well as the best elastic modulus and energy absorption performance (See Figs. 10c–10e). As shown in Figure 10f, the H-type structure has the lowest critical force for compression buckling, indicating the excellent stiffness of the concave hexagonal units. This means that a greater proportion of hexagonal units in the combination can resist compression buckling and achieve higher overall stiffness. The combination structures can achieve different NPR characteristics depending on the ratio of constituent cells, offering significant potential in engineering applications. For instance, the H-type structure demonstrates the best impact resistance and can be applied in blast-resistant armor and automotive safety components. Incorporating more hexagonal units can further enhance the load-bearing capacity, making it suitable for industrial vibration dampers.

Not only the arrangement and combination of NPR unit cells can achieve an overall NPR effect, but they can also be combined with non-NPR unit cells to realize structures with tunable Poisson's ratios, ranging from positive to negative. Wang et al. [53] proposed a re-entrant hybrid honeycomb (REHH) structure composed of re-entrant octagonal and re-entrant hexagonal unit cells (See Fig. 10g). They developed a theoretical model for the in-plane elastic modulus and Poisson's ratio of the structure and conducted experiments using 3D printing to fabricate specimens (See Fig. 10h). The theoretical and simulation results (See Fig. 10i) exhibited small errors. From Figure 10g, it can be observed that changing the re-entrant angles of the hexagonal unit cell  $\theta_1$  and the octagonal unit cell  $\theta_2$  and  $\theta_3$  alters the shape of the REHH structure's unit cells. Figure 10j illustrates the effects of

changing the internal angles  $\theta_2$  on the relative elastic moduli  $E_x/E_s$ ,  $E_y/E_s$ , and Poisson's ratio  $\nu_{yx}$  according to the theoretical model. Variations in the  $\theta$  angles affect the mechanical properties of the structure, allowing for adjustable Poisson's ratio and mechanical performance. Compared to traditional re-entrant hexagonal honeycomb structures, the REHH structure shows excellent tensile capacity in the x-direction and can withstand larger deformations. Due to its flexible adjustable parameters, it can meet different engineering requirements and holds great potential for applications in aerospace, automotive, and biomedical fields.

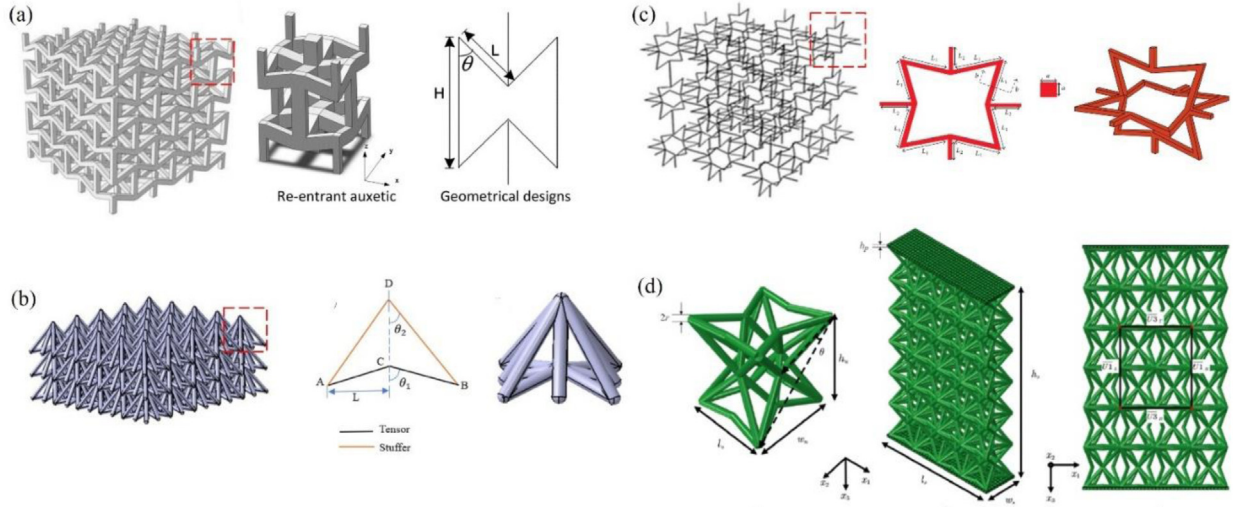
3D re-entrant structures are derived from 2D re-entrant unit cells. By employing techniques such as rotation, inversion, arraying, gridding, and mirroring, 2D re-entrant structures can be mapped into 3D configurations, giving rise to a variety of novel 3D re-entrant structural designs. In recent years, the rapid development of 3D printing technologies has made the fabrication of complex structural models feasible. Many studies have shifted focus from 2D to 3D re-entrant structures and conducted mechanical analyses on printed specimens. For instance, Li et al. [54] performed compression and three-point bending tests on 3D-printed sandwich structures with positive and negative Poisson's ratios. Due to the relatively uniform stress distribution, the auxetic sandwich structures exhibited a global failure mode. Additionally, these structures underwent successive buckling instabilities, significantly enhancing energy absorption. Yang et al. [18] designed unit cells whose projections along both the x and y directions form re-entrant hexagons (See Fig. 11a) and fabricated auxetic specimens using electron beam melting.



**Fig. 10.** Nine-grid combination and re-entrant hybrid NPR structures. (a) Nine-grid combination multi-cell NPR structures, (b) the predicted deformation state of nine-grid combination structures based on FEA, (c)–(e) X-type, H-type and Sd-type x-y displacement relationships, (f) force-displacement curves and displacement relationships of X-type, H-type, and Sd-type structures [37]. (g) Geometric parameters of REHH structures, (h) y-axis and x-axis stretch, (i) displacement analysis results under tensile loading, (j) Poisson's ratio and elastic modulus vs.  $\theta_1$  for various internal angles  $\theta_2$  [53].

Experimental results agreed well with simulations, indicating that 3D structures can also exhibit negative Poisson's ratio characteristics. Xue et al. [19] obtained 3D double-arrow unit cells by rotating and arraying planar double-arrow structures (See Fig. 11b), and 3D-printed specimens were tested under compression. The results showed progressive hardening behavior in the stress plateau stage, and the Poisson's ratio was closely related to structural parameters. Shokri et al. [55] generated 3D star-shaped structures by orthogonally arranging fourth-order star-shaped cells (See Fig. 11c) and investigated the influence of geometric parameters on elastic modulus, Poisson's ratio, and other fundamental mechanical properties through theoretical calculations and finite element analysis, providing design guidelines for 3D auxetic star-shaped honeycombs.

These studies generally started from unit cells that could potentially exhibit negative Poisson's ratio and achieved NPR behavior by modifying the unit cell geometry and connections. Sigmund [56] formulated the design of materials with specific constitutive tensors as a parameter optimization problem, using topology optimization combined with numerical homogenization based on inter-element energy interactions to obtain microstructures that satisfy the given constitutive requirements at minimal cost, effectively enabling performance-driven structural design. More recently, artificial intelligence (AI) has greatly facilitated unit cell design. Fang et al. [57] employed a deep learning-based inverse design method to construct novel 3D auxetic lattice sandwich structures, with the designed unit cells shown in Figure 11d. Tang et al. [58] combined homogenization theory with nonlinear topology optimization to rapidly obtain initial structures



**Fig. 11.** 3D re-entrant structures. (a) 3D re-entrant hexagonal structure and its unit cell [18], (b) 3D double-arrow structure and its unit cell [19], (c) 3D STAR-shaped structure and its unit cell [55] and (d) finite element model of the data-driven 3D auxetic unit cell and lattice specimen [57].

with mechanical properties close to the target. They extracted geometric features using principal component analysis and constructed a back propagation neural network to quickly predict the mechanical properties of the structures. By integrating evolutionary strategies, they achieved the inverse customization of structures that meet the expected targets. FEA and experiments showed that compared with traditional nonlinear topology optimization, this method not only improved accuracy but also shortened the design process. With the advancement of additive manufacturing technologies, the concept of four-dimensional (4D) printing has been proposed. 4D printing is an integrated technology combining additive manufacturing and smart materials. Through external energy stimulation, the printed objects can achieve dynamic changes in shape and/or functionality according to a preprogrammed procedure [59]. Shadman et al. [60] fabricated re-entrant hexagonal honeycomb structures of polyethylene terephthalate glycol (PETG) via 4D printing and investigated their mechanical properties and shape-memory behavior through compression experiments. The results showed that the PETG re-entrant honeycomb structures maintained their functional integrity after multiple loading cycles, and that cold programming exhibited a higher recovery rate than thermal programming. Owing to the combined advantages of impact resistance provided by the negative Poisson's ratio and the reusability enabled by the shape-memory effect, this structure offers new possibilities for reusable cushioning systems.

### 3.2 Rotating rigid unit structures

Some crystalline materials, such as  $\alpha$ -quartz, natrolite, and thomsonite, possess internal geometrical frameworks composed of rigid units connected in specific ways, forming structures similar to rotating rigid units. This unique

configuration endows the materials with special mechanical properties, such as NPR. Grima et al. [61] proposed a novel mechanism for achieving an NPR effect. When subjected to uniaxial tensile loading, the rigid units rotate relative to each other around the hinges, causing the gaps between the units to expand and thus exhibiting an auxetic behavior (See Fig. 12a). The square rotating rigid unit structure can be regarded as a 2D array or as the projection of a 3D configuration onto a plane. Through theoretical derivation, the Poisson's ratio of this structure was found to be  $\nu_{12} = \nu_{21} = -1$ , demonstrating an ideal NPR characteristic. Assuming that the stiffness of the structure is determined by the hinge stiffness, the Young's modulus and compliance matrix of the structure can be derived based on the principle of energy conservation as follows:

$$E_1 = E_2 = \frac{K_h 8/l^2}{1 - \sin \theta}. \quad (13)$$

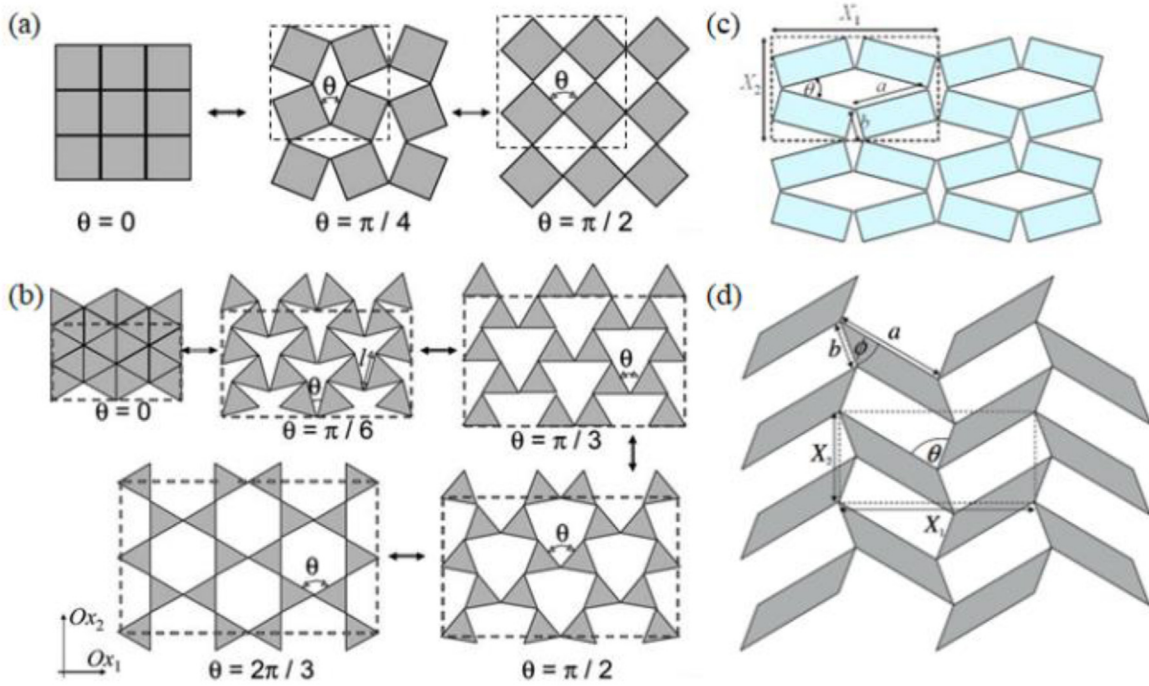
The corresponding compliance matrix is given by:

$$S = \begin{pmatrix} \frac{1}{E_1} & \frac{-\nu_{21}}{E_2} & 0 \\ \frac{-\nu_{12}}{E_1} & \frac{1}{E_2} & 0 \\ 0 & 0 & 0 \end{pmatrix} \quad (14)$$

where  $K_h$  represents the hinge stiffness,  $l$  is the side length of the square, and  $\theta$  denotes the rotation angle between adjacent squares. Subsequently, a similar triangular rotating structure with NPR characteristics was proposed [62]. Its deformation mechanism is analogous to that of the square rotating rigid unit structure (See Fig. 12b). The Poisson's ratio function of this structure is expressed as:

$$\nu_{21} = (\nu_{12})^{-1} = -1 \quad (15)$$





**Fig. 12.** 2D rotating rigid unit structures. (a) Square rotating structure [61], (b) triangular rotating structure [62], (c) rectangular rotating structure [63] and (d) parallelogram rotating structure [64].

and the corresponding Young's modulus is:

$$E_1 = E_2 = K_h \frac{4\sqrt{3}}{l^2[1 + \cos(\pi/3 + \theta)]}. \quad (16)$$

The compliance matrix can be written as:

$$S = \begin{pmatrix} \frac{1}{E_1} & \frac{-\nu_{21}}{E_2} & 0 \\ -\nu_{12} & \frac{1}{E_2} & 0 \\ \frac{1}{E_1} & \frac{-\nu_{21}}{E_2} & 0 \end{pmatrix} \quad (17)$$

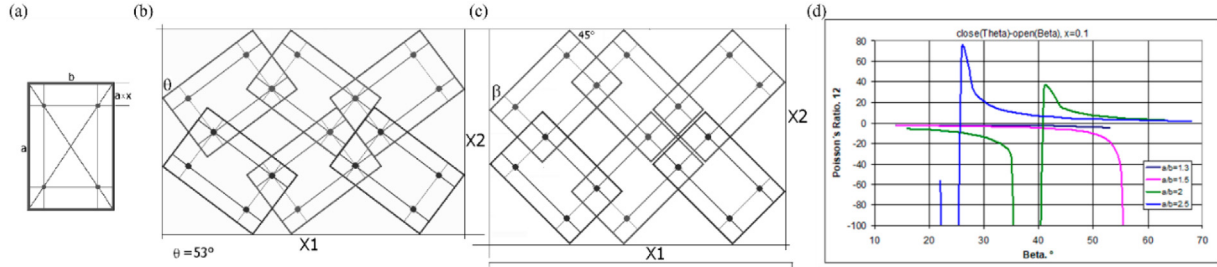
where  $K_h$  is the stiffness of the hinge joint,  $l$  is the side length of the equilateral triangle, and  $\theta$  is the angle between adjacent triangles. From the above expressions, it can be seen that both the square and triangular rotating structures are isotropic, and their Poisson's ratio equals  $-1$ . Therefore, their compliance matrices are symmetric, and the five elements associated with shear deformation are zero, implying that the shear modulus is infinite in this theoretical model. However, in practical situations, the shear modulus is finite because the rotating units cannot be perfectly rigid. Thus, the magnitude of the NPR depends on which deformation mechanism dominates, either hinge rotation or unit deformation [16]. Furthermore, the numerical value of the Poisson's ratio also depends on the relative stiffness between the rotating unit and the hinge joint [63]. Besides, they extended the square rotating structure to rectangular and rhombic rotating configurations,

and further generalized it into a more universal parallelogram rotating structure (See Figs. 12c-12d) [63,64]. The auxetic behavior of these structures was investigated, revealing the relationship between the NPR, geometric shape, rotation angle, and loading direction. In addition, the NPR can be tuned by changing the arrangement of rigid units and the size of the surrounding space, which provides valuable insights for the design of novel auxetic structures and the explanation of deformation mechanisms in natural auxetic materials.

To address the issues of joint fragility and performance degradation commonly observed in traditional rotating rigid unit structures, Plewa et al. [65] proposed a modified rectangular rotating structure. In this design, pivot points are connected at the corners of rectangular units (See Fig. 13a). The rectangular units are linked via pivots positioned along the diagonals, forming a metamaterial structure consisting of a minimum of four units. Figure 13b shows the closed position, where partial edge contact between rigid rectangles generates resistance, thereby enhancing the load-bearing capacity of the structure. Figure 13c presents the open position, in which the rigid rectangles can rotate freely relative to each other. When an axial force is applied horizontally, the structure expands while the rectangles rotate about their pivots. The shear force acting on each pivot depends on the applied tensile or compressive stress. The deformation mechanism satisfies the condition

$$x < \frac{1}{2} \left( \frac{a}{b} + 1 \right) \quad (18)$$





**Fig. 13.** Modified structure of rotating rectangles [65]. (a) Rectangle structural unit. (b) Closed position. (c) Open position. (d) Changes of the Poisson's ratio as a function of the opening angle for structures made of rectangles with different  $a/b$ .

where  $a$  and  $b$  are the length and width of the rectangle, respectively, and  $x$  is the tensile parameter. To achieve the NPR effect, the closed angle  $\theta$  and open angle  $\beta$  ( $\beta > \theta$ ) must be determined. The relationship between the Poisson's ratio and the opening angles is shown in Figure 13d. It can be observed that by adjusting these geometric parameters, the structure can exhibit a fully auxetic response with tunable Poisson's ratio, ranging from positive to negative. Such a mechanism demonstrates potential for applications in robotics as well as in the study of buckling and fracture mechanics.

Similar to quadrilateral units, simpler triangular cells can also form NPR rotating rigid unit structures, which further gives rise to other rotating units with arbitrary or non-uniform triangular shapes. Grima et al. [66] proposed a generalized structure model based on non-equilateral rigid triangles (See Fig. 14a), which exhibits NPR behavior depending on the triangle shapes and their connection patterns. It has been shown that all structures composed of two similar triangles are isotropic with a Poisson's ratio of  $-1$ , whereas for other configurations, the Poisson's ratio depends on the triangle edge lengths, hinge angles between triangles, and the loading direction. Inspired by a seesaw mechanism, Lim [67] designed a 2D NPR metamaterial composed of isosceles and right triangles (See Fig. 14b), where the Poisson's ratio can be tuned by adjusting the internal angle  $\phi$ , and remains constant at  $-1$  when  $\phi = 45^\circ$ . Furthermore, Lim [68] proposed a composite NPR structure inspired by the tangram, consisting of rotating rhombuses and right triangles (See Fig. 14c).

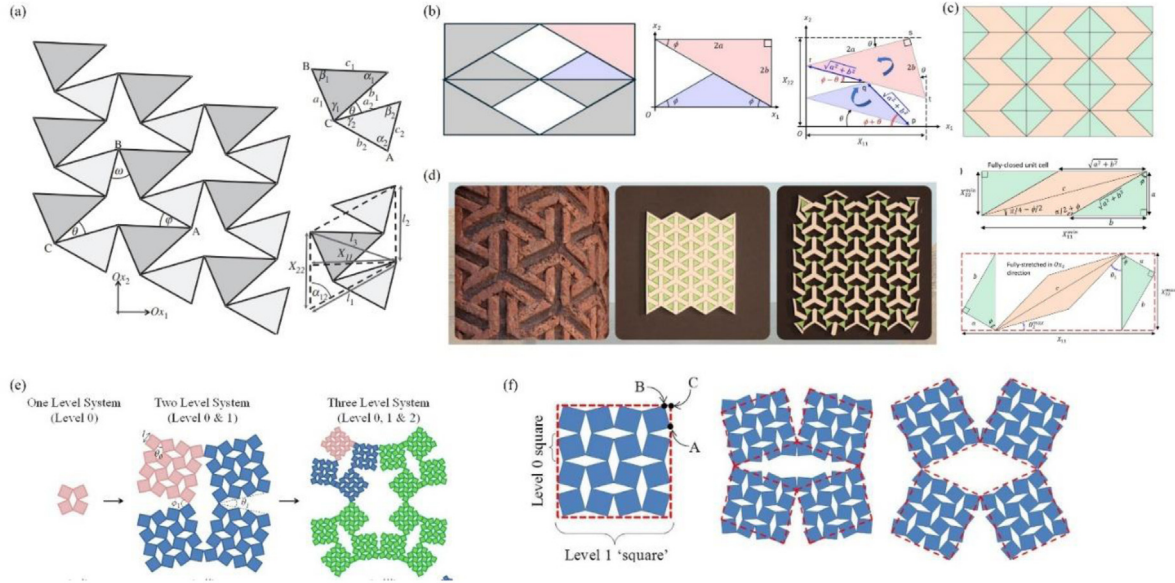
In addition, existing geometric patterns have also inspired the design of NPR rotating rigid unit structures. Rafsanjani et al. [69] designed a bistable NPR structure (See Fig. 14d), characterized by two features: (i) it maintains its state at either of the two extreme positions without external force; and (ii) its Poisson's ratio remains negative throughout the tensile process, approaching  $-1$  when fully extended. Moreover, Gatt et al. [70] proposed a hierarchical NPR structure based on the rotating rigid unit mechanism (See Fig. 14e), whose deformation mechanism is similar to that of standard rotating rigid units. Unlike conventional designs, the auxetic response of the hierarchical system depends on the relative stiffness of the hinges, and the effective geometry of the multi-level system is determined by the connections of the subunits rather than the subunits themselves (See Fig. 14f). Multiphysics

programmable intelligent materials represent a major direction for future research. Dudek et al. [71] embedded magnets inside rotating rigid unit cells. An external uniform magnetic field drives the rotation of the magnets via magnetic torque to achieve structural deformation. The negative Poisson's ratio of the material can be remotely adjusted by changing the magnitude and direction of the magnetic field. This structure features reversible deformation and programmability, holding great promise in smart material applications such as tunable smart dampers.

Due to the inherent limitations of 2D models, they are unable to capture or explain auxetic behavior occurring simultaneously in both in-plane and out-of-plane directions. To address this, Grima et al. [20] further proposed rotating units exhibiting 3D NPR effects (See Fig. 15a). When the hinge angle  $\theta$  is small, the structure is more likely to exhibit NPR behavior along all three directions. Scaling such structures down to the micro- or nanoscale can result in a system that may be regarded as an auxetic material rather than merely an auxetic structure. Moreover, 3D NPR structures provide a better explanation for the auxetic behavior of existing (artificial or natural) auxetic materials. Junhyun et al. [72] proposed 3D auxetic structures composed of regular polygonal prisms, including square-prism, triangular-prism, and hexagonal-prism structures (See Figs. 15b–15d). They derived the corresponding Poisson's ratio formulas and verified the auxetic behavior experimentally. According to these formulas, the auxetic response is related to the ratio of prism height  $b$  to base edge length  $a$  ( $b/a$ ). Currently, most studies on rotating rigid unit structures remain at the theoretical calculation stage, where structural units are assumed to be rigid bodies. Since absolute rigidity does not exist in practice, experimental validation of theoretical predictions is essential. Furthermore, research on the mechanical performance of rotating rigid unit structures remains limited, suggesting that further investigation combining theory and experiment is necessary.

### 3.3 Chiral structures

The term “chiral” originates from Greek and is used to describe spatial structures that cannot be superimposed onto their mirror images. At the microscopic level, Wojciechowski [73] first proposed a chiral molecular structure composed of hard hexamers with an NPR.

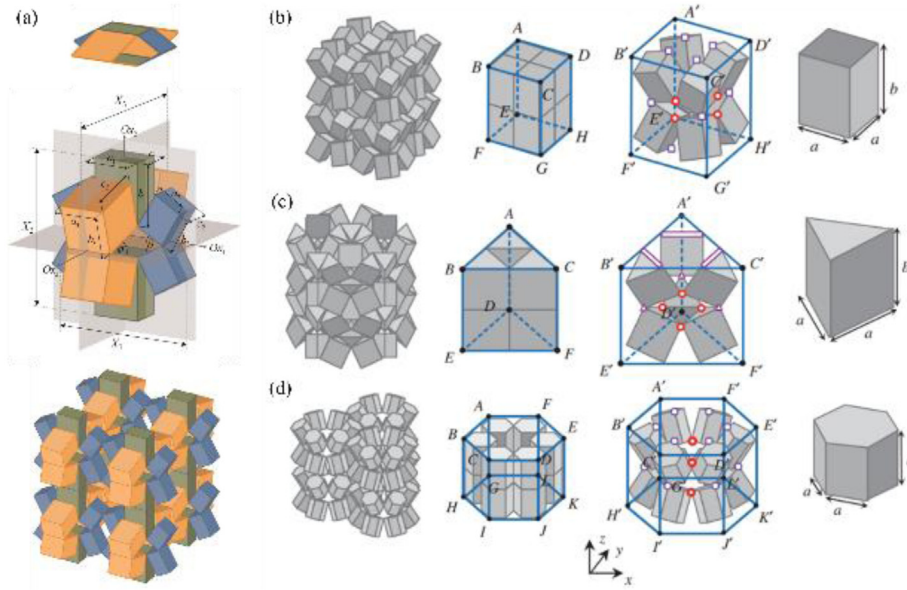


**Fig. 14.** Other rotating rigid unit structures. (a) General structure based on non-equilateral triangular rotating units [66]. (b) Seesaw-inspired rotating triangular unit [67]. (c) Hybrid unit composed of triangles and quadrilaterals [68]. (d) NPR bistable unit [69]. (e) Multi-level rotating square structure. (f) Hierarchical structure with different subunit connection arrangements [70].

At the macroscopic level, Lakes et al. [41] first proposed that an asymmetric structure composed of rigid nodes and ligaments could exhibit a NPR, and further introduced the hexachiral structure (See Fig. 16a) [74]. The structure also possesses hexagonal symmetry, with its Poisson's ratio being isotropic. When a longitudinal tensile load is applied to the structure, the circular nodes at both ends of the ligaments undergo rotation in the same direction, causing the distance between the two nodes to increase, thereby achieving the auxetic behavior. The Poisson's ratio remains stable at  $-1$  over a wide range of strains. Additionally, based on the number of ligaments tangent to each node, multiple chiral structures can exist. However, to construct a periodic chiral structure, the constraint of rotational symmetry must be satisfied. Therefore, the number of ligaments connected to each node should equal the order of rotational symmetry,  $n$  [75]. Only building blocks with  $n = 3, 4$ , or  $6$  can be used to create space-filling periodic structures [76]. Therefore, there are also trichiral and tetrachiral structures (See Figs. 16b and 16c). By relaxing this constraint, more auxetic structures can be constructed using chiral units, such as the meta-chirals (See Fig. 16d) [76], whose Poisson's ratio is influenced by geometric parameters and can vary from  $-\infty$  to  $+\infty$ , exhibiting characteristics of either auxetic or conventional honeycomb materials. When a chiral structure is subjected to a load and the rotation directions of the nodes at the ends of the ligaments differ, it is referred to as an anti-chirals structure, such as the anti-trichiral structure and anti-tetrachiral structure (See Figs. 16e and 16f).

The study of mechanical properties is essential for practical engineering applications. Spadoni et al. [77] investigated the buckling behavior of chiral honeycomb structures under in-plane compression through analytical calculations and finite element analysis. By comparing

chiral, re-entrant hexagonal, and conventional honeycomb structures, they found that chiral structures can withstand higher buckling loads (See Fig. 17a), making them more suitable for use as sandwich core materials. Alderson et al. [78] conducted finite element analysis and experimental studies on tetrachiral, anti-tetrachiral, trichiral, anti-trichiral, and hexachiral structures. Three dimensionless parameters,  $\alpha = L/r$ ,  $\beta = t/r$ , and  $\gamma = d/r$ , were defined to describe the structural characteristics, where  $r$  is the radius of the circular nodes,  $L$  is the ligament length,  $t$  is the uniform wall thickness of both nodes and ligaments, and  $d$  is the structural depth. Research indicates that the Young's modulus ( $E$ ) of chiral honeycomb structures generally increases with the number of ligaments (See Fig. 17b). For structures with the same number of ligaments, the Young's modulus is positively correlated with  $\beta$  (See Fig. 17c) and negatively correlated with  $\alpha$  (See Fig. 17d). Under in-plane uniaxial loading, the off-axis ligaments of hexachiral and tetrachiral honeycomb structures bend into a full-wave shape, which facilitates the formation of a negative Poisson's ratio. When  $\beta$  is constant, both structures maintain a negative Poisson's ratio close to  $-1$  (See Fig. 17e). In trichiral honeycomb structures, the bending of off-axis ligaments into a full-wave shape is the dominant deformation mechanism. However, the smaller angle between the orientation of the off-axis ligaments and the loading direction makes it difficult to achieve a negative Poisson's ratio. In contrast, anti-trichiral honeycomb structures can exhibit a negative Poisson's ratio under the limit condition of short ligaments. For chiral honeycomb structures, when the nodes are sufficiently small, their properties tend to approach those of traditional honeycomb structures. Therefore, chiral structures can be combined with concave polygonal structures to form a new type of concave chiral structure. Such as the



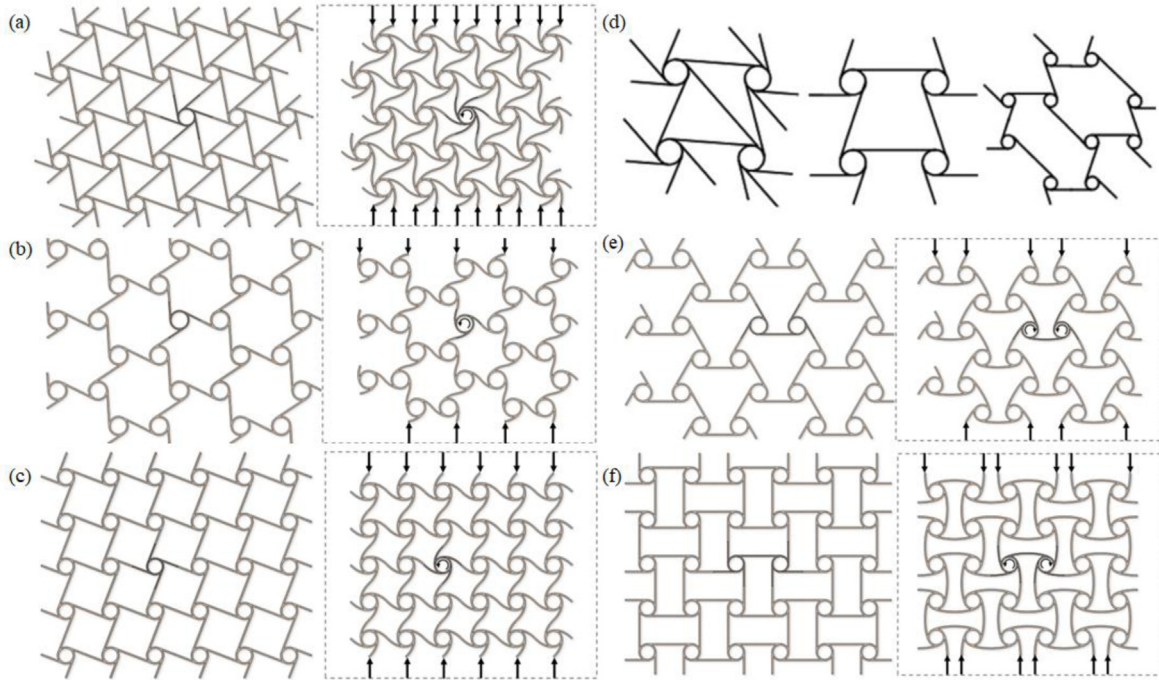
**Fig. 15.** 3D rotating rigid unit structures. (a) 3D rotating cuboid [20], (b) square-prism structure and its deformation, (c) triangular-prism structure and its deformation, and (d) hexagonal-prism structure and its deformation [72].

double-arrowhead chiral structure [79] and the concave hexachiral structure [80] (See Fig. 17f). By establishing equivalent models, the mechanical performance of the structure can be predicted. Lakes et al. [74] used standard beam theory and the energy method to predict that the Poisson's ratio of hexachiral honeycomb structures remains constant at  $-1$  under small strain. This results in an infinite shear modulus; however, the NPR and enhanced shear resistance are not attributed to individual structural members, but rather to the collective behavior of a large number of unit cells. Consequently, this leads to uncertainty in the constitutive law of such materials. To eliminate this uncertainty, Spadoni et al. [81] analyzed the in-plane mechanical behavior of hexachiral structures using a micropolar continuum model. Under the assumption of rigid nodes, the Poisson's ratio depends on the thickness-to-length ratio of the ligaments ( $t/L$ ). The Poisson's ratio equals  $-1$  only when  $t/L = 0$ . This approach effectively eliminates the uncertainty in the constitutive law of the equivalent continuum model. Bacigalupo et al. [82] investigated the static and dynamic responses of anti-tetrachiral honeycomb structures using two distinct models. The first model, a beam model, simplifies the actual solid into a discrete system of interconnected beams while neglecting the presence of the matrix. The second model, a continuum model, employs a first-order computational homogenization technique to evaluate the overall constitutive response. The results of both models are found to be highly consistent when the matrix is not considered, and the NPR effect is most pronounced under these conditions. The study also revealed that the presence of the matrix material between the ligaments significantly reduces the auxetic behavior of the structure. Most previous studies have focused on ideal chiral structures, whereas practical structures inevitably contain geometric imperfections. Therefore, investigating the influence of

such imperfections on the mechanical behavior of hexachiral honeycomb structures is of great importance. Mizzi et al. [83] employed the finite element method to examine the effect of nodal translational disorder (See Fig. 17g) on the mechanical properties of hexachiral systems. The results demonstrated that, as long as the ligament slenderness ratio (length-to-thickness ratio) is sufficiently high and the overall aspect ratio ( $a/b$ ) of the disordered system does not differ significantly from that of the ordered one, the Poisson's ratio of the hexachiral honeycomb remains largely unaffected by nodal disorder. However, the Young's modulus increases with the degree of disorder (See Fig. 17h). For irregular hexachiral structures, changes in the aspect ratio ( $a/b$ ) lead to significant variations in their mechanical performance (See Fig. 17i). Unlike other NPR structures, the hexachiral honeycomb exhibits remarkable tolerance to translational disorder, maintaining approximately its original Poisson's ratio. This characteristic represents a significant advantage for practical engineering applications. The auxetic behavior of chiral structures arises from the bending of ligaments and the rotation of nodes. When the chiral unit cell contains non-axially symmetric nodes (See Fig. 17j), the rotation direction of chirality significantly affects the mechanical performance [84]. This implies that clockwise and counterclockwise chiralisation yield two distinct types of NPR chiral structures, each exhibiting markedly different mechanical characteristics.

In addition, there exists another type of ligament-only chiral-like structure. This design originates from the missing-rib model proposed by Smith et al. [85] to explain the auxetic behavior of NPR foam materials. Farrugi et al. [86] conducted a comprehensive study on the NPR deformation mechanism of the missing-rib structure (See Fig. 18a) through FEA and experiments on 3D-printed specimens. Their results revealed two deformation





**Fig. 16.** Schematic of 2D chiral structures and their compressive deformation. (a) Hexachiral structure, (b) trichiral structure and (c) tetrachiral structure [16]. (d) Meta-chirals [76]. (e) Anti-trichiral structure and (f) Anti-tetrachiral structure [16].

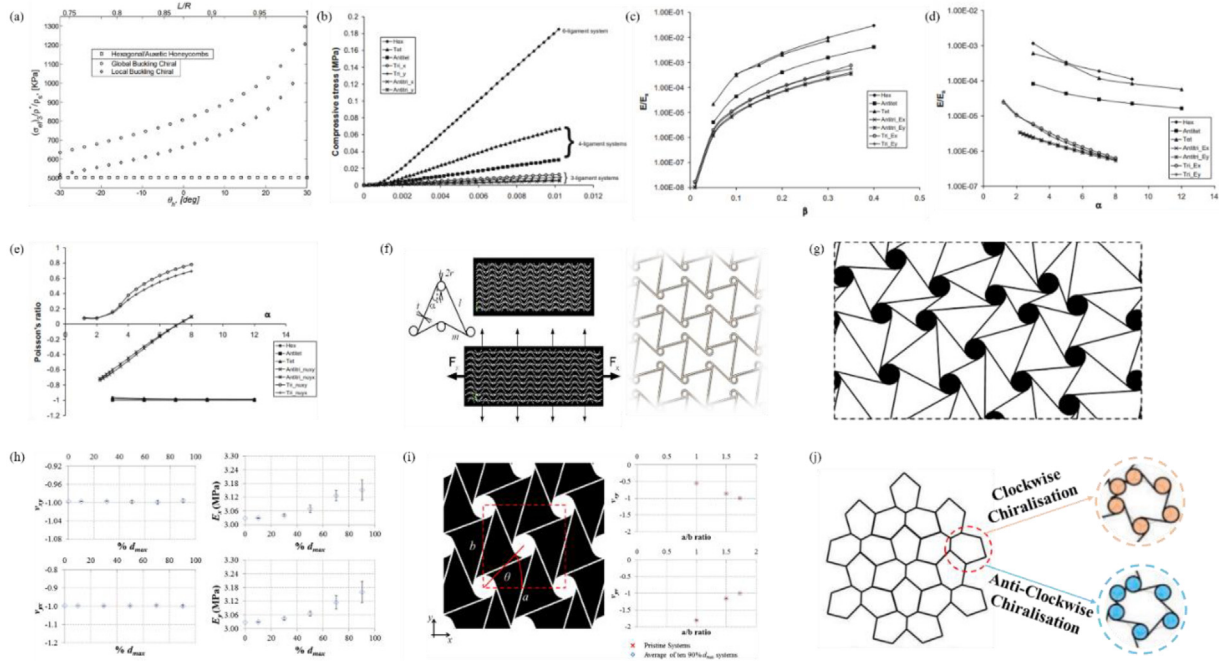
mechanisms under uniaxial loading: the bending of ligaments and the bending of cross ligaments. The former was found to be more effective in producing the NPR effect. Therefore, the extent to which the cross ligaments act as rigid rotational centers plays a crucial role in determining the resulting Poisson's ratio, similar to the case of chiral honeycomb structures.

The cross-chiral structure combines the characteristics of both chiral and re-entrant polygonal geometries (See Fig. 18b), and its deformation mechanism is associated with the rotational behavior at nodes and the hinging at ligament joints. Dong et al. [87] optimized the cross-chiral structure by integrating a genetic algorithm with finite element analysis. This approach not only enhanced its mechanical performance but also introduced a new modeling method that effectively addresses the complex anisotropy of components fabricated by fused deposition modeling (FDM).

Building on the chiral characteristics, Liu et al. [88] proposed a novel cross-tetrachiral honeycomb metamaterial (See Fig. 18c). Compared with conventional chiral honeycomb structures, the cross-tetrachiral honeycomb metamaterial introduces additional tunable geometric parameters, enabling the realization of both narrower and higher-frequency bandgaps. The integrated design without additional mass makes the manufacturing process easier and more precise. Research has demonstrated that the cross-tetrachiral honeycomb metamaterial not only exhibits a significant NPR effect but also provides excellent vibration attenuation and wave isolation capabilities. Consequently, by adjusting geometric parameters or introducing small linear deformations, the cross-tetrachiral

honeycomb metamaterial offers tunable static and dynamic properties, indicating its promising potential for engineering applications.

Based on the aforementioned types of 2D chiral honeycomb structures, researchers have further proposed 3D chiral metamaterials with unique mechanical behaviors. Frenzel et al. [89] proposed a compression-twist 3D chiral structure (See Fig. 19a) and revealed its underlying deformation mechanism through micropolar theory and experimental validation. Fu et al. [90] proposed a 3D NPR structural design based on the rotational mechanism of chiral honeycombs, in which 2D tetrachiral honeycomb layers are stacked, and adjacent layers are connected by inclined rods (See Figs. 19b and 19c). The study showed that this structure exhibits NPR in all three directions, and the out-of-plane Poisson's ratio can be switched from negative to positive by changing the inclination direction of the rods. The deformation is mainly governed by the bending of ligaments and rods. Under small deformations, the nodes merely serve as connectors transmitting moments and can be regarded as rigid components, meaning the node shape has negligible influence on structural performance. In other cases, structures with square nodes show higher stiffness, lighter weight, and greater load-bearing capacity than those with circular nodes. This configuration can also be extended to trichiral structures with different numbers of ligaments. Similarly, Qi et al. [91] designed 3D tetrachiral, anti-tetrachiral, and hybrid tetrachiral structures (See Fig. 19d) by coupling the deformation mechanisms of square-node tetrachiral structures and re-entrant hexagonal structures. Through theoretical, experimental, and numerical studies under



**Fig. 17.** The chiral structures and their mechanical properties of auxetic metamaterials. (a) Normalized buckling stress of chiral and hexagonal honeycombs with respect to relative density [77]. (b) Finite element prediction of  $E$  as a function of the number of ligaments [78]. (c) Finite element prediction of  $E$  as a function of  $\beta$  [78]. (d) Finite element prediction of  $E$  as a function of  $\alpha$  [78]. (e) Finite element prediction of  $\nu$  as a function of  $\alpha$  [78]. (f) Schematic illustrations of double-arrow [79] and re-entrant hexachiral [80] structures. (g) Schematic of a disordered hexachiral system. (h) Mean Poisson's ratio and Young's modulus of chiral structures with different degrees of disorder, together with standard deviations of the results. (i) Structural parameters of hexachiral structures and Poisson's ratio variation of irregular hexachiral structures. (j) Clockwise and counter-clockwise chiralisation of a hexagon with triangular rotational symmetry [83].

large deformations, it was found that the Poisson's ratio is sensitive to both the length of square nodes and the interlayer spacing, and a wide range of negative Poisson's ratios can be obtained by adjusting the geometric parameters. Lu et al. [92] proposed two new types of 3D chiral structures: one formed by rotating a 2D cross-chiral structure, and another formed by adding star-shaped elements to the former (See Figs. 19e and 19f). Using beam theory and FEA, they predicted the mechanical performance of these structures. The first structure exhibits anisotropic auxetic behavior, whereas the second one shows isotropic auxetic properties, with all axial Poisson's ratios tunable to values close to  $-1$ . The addition of star-shaped elements significantly enhances the Young's modulus, leading to higher stiffness and load-bearing capacity. This provides a new strategy for tuning the overall mechanical properties of auxetic materials. In addition, other forms such as 3D isotropic anti-tetrachiral metastructure [93], 3D alternating anti-tetrachiral structures [94], and node-enhanced 3D chiral NPR structure based on the missing rib architecture [21] have also been proposed (See Figs. 19g – 19i).

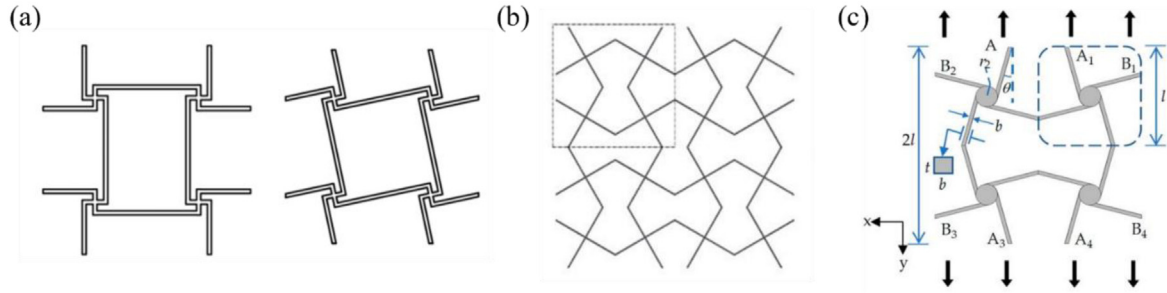
At present, analytical models for cross-chiral structures remain highly simplified, and most studies have focused on missing-rib configurations, with relatively limited research on 3D cross-chiral structures. The mechanical analyses of 2D chiral NPR materials are mostly based on the assumption of linear deformation, while few studies have

addressed the influence of nonlinear deformation on their structural behavior. Moreover, investigations into the effects of local defects on the mechanical performance of both 2D and 3D chiral honeycomb structures are still scarce. Therefore, further research is required in these aspects.

### 3.4 Perforated sheet structures

The design of perforated sheet structures is generally achieved by machining holes or slits with specific geometries into thin sheets made of conventional materials. By tailoring the patterns of these perforations, the overall mechanical performance of the structure can be adjusted. The auxetic behavior of such systems primarily arises from the shape and distribution of the holes or slits, and the deformation mechanism of the resulting structure is similar to that of certain known NPR structures.

Grima et al. [95] achieved an NPR structure by introducing rhombic perforations into thin sheets made of conventional materials (See Fig. 20a). The deformation mechanism of this structure is similar to that of the rotating rectangular model, as both rely on the rotation of hinge regions between adjacent rectangles. However, in this case, the structural units themselves deform under loading, which influences the overall performance. The study revealed that the Poisson's ratio increases with the internal angle between rectangles, and further increases under large



**Fig. 18.** Missing-rib and cross-chiral structures. (a) Tetrachiral and anti-tetrachiral missing-rib structures [86]. (b) Cross-chiral structure [88]. (c) Unit cell of the cross-tetrachiral honeycomb metamaterial [88].

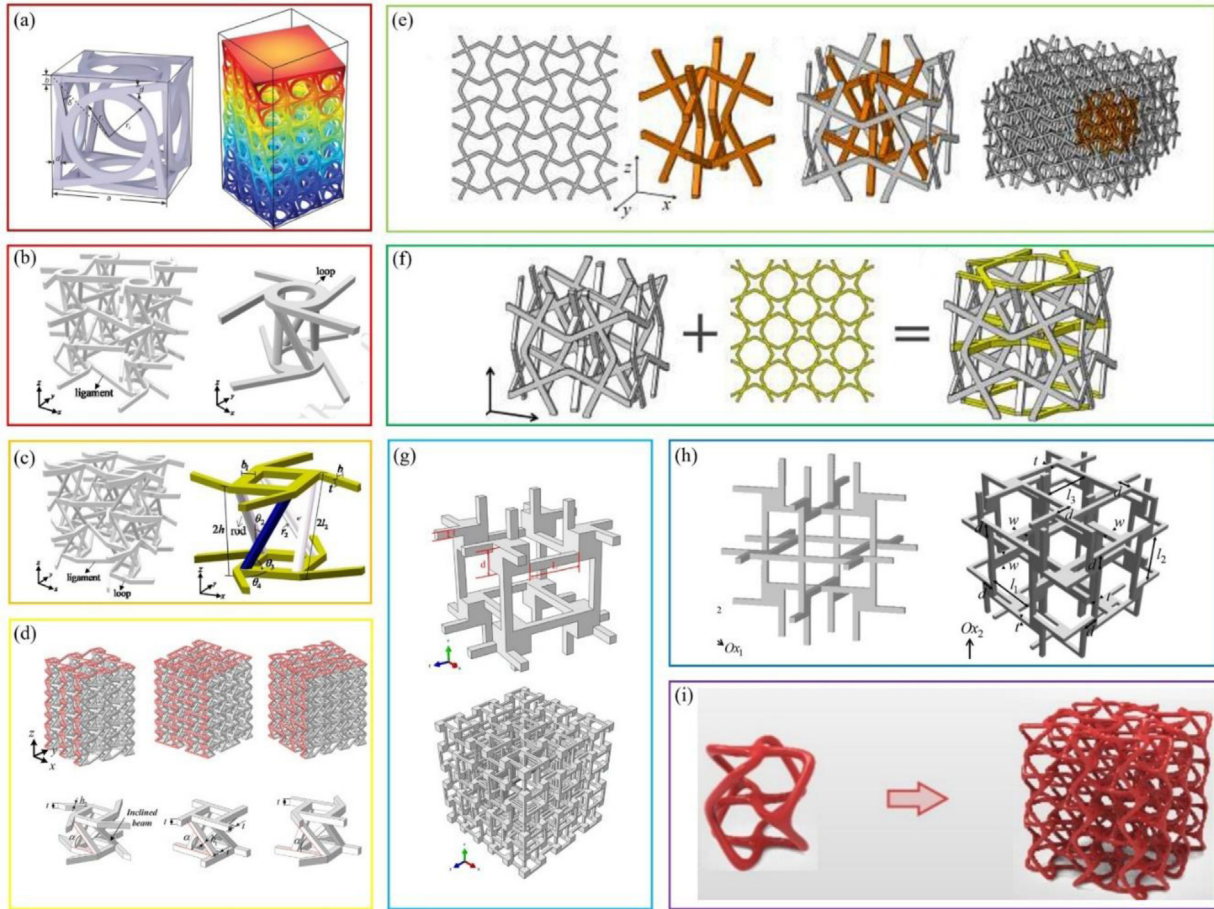
deformations. Subsequently, Grima and co-workers investigated the auxetic behavior of perforated sheet structures with star-shaped and triangular holes (See Fig. 20b) [96]. This structure can, to some extent, replicate the deformation mechanism of rotating triangular systems, with a smaller connection-width  $s$  yielding a closer resemblance. Under otherwise identical conditions, increasing the internal angle between adjacent triangles leads to a higher Poisson's ratio. Such structures significantly reduce the cost of fabricating auxetic materials, and their overall performance depends on the mechanical properties of the base sheet material. Most studies on NPR structures have focused on isotropic systems, where the Poisson's ratio typically ranges from 0 to  $-1$ . However, the above-mentioned perforated sheet structures demonstrate that the Poisson's ratio can be less than  $-1$ , and theoretically may even approach  $-\infty$ , exhibiting anisotropic behavior. Mizzi et al. [97] further proposed perforated sheet structures composed of two sets of parallelogram units with different sizes, derived from the rotating parallelogram model, and an equivalent design based on elliptical perforations (See Fig. 20c). Their results demonstrated that a wide spectrum of Poisson's ratios, ranging from positive to negative, can be achieved by simply adjusting the size, shape, or orientation of the perforations. However, similar to rotating rigid-unit structures, highly concentrated local stresses were observed around the connecting regions [98].

Shan et al. [99] proposed a novel method for creating isotropic 2D materials with a negative Poisson's ratio by introducing periodic arrays of slit perforations into elastic sheets. By investigating five different slit patterns (See Fig. 20d), they found that configurations with threefold and sixfold symmetry produce isotropic mechanical responses, while those with twofold and fourfold symmetry result in anisotropic responses. The Poisson's ratio can be easily and significantly tuned by adjusting the slit length, yielding an extensive range of negative values. Furthermore, the degree of isotropy is governed by the rotational symmetry of the slit pattern. Afterwards, Mizzi et al. [17] improved upon conventional perforated sheet designs by developing slit-perforated sheet structures, which require less material removal, thereby minimizing waste and reducing manufacturing cost and time. Compared with traditional perforated sheet structures, the slit-perforated design can not only mimic the deformation mechanisms of

rotating rigid-unit structures but also emulate concave polygonal and chiral configurations (See Fig. 20e). Owing to the nearly closed configuration of these idealized mechanisms, the structures exhibit greater stretchability and an exceptionally broad range of negative Poisson's ratios. However, during the fabrication of perforated sheets, the more complex the structure, the higher the likelihood of defects. Despite the increasing number of defects, the deformation behavior of the structure is not significantly affected [100], indicating that fabrication imperfections have minimal impact on structural performance. The aforementioned perforated sheet units all possess high symmetry and periodicity, without considering the influence of irregular pore distributions on overall performance. Grima et al. [101] investigated perforated sheets with randomly oriented cuts (See Fig. 20f), which mimic the deformation behavior of square rotating structures and achieve an NPR through pore compression. The study demonstrated that deviations from ordered symmetry do not lead to drastic changes in the Poisson's ratio, implying that high fabrication precision is not strictly necessary for these perforated sheet structures. Cho et al. [102] proposed a novel approach to simply modify materials using fractal cutting patterns, enabling materials to achieve large strains and a wide range of negative Poisson's ratios. By varying the hierarchical levels of cuts and the base cutting patterns used to partition material units, the expansion behavior and mechanical performance of the material can be customized, and the cutting scheme corresponding to a target morphology can be inversely derived (See Fig. 20g).

In addition, mechanical instabilities in 2D periodic porous structures can induce significant transformations of the initial geometry. Bertoldi et al. [103] found that when a square array of circular holes in elastomeric materials is subjected to uniaxial loading, elastic instability leads to alternating orthogonal elliptical patterns, resulting in unidirectional NPR behavior (See Fig. 20h), which occurs only under compression. Subsequently, Wang et al. [104] improved the above orthogonal elliptical-hole structure using experiments, finite element simulations, and machine learning methods, designing an orthogonal peanut-shaped hole configuration (See Fig. 20i) to address the stress concentration problems of conventional elliptical or diamond-shaped hole structures. This machine learning model based on artificial neural networks provides a new





**Fig. 19.** Schematic diagrams of 3D chiral structures and unit cells. (a) 3D mechanical metamaterial with a twist [89]. (b) 3D auxetic structure with circular loops [90]. (c) 3D auxetic structure with square loops [90]. (d) 3D tetrachiral, anti-tetrachiral, and hybrid-tetrachiral structures [91]. (e) 3D cross-chiral structure [92]. (f) 3D cross-chiral structure with isotropic auxetic behavior [92]. (g) 3D isotropic anti-tetrachiral metastructure [93]. (h) 3D alternating anti-tetrachiral structures [94]. (i) Node-enhanced 3D chiral NPR structure based on missing-rib architecture [21].

approach for analyzing perforated sheets, achieving high efficiency and accuracy without being constrained by complex explicit relationships between input and target variables.

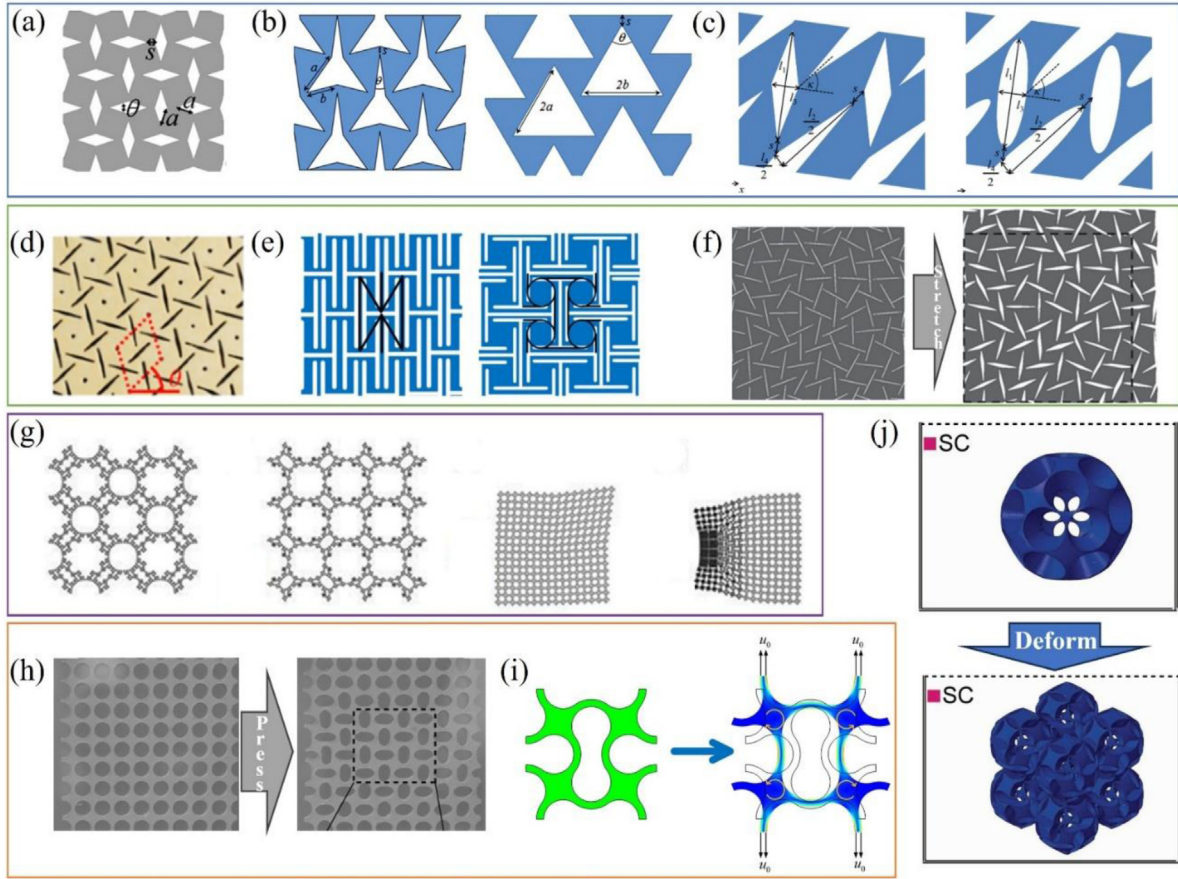
For 3D perforated sheet structures, NPR behavior can also arise under elastic instability. Babaee et al. [22] designed a buckling-induced 3D metamaterial constructed from porous spherical shells (See Fig. 20j). Experiments and FEA demonstrated that these buckling-designed 3D NPR structures exhibit negative Poisson's ratio under compressive loads and maintain NPR over a wide strain range.

### 3.5 Other structures

With the expanding research on NPR metamaterials and the continuous development of auxiliary technologies such as AI, a greater variety of NPR structures has emerged. Inspired by traditional art origami, origami-based metamaterials are fabricated by folding a 2D planar material along crease patterns into 3D configurations. Due to their lightweight nature, scale-independence, multi-stability, and other dynamic characteristics, as well as the

widespread occurrence of NPR in origami structures [105], they are particularly suitable for constructing NPR metamaterials. Fang et al. [106] proposed a general 4-vertex origami unit cell (See Fig. 21a), which can exhibit NPR behavior in all three directions within a single-layer origami structure. Lv et al. [107] corrected a common misconception regarding the Poisson's ratio of the Miura origami structure, demonstrating that the Poisson's ratio should be evaluated based on the entire structure rather than just the unit cell, which means the Poisson's ratio of the structure is not always negative and can also be positive. They further showed that the Ron-Resch rigid origami structure possesses high load-bearing capacity.

Ravirala et al. [108] proposed an interlocking hexagonal model structure (See Fig. 21b), which consists of multiple interlocked rigid hexagonal unit cells. These cells are connected via springs located at corresponding rectangular protrusions and indentations along adjacent edges. The NPR arises from the translational motion of the hexagons, facilitated either by compression of the springs or by the elastic potential energy stored in the springs sliding along the rectangular protrusions. Derived from this type of interlocking structure, 3D structures have been developed.

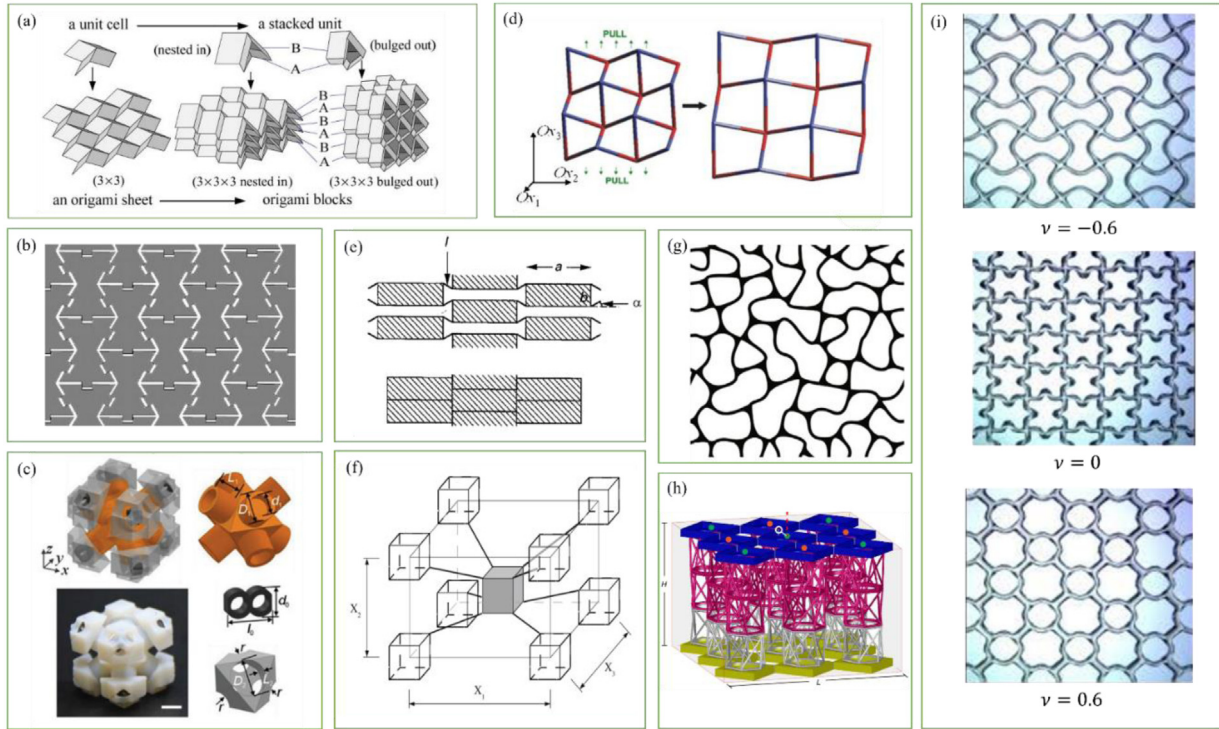


**Fig. 20.** Schematic of perforated sheet structures. (a) Rhombic perforated sheet structure [95]. (b) Star- or triangular-shaped perforated sheet structure [96]. (c) Elliptical perforated sheet structure [97]. (d) Isotropic perforated sheet structure [99]. (e) Slit perforated sheet structure [17]. (f) Perforated sheet structure with randomly oriented cuts [101]. (g) NPR structure obtained via fractal cutting technique [102]. (h) Deformation schematic of perforated sheet with circular holes induced by elastic instability [103]. (i) Peanut-shaped perforated sheet [104]. (j) Bucklicrystal with simple cubic (SC) [22].

Li et al. [109] designed a tiled auxetic metamaterial with high resilience and mechanical hysteresis (See Fig. 21c), which adopts a multi-material 3D printing process to achieve an assembly-free double-ring connected structure in one piece. The auxetic effect is realized through the internal elastic material, and its mechanical properties and deformation mechanism can be adjusted by changing the friction coefficient and direction between the keys and channels. Grima et al. [110] designed a network structure resembling an egg rack made of steel wire (See Fig. 21d). This structure is composed of alternately oriented “four-legged claws” arranged on a square grid. When the structure is subjected to a tensile load, the connectivity of the “claws” forces them to open in all directions like an umbrella, thus producing a negative Poisson’s ratio in the plane of the structure, while being accompanied by a large positive Poisson’s ratio in the out-of-plane direction. Alderson et al. [111] proposed a 2D “node-fibril” structure (See Fig. 21e) by observing the microstructure of microporous polymers composed of a network of nodules and fibrils. This structure consists of rectangular nodules connected by fibrils. Through calculations on this structure, it can be concluded that the negative Poisson’s ratio

of microporous polymers is jointly dominated by fibril hinging and stretching, while the flexure of fibrils has little impact on it. Gaspar et al. [112] proposed a generalized 3D tethered-nodule model structure (See Fig. 21f) to address the limitations of the aforementioned 2D model structures. This structure is a periodic structure composed of tetragonal nodules interconnected by rods of equal length, and its negative Poisson’s ratio is dominated by the bending of the rods at the re-entrant angles. Zheng et al. [113] used the Voronoi tessellation algorithm to generate porous patterns for simulating NPR foam structures. They calculated the effective elastic moduli via the homogenization algorithm, and then used the resulting data to construct a dataset for training a conditional generative adversarial network (CGAN). Through this trained learning model, they could inversely design 2D NPR materials with specified Young’s moduli and Poisson’s ratios (See Fig. 21g). Zhao et al. [114] proposed a modular chiral origami metamaterial (See Fig. 21h), composed of rotating rigid structures and Kresling origami columnar arrays. Its deformation behavior mainly includes in-plane twisting and contraction dominated by square rotating rigid bodies, as well as out-of-plane contraction dominated by tubular





**Fig. 21.** Other structures of auxetic metamaterials. (a) General 4-vertex origami unit cell structure [106]. (b) Interlocking hexagonal model structure [108]. (c) Assembly-free double-ring connected structure [109]. (d) Egg-box structure [110]. (e) Node-fibril structure [111]. (f) 3D generalized tethered-nodule model [112]. (g) 2D negative Poisson's ratio material designed via Voronoi tessellation and conditional generative adversarial network [113]. (h) Modular chiral origami structure. (i) Programmable NPR metamaterial structure [115].

Kresling origami arrays. Based on a highly modular assembly method, this metamaterial possesses properties such as programmability, tunable load-bearing capacity, and multi-physics integration. It can be applied in scenarios including robotic transformers, mechanical memory, and information encryption, providing an innovative solution for intelligent adaptive systems. Clausen et al. [115] proposed a method that combines topology optimization with 3D printing technology to design programmable structures with Poisson's ratios ranging from  $-0.8$  to  $0.8$ . This method features scalability, and the designed structures exhibit an almost constant Poisson's ratio under large deformations. Additionally, metamaterial structures with the desired Poisson's ratio can be rapidly designed through the parameterization of super ellipses (See Fig. 21i).

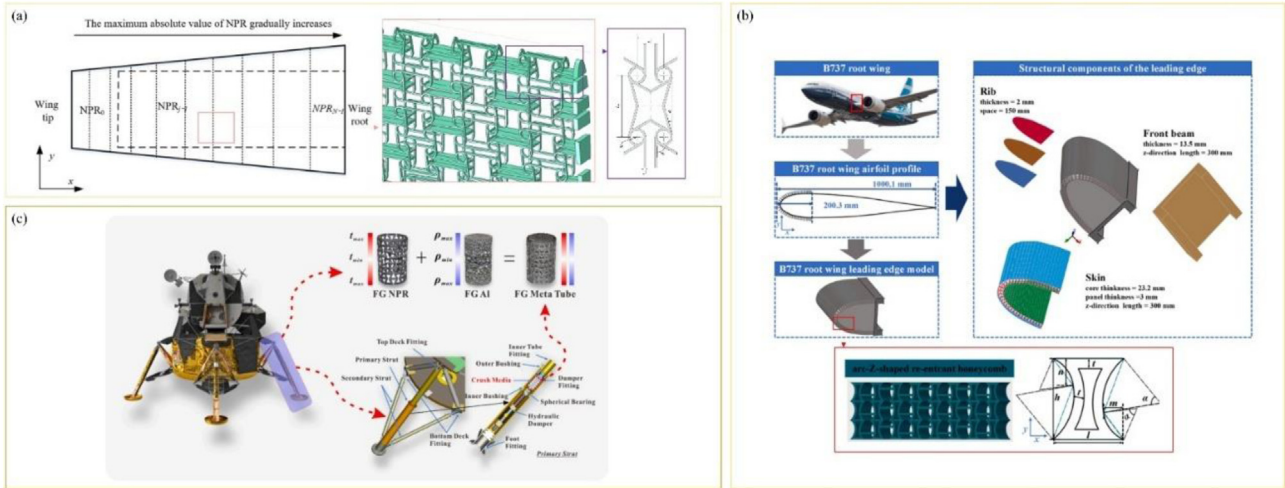
## 4 Applications of auxetic metamaterials

NPR metamaterials are commonly realized as porous materials and lattice structures, which naturally possess lightweight characteristics and show great potential in aerospace applications. Traditional morphing wings (e.g., telescopic or folding wings) suffer from surface discontinuities, which adversely affect aerodynamic performance. Zero-Poisson's-ratio metamaterials can only increase the wing area in one dimension, limiting deformation potential, whereas NPR honeycomb structures can generate larger 2D in-plane deformations. Wang et al. [116] proposed a gradient-controlled NPR

deformation strategy, dividing the wing into multiple regions and adjusting the anti-tetrachiral NPR values in each region (See Fig. 22a), enabling the wing to morph from a rectangular to a trapezoidal shape. Bird strikes pose significant safety threats to aircraft wings. While conventional sandwich structures have been extensively studied for bird-impact resistance, NPR structures with energy-absorbing and vibration-damping characteristics have been less explored. Tan et al. [25] designed an arc-shaped Z-type re-entrant honeycomb core to improve wing bird-strike resistance (See Fig. 22b). Simulation results show that using a Ti-6Al-4V titanium alloy arc-shaped Z-type honeycomb core at the wing leading edge reduces Z-deformation by 25.33% compared with a coreless panel, and improves specific energy absorption by 3.56% relative to conventional re-entrant hexagonal honeycombs. Nian et al. [117] designed gradient NPR foam structures and gradient re-entrant hexagonal structures for dual-gradient design in aircraft landing gear sandwich layers and external panels (See Fig. 22c). Multi-objective optimization using the NSGA-II algorithm improved the energy absorption performance of the optimized structures by 80%.

Auxetic structures possess high impact resistance and vibration isolation capabilities, making them highly promising for applications in the marine sector. During ship navigation, vibrations from onboard machinery are inevitable, which can lead to structural wear and reduced service life of equipment. Pan et al. [118] designed a honeycomb-based support structure with a re-entrant





**Fig. 22.** NPR structures for aerospace applications. (a) Morphing wing with gradient anti-tetrachiral structure [116]. (b) Arc-shaped Z-type re-entrant honeycomb core for bird-strike resistant wings [25]. (c) Aircraft landing gear with dual-gradient NPR foam and re-entrant hexagonal structures [117].

hexagonal configuration to reduce vibrations in ship hulls and related structures. By analyzing the band structures and frequency response curves of the ship support using COMSOL software and comparing with experimental results, it was found that the auxetic support exhibits superior vibration isolation performance compared to conventional supports. Composite supports consisting of unit cells with varying Poisson's ratios can achieve better vibration isolation across a wider frequency band. Additionally, adding masses at the re-entrant corners of the unit cells can further enhance the vibration damping performance.

Explosions are among the main causes of severe accidents on offshore platforms. Therefore, the blast resistance of ships and offshore platforms should be considered in their design. Compared with conventional material protective layers, auxetic metamaterial layers provide superior blast mitigation. Luo et al. [119] investigated the blast resistance of auxetic metamaterial protective structures under consecutive explosive loads, primarily for use in offshore platform blast walls and double hulls of ships. The core of these protective structures is composed of re-entrant hexagonal honeycomb (See Fig. 23a). Numerical simulations of structural deformation and strain distribution revealed two distinct deformation modes under continuous external and internal explosions: local collapse with compression-based energy absorption and global bending accompanied by structural densification. In either case, auxetic metamaterial structures exhibit outstanding blast resistance.

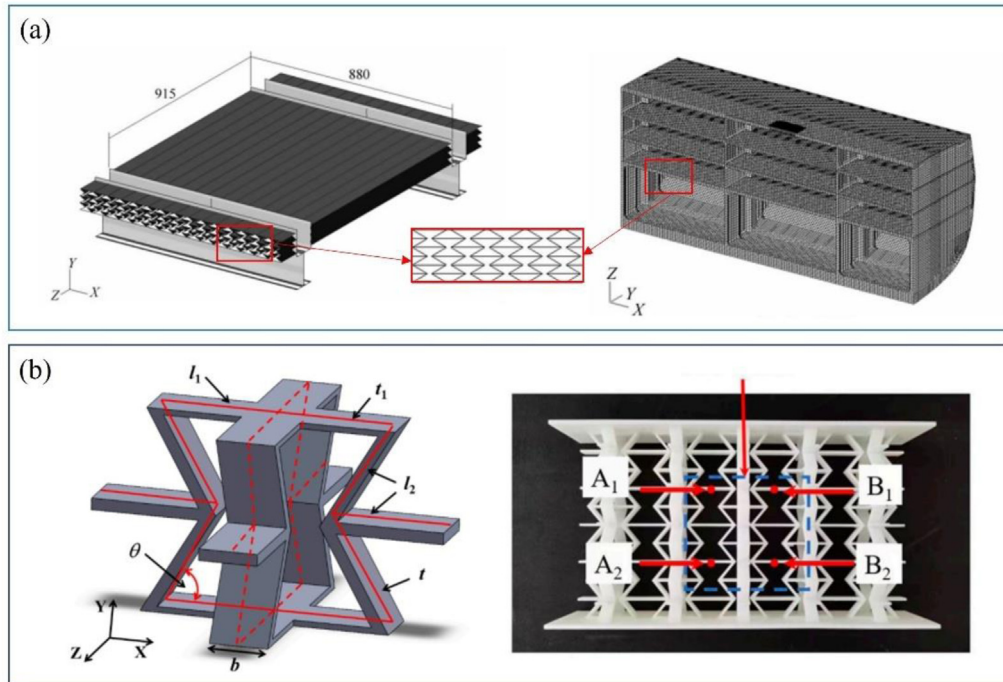
While most protective auxetic structures focus on energy absorption, their stiffness is often overlooked. Lin et al. [120] designed a 3D frame-plate protective structure based on 2D re-entrant hexagonal honeycombs (See Fig. 23b), which exhibits auxetic behavior in multiple directions while maintaining sufficient load-bearing capacity. The effectiveness of this design was verified through theoretical derivation of equivalent mechanical models, combined with 3D printing experiments and numerical simulations.

Similarly, due to their unique deformation mechanisms and excellent indentation resistance, NPR structures have numerous applications in vehicle engineering.

In frontal collisions, the plastic deformation of a vehicle's front bumper system can absorb the impact energy generated during the crash, thereby reducing the force transmitted to occupants. Crash boxes are crucial protective components within bumper systems. Wang et al. [121] designed 2D and 3D re-entrant hexagonal NPR honeycomb structures (See Fig. 24a) by utilizing their lightweight, energy-absorbing, and excellent impact-resistant properties, filling them inside conventional crash boxes. Studies indicate that NPR crash boxes improve crashworthiness compared with traditional boxes, with 3D NPR boxes exhibiting the best crash performance.

For electric vehicles, collisions may cause damage to the internal components of the battery, leading to combustion or explosion and posing serious risks to personal safety. Scurtu et al. [122] proposed employing cylindrical re-entrant hexagonal structures as the sandwich core inside the battery casing (See Fig. 24b) to absorb impact energy during collisions. Finite element analysis revealed that, compared with conventional materials, auxetic materials can significantly improve the energy absorption efficiency of the battery casing, prevent local fractures within the shell, and enhance the protective performance of the battery cells.

During normal vehicle operation, ride comfort and smoothness are also important. Wang et al. [123,124] designed cylindrical suspension buffer blocks based on 2D double-arrow NPR structures to optimize suspension mechanical performance (See Fig. 24c). Through numerical simulation and experimental testing, they obtained the uniaxial compression behavior of the NPR buffer blocks and conducted virtual ride smoothness tests. Results demonstrate that the NPR buffer blocks can achieve more ideal "wheel force–bounce height" curves without adjusting the free travel, significantly improving vehicle smoothness over uneven roads.



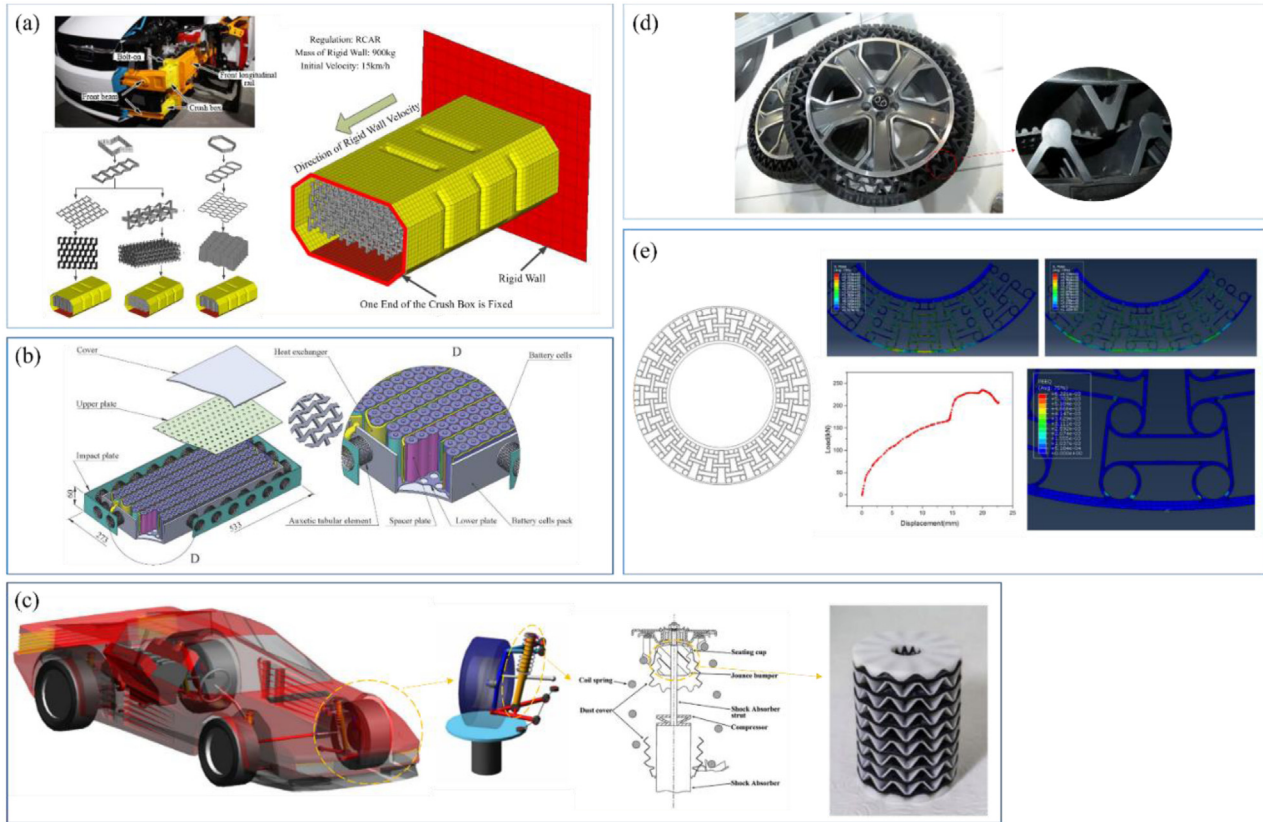
**Fig. 23.** NPR structures for marine applications. (a) 2D re-entrant hexagonal honeycomb blast-protective sandwich [119]. (b) 3D re-entrant hexagonal frame-plate protective structure [120].

The tire serves as the medium for force transmission between the vehicle and the road surface and is often used under complex and demanding conditions. Therefore, the safety requirements for tires have become increasingly stringent. As one of the research directions aimed at enhancing tire safety, non-pneumatic tires have attracted considerable attention. Among them, NPR non-pneumatic tires [26] are mainly composed of a double-arrowhead NPR supporting structure, a rubber buffer layer, a rubber tread, and a rim (See Fig. 24d). This airless tire not only improves impact resistance but also eliminates the risk of blowouts in conventional tires, thereby ensuring vehicle safety under complex road conditions. Wu et al. [125] designed a novel airless tire based on a gradient anti-tetrachiral structure (See Fig. 24e) and investigated its deformation modes and mechanical performance under load via FEA. The results show that the deformation pattern of the gradient anti-tetrachiral tire closely matches that of other gradient NPR structures [126], with significantly improved load-bearing capacity, demonstrating strong application potential.

NPR materials have also found extensive applications in the medical field. Owing to their auxetic characteristics, they exhibit excellent skin conformability and adjustable permeability, making them suitable for use as medical bandages [127]. When therapeutic drugs are carried on the NPR bandage, swelling at the wound site enlarges the pores, allowing the drugs to permeate into the injured tissue for targeted treatment (See Fig. 25a). NPR structures can also serve as medical stents. Xiao et al. [27] designed a cardiovascular stent based on an anti-tetrachiral NPR tubular structure (See Fig. 25b), fabricated using high-resolution projection micro-stereo-

lithography 3D printing, with a gold nanofilm deposited on its surface via radio frequency magnetron sputtering. Results show that with a 10%–20% reduction in wall thickness, the radial support force increased by 20%–70%, while toughness was slightly improved. Liu et al. [128] developed a novel stent with a hybrid configuration of tetrachiral and anti-tetrachiral NPR structures, in which the inner cavity was filled with a porous silicone sponge (See Fig. 25c). The study revealed that the stent maintained substantial ventilation space even under 50% axial strain, demonstrating enhanced anti-migration capability and flexibility comparable to that of natural tracheal tissue. The porous silicone sponge inside not only provides sufficient strength to prevent granulation tissue ingrowth but also facilitates the regeneration of ciliated epithelium on the inner wall of the stent, potentially addressing the complication of mucus blockage within the stent. In addition, NPR materials have promising applications in scar therapy [33], cardiac patches [129,130], and orthopedic implants [131,132].

In fact, NPR structures also play an important role in other engineering fields, such as nails, connectors, sensors, and footwear. For example, Ren et al. [133] designed a perforated-sheet NPR nail fabricated through metal 3D printing. Theoretically, based on the auxetic deformation mechanism, such a nail exhibits a smaller insertion force and a greater pull-out resistance (See Fig. 26a). However, in practice, factors such as the material of the target object and the surface smoothness of the nail influence its performance. As a result, the NPR nail does not always outperform conventional nails in both insertion and pull-out behavior. Furthermore, the presence of perforations



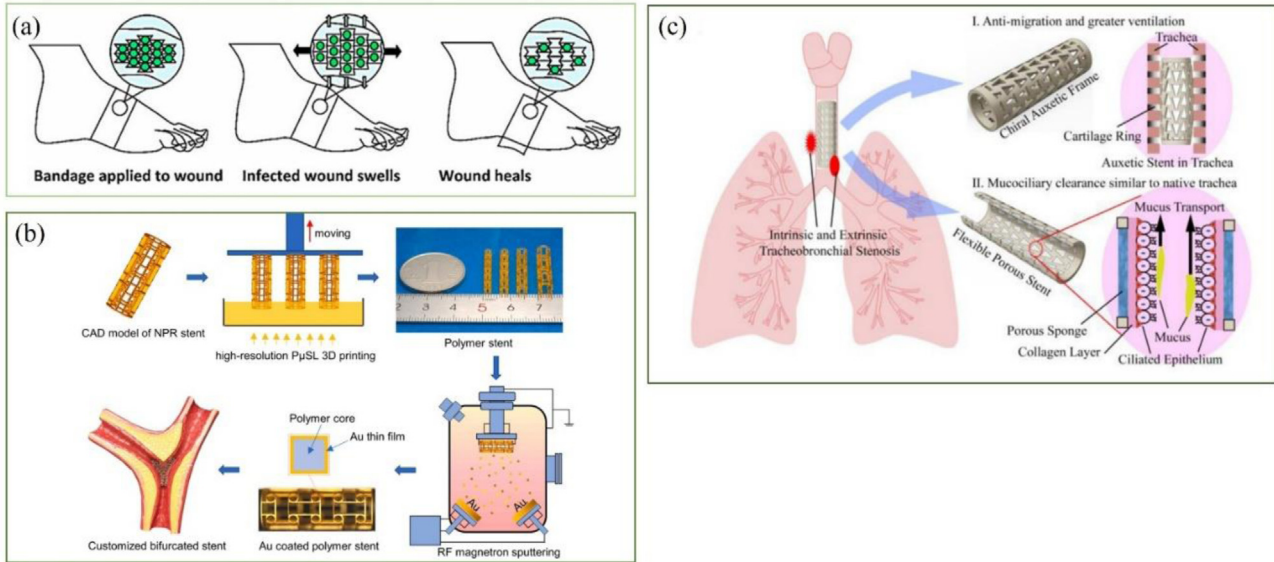
**Fig. 24.** Vehicle applications of auxetic metamaterials. (a) 3D NPR crash box [121]. (b) The design and components of the battery pack [122]. (c) NPR structural buffer used in the automobile suspension frame system [123,124]. (d) Non-pneumatic tire with double-arrow NPR structure [26]. (e) Non-pneumatic tire with anti-tetrachiral NPR structure for mechanical design and performance [125].

reduces its overall stiffness, indicating that further optimization is required. Similarly, NPR wooden dowels [134] share the same advantages and limitations as the NPR nail. To address the issues of insufficient connection strength and poor energy absorption performance in deployable energy-absorbing structures, Xu et al. [135] proposed an interlocking NPR connector structure (See Fig. 26b). The connector features a re-entrant polygonal orthogonal-elliptical perforated-sheet design, in which a mortise-tenon configuration is used to achieve geometric interlocking and stable interface connection. This design significantly enhances joint strength while maintaining excellent energy absorption capability. Furthermore, by integrating the connector with a rigid plate, a bistable origami structure can be formed. Inspired by the starfish structure, Guo et al. [136] fabricated a flexible capacitive pressure sensor with a fourth-order star-shaped NPR structure via 3D printing technology. The dielectric layer, designed with an NPR configuration, exhibits high sensitivity, a wide detection range, and a fast response time. The sensor was successfully applied to tactile sensing in flexible grasping and gesture recognition applications (See Fig. 26c). Sun et al. [137] designed a shoe midsole based on a 3D tetrachiral NPR structure (See Fig. 26d). Through finite element analysis, the structural parameters were optimized, and the prototype was fabricated by 3D

printing. Static compression, dynamic impact simulation, and wear tests verified its advantages in shock absorption, propulsion, and comfort, providing a novel design concept for the development of high-performance athletic shoe midsoles. Kang et al. [138] fabricated cubic lattice auxetic mechanical metamaterials (AMMs) containing spherical voids using digital light processing 3D printing technology and developed two types of tactile sensors, capacitive and resistive, based on these AMMs (See Fig. 26e). The capacitive sensor utilizes pressure-induced changes in electrode spacing and effective permittivity, whereas the resistive sensor relies on conductive pathways formed within the carbon nanotube-coated ligaments of the AMMs. Compared with conventional porous structures with a positive Poisson's ratio, the AMM-based sensors show higher pressure sensitivity, and their performance is not affected by spatial constraints.

Auxetic materials, due to their extraordinary mechanical properties and unique deformation mechanisms, have great innovation and application potential in aerospace, transportation equipment, and biomedical fields. To be better clarified, these applications and linked their functions to the specific mechanical properties of NPR are summarized in Table 1. As shown in Table 1, shear resistance, indentation resistance, and energy absorption, together with auxetic deformation, are the most frequently





**Fig. 25.** Biomedical applications of auxetic metamaterials. (a) Schematic of auxetic smart bandage [127]. (b) Cardiovascular stent with anti-chiral NPR structure [27]. (c) A flexible porous chiral auxetic tracheal stent [128].

used aspects in practical applications, indicating that these four factors should be given priority when designing NPR structures. It is hoped that this will provide guidance for the future design and application of auxetic materials.

## 5 Conclusions and prospects

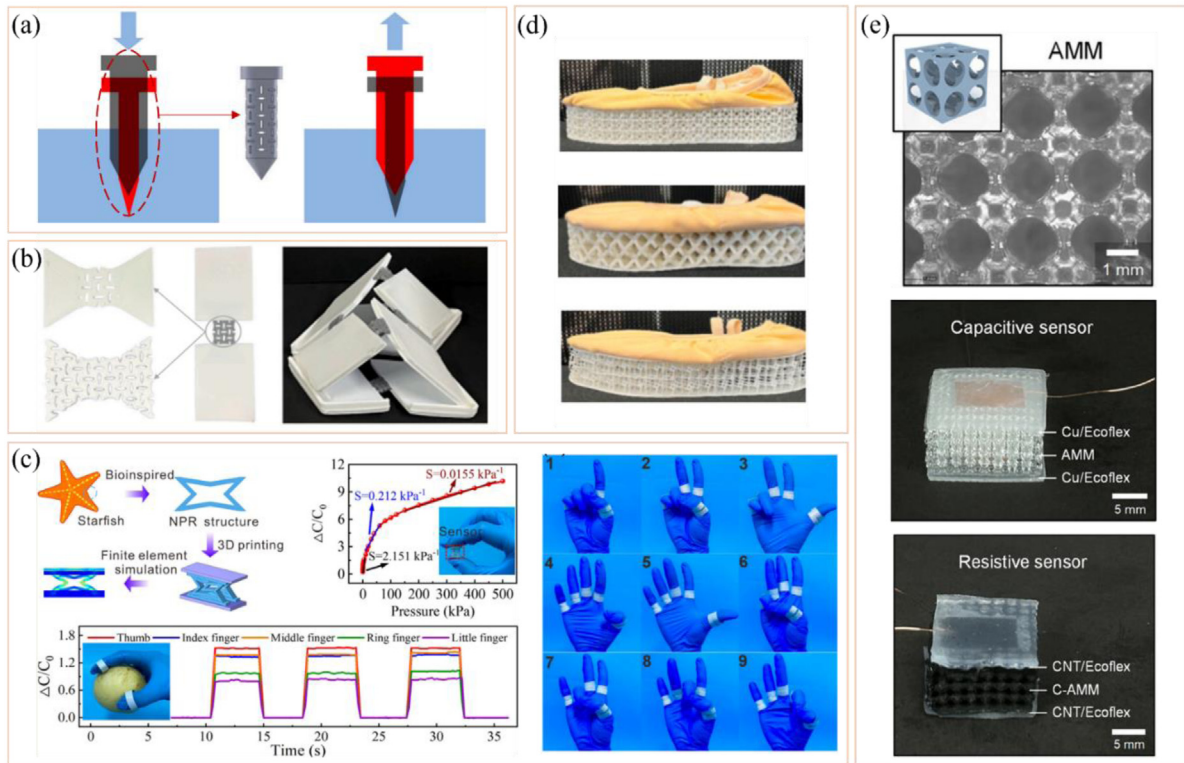
This paper provides an overview of the mechanical properties and structural classification of NPR metamaterials, as well as their practical applications. It offers an in-depth analysis of the deformation mechanisms of various NPR structures, the establishment of mathematical equivalent models, the influence of design parameters on mechanical performance, and structural optimization strategies. The paper also identifies current research gaps in NPR structures and provides personal insights. By highlighting their excellent mechanical properties and engineering applications, the study demonstrates the future potential and advantages of NPR structure design. Although significant progress has been made in NPR metamaterials research in recent years, facilitated by advanced manufacturing techniques such as 3D printing, many challenges remain to be explored. In view of this, this paper presents several perspectives and outlooks from the aspects of structural design, fabrication, practical applications, and design methodologies, with the aim of providing references and insights for promoting the further development of auxetic metamaterials.

– Most current research on NPR metamaterials focuses on their mechanical performance under load-induced deformation. However, with the development of smart materials and 4D printing, NPR materials are expected to exhibit dynamic changes in their physical properties in response to external stimuli. Future research may explore the structural response and performance evolution under

coupled multi-physical fields. Moreover, NPR metamaterials are anticipated to evolve toward programmability, multistability, customizable performance, and modular design. This will allow NPR metamaterials to transcend purely mechanical applications and integrate multifunctional intelligence from other fields.

– Structural design of NPR metamaterials is largely based on empirical approaches combined with finite element simulations. With the increasing adoption of artificial intelligence (AI), integrating AI into structural design has become a significant trend. AI can assist in finite element simulations and topology optimization, improving the efficiency of complex structural design and performance prediction, such as gradient-based design and hierarchical design. Furthermore, machine learning can be employed for the inverse design of target structures. Future work may focus on developing new algorithms, enhancing datasets, and integrating physical principles with machine learning to construct predictive models with improved interpretability. Such models could enable the inverse design of theoretically supported structures that meet specific performance requirements.

– Currently, structural designs of NPR metamaterials fabricated via 3D printing seldom take into account defects unique to additive manufacturing, which differ from those in traditional methods. For instance, layer stepping effects and print orientation in 3D printing can affect surface quality and mechanical performance. In the future, in addition to iterative technological improvements, 3D printing could be combined with AI for real-time monitoring of printed components, dynamically adjusting printing parameters to reduce defects and improve print quality and efficiency. By collecting data on defects that occur during printing, machine learning could be used to predict the quality of NPR structures during fabrication.



**Fig. 26.** Applications of auxetic metamaterials in other fields. (a) Schematic of an auxetic nail in insert and pull-out states [133]. (b) Interlocking NPR connectors design for deployable energy absorption structures [135]. (c) Flexible capacitive pressure sensor with fourth-order star-shaped NPR structure [136]. (d) Shoe midsole with 3D tetrachiral NPR structure [137]. (e) AMM structures and the corresponding capacitive and resistive tactile sensors [138].

**Table 1.** The relationship between applications and properties of auxetic metamaterials.

| Field      | Application         | Properties                   |                     |                   |                       |                     |
|------------|---------------------|------------------------------|---------------------|-------------------|-----------------------|---------------------|
|            |                     | Shear/Indentation resistance | Synclastic behavior | Energy absorption | Variable permeability | Auxetic deformation |
| Aerospace  | Morphing wings      |                              | ✓                   |                   |                       | ✓                   |
|            | Resistant wings     | ✓                            | ✓                   | ✓                 |                       |                     |
|            | Landing gear        | ✓                            |                     | ✓                 |                       |                     |
| Marine     | Ship base           |                              |                     | ✓                 |                       | ✓                   |
|            | Blast walls         | ✓                            |                     | ✓                 |                       |                     |
| Vehicle    | Crush box           | ✓                            |                     | ✓                 |                       | ✓                   |
|            | Battery pack        | ✓                            |                     | ✓                 |                       | ✓                   |
|            | Suspension system   |                              |                     | ✓                 |                       |                     |
|            | Non-pneumatic tires | ✓                            |                     | ✓                 |                       |                     |
| Biomedical | Bandage             |                              | ✓                   |                   | ✓                     | ✓                   |
|            | Stents              | ✓                            |                     | ✓                 |                       | ✓                   |
| Others     | Nails               |                              |                     |                   |                       | ✓                   |
|            | Connectors          |                              |                     | ✓                 |                       | ✓                   |
|            | Sensors             |                              | ✓                   |                   |                       | ✓                   |
|            | Shoe midsoles       | ✓                            | ✓                   | ✓                 |                       | ✓                   |

In summary, NPR metamaterials, with their unique structural features and superior properties, hold great application potential. Future research should focus on structural optimization, advanced manufacturing techniques, and engineering applications to further advance innovation and development in this field.

## Funding

This research was funded by the Natural Science Foundation of Shanghai (25ZR1401157), the National Natural Science Foundation of China (23010501100) and Shanghai Rising-Star Program (23YF1413900).

## Conflicts of interest

The authors have nothing to disclose.

## Data availability statement

This article has no associated data generated and/or analyzed.

## Author contribution statement

Writing – Original Draft Preparation, X.H.; Writing – Review & Editing, J.T., Z.Z. and G.G.; Supervision, J.T., K.S. and R.F.; Project Administration, K.S.; Funding Acquisition, X.X. and K.S.

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