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Mechanical design and multifunctional applications of chiral mechanical metamaterials: A review

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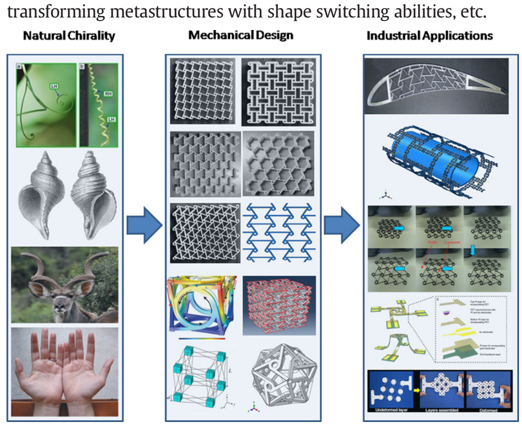
HIGHLIGHTS

- Design of chiral mechanical metamaterials are reviewed, theoretical models are elaborated for exploring the deformation mechanisms.
- Multifunctional mechanical benefits and limitations of chiral mechanical metamaterials are reviewed and discussed.
- Industrial applications of chiral mechanical metamaterials are reviewed, perspectives and challenges are discussed.

GRAPHICAL ABSTRACT

Rational design of artificial micro-structured metamaterials with advanced mechanical and physical properties that are not accessible in nature materials is challenging and important. In the past several years, making use of the node rotation and ligament bending deformation features of chiral elements, various types of 2D and 3D chiral mechanical metamaterials are designed and proposed for industrial application. In our paper, mechanical designs of 2D and 3D chiral mechanical metamaterials are reviewed, and their mechanical behaviors and deformation mechanisms can be investigated through force and momentum equilibrium principle, strain energy analysis, micropolar elasticity and homogenization theories. Afterwards, multifunctional properties of chiral mechanical metamaterials are elaborated, such as: vibration attenuation and bandgap features, impact energy absorption and negative coefficient of thermal expansion (CTE). Finally, several successful industrial applications of chiral mechanical metamaterials are demonstrated, such as: morphing airfoil with chiral core configuration, shape memorial smart deployable antenna and reconfigurable structures, auxetic stent for biomedical application, chiral flexible electronics and phase transforming metastructures with shape switching abilities, etc.



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ABSTRACT

Rational design of artificial micro-structured metamaterials with advanced mechanical and physical properties that are not accessible in nature materials is challenging and important. In our paper, mechanical designs of 2D and 3D chiral mechanical metamaterials are reviewed, and their mechanical behaviors and deformation mechanisms can be investigated through equilibrium principle, strain energy analysis, micropolar elasticity and homogenization theories. Afterwards, multifunctional properties of chiral mechanical metamaterials are elaborated, such as: vibration attenuation, impact energy absorption and negative coefficient of thermal expansion (CTE). Finally, several successful industrial applications of chiral mechanical metamaterials are demonstrated, such

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as: morphing airfoil smart deployable antenna and reconfigurable structures, auxetic stent, chiral flexible electronics and phase transforming metastructures, etc. Finally, perspectives and challenges on chiral mechanical metamaterials are discussed.

Contents

1. Introduction

Auxetics are structures or materials that have a negative Poisson's ratio (NPR), and are also known as materials with anti-rubber or dilational features. Different from traditional materials, auxetics will be elongated along directions perpendicular to the tensile loading direction. Compared to traditional materials with positive Poisson's ratio, auxetic materials with NPRs have the following enhanced mechanical properties: (a) enhanced in-plane indentation resistance; (b) enhanced fracture toughness; (c) elevated transverse shear modulus; and, (d) enhanced dynamic properties such as: impact energy absorption, wave attenuation performances, etc. The term auxetic derives from the Greek word αὐξητικός (auxetikos), which means "that which tends to increase". Large-scale cellular structures with NPR property were first fabricated in the form of 2D silicone rubber or aluminum honeycombs deforming by flexure of the ribs in 1982 [1,2]. The earliest published example of a material with negative Poisson's constant is carried out by Kolpakov [3] in 1985.The first artificial synthetic auxetic foam material was described by Lakes [4], and terminology of "auxetics" was firstly initiated by Evans in 1991 [5]. Afterwards, various types of artificial fabricated auxetic foams, fibers, composites, and structured metamaterials are proposed and fabricated with advanced manufacturing techniques. Key literatures related to the evolution of auxetics metastructures are summarized in Table 1 [3–23]. Moreover, auxetics based on origami, kiragami planar and tube structures are also proposed for multi-functional application, such as: impact energy absorption, deployment, stent, etc. [24–32]. According to the structural deformation models, these auxetic metastructures can be classified into following categories: missing-rib, rigid (or semi-rigid) rotation, re-entrant, chiral and elastic instability, etc. [3–37]. A more general classification of artificial auxetic mechanical metamaterials is shown in Fig. 1 [15,38–44].

The term chirality for describing the property of handedness was first introduced by Sir William Thomson (later Lord Kelvin) in a Robert Boyle lecture, on the molecular tactics of a crystal, delivered before the Oxford University Junior Scientific Club, May 16, 1893. A printed version of this lecture is described in the Appendix of the Baltimore Lectures by Lord Kelvin [6], "*I call any geometrical figure or group of points chiral, and say that it has chirality if its image in a plane mirror, ideally realized, cannot be brought into coincidence with itself.*", which is recorded for describing the relational geometric-physical property for the first time [45]. An object is said to be chiral, or with handedness, if it cannot be superposed to its mirror image by rotations and translations alone [6]. As shown in Fig. 2, various types of chiral structures exist commonly in natural plants, animals and artificial synthesized materials, such as: helical goat horns, right-handed and left-handed sea shell, DNA, chiral carbon nanotube, twisting flower petals and stems, plant climbing tendrils and twisted leaves, chiral cellulose, etc. [46–48]. Chirality is encountered in many branches of science, including physics, biology, chemistry and optics. It pervades much of modern science: from the physics of elementary particles, through organic stereochemistry, to the structure and behavior of the molecules of life, with much else besides (nonlinear optics, nanotechnology, materials, electrical engineering, pharmaceuticals, etc.). From mechanical and physical aspects of view, chiral material should be described by an adequate constitutive equation with handedness in order to characterize the distinct features. In continuum mechanics, chirality is considered in the context of generalized elasticity, such as: micropolar (Cosserat) theory [49–51]. Chiral elasticity approach can describe the coupling between local rotation, bending, and bulk deformation, thus providing institutive explanation for the origin of many unusual behaviors (negative Poisson's ratio, high compressibility, etc.) of chiral materials. The evolution of important concepts related to chiral mechanical metamaterials is shown in Fig. 3. Meanwhile, with the progress of advanced manufacturing techniques, various types of advanced additive manufacturing (AM) are widely employed for biomedical, aerospace, automotive, marine and offshore industrial sections. These low-cost AM techniques demonstrated superior manufacturing efficiencies and economic advantages for advanced lightweight industrial components with unlimited arbitrary topological layouts and complex internal microstructures, and are proposed for fabrication of auxetic materials and structures [48–61].

In this paper, the design evolution of 2D and 3D chiral mechanical metamaterials are elaborated, and theoretical models for understanding the deformation mechanics and mechanical behaviors are summarized.

Table 1
Important literatures for auxetics and chiral mechanical metamaterials.

Year	Concepts and configurations related to auxetics or chiral	Refs.
1904	Concept of chirality	[6]
1980	Auxetic Miura origami	[7]
1985	Designed artificial material with negative Poisson ratio	[4]
1985	Designed 2D re-entrant honeycomb	[8]
1987	Artificial manufactured foam with negative Poisson ratio	[5]
1989	Auxetic chiral configuration based on rotating disks and nearest neighbour inverse nth power interactions	[9]
1991	Concept of auxetic (dilation)	[3]
1996	Chiral cellular auxetic metastructures with negative thermal expansion coefficients	[10]
1997	Mechanical properties of 2D hexachiral honeycomb	[11]
2000	Auxetic with rigid rotating polygonal geometries	[12]
2008	Auxetic ferrogel concept	[13]
2008	Hybrid chiral meta mechanical materials	[14]
2010	Auxetic elastic instability	[15]
2010	Hybrid chiral meta mechanical materials	[16]
2014	Fractal kirigami auxetic structure	[17]
2016	Double-negative mechanical metamaterial proposed	[18]
2016	3D chiral mechanical metamaterials	[19]
2017	Hierarchical chiral mechanical metamaterials	[20]
2017	3D compression-twist mechanical metamaterials	[21]
2018	Hybrid 3D chiral mechanical metamaterials	[22]
2018	Chiral flexible electronics	[23]

Then, making use of the local resonant mechanisms, the vibration attenuation performances are reviewed, and the impact energy and thermal expansion features of chiral mechanical metamaterials are summarized. Benefit from the multifunctional characteristics of chiral mechanical metamaterials, various types of conceptual industrial applications are presented. Finally, perspectives on the future and challenges of chiral mechanical metamaterials are discussed.

2. Design and mechanical properties of chiral mechanical metamaterials

2.1. Design of 2D and 3D chiral mechanical metamaterials

In 1989, Wojciechowski [9] proposed an auxetic design with chiral configuration for the first time. Lakes et al. [11] proposed the design of hexachiral honeycomb and investigated its in-plane mechanical properties based on linear elasticity model. Alderson et al. [62] proposed the design of tetrachiral, anti-tetrachiral, trichiral and anti-trichiral honeycombs, where anti-chiral ligament forms half-wave shape while chiral ligament forms full-wave shape. Besides these traditional unit cell designs, novel auxetic tetrachiral and anti-tetrachiral hybrid meta-tetrachiral mechanical metamaterials are also proposed [14]. Moreover, the mechanical properties of re-entrant trichiral and re-entrant anti-trichiral honeycombs are investigated through finite element modeling [16]. As shown in Fig. 4, the structural evolutions of various types of chiral mechanical metamaterials can be classified into chiral, anti-chiral and meta-chiral categories. Besides these periodic regular designs, mechanical properties of irregular and disordered chiral mechanical metamaterials are also investigated [63–67]. Irregular chiral system possesses a lower level of rotational or axial symmetry, and exhibits highly anisotropic behavior, thus has the ability to exhibit a much wider range of mechanical properties in comparison to their regular counterparts. However, a disordered chiral mechanical metamaterials system is asymmetric, and cannot be described by periodic unit cell. Mizzi [63] proposed the design of hexachiral with less symmetric generic form for achieving wide tunable range of negative Poisson's ratios and elastic anisotropy, thus enhance its functionality and applicability. Anisotropic anti-tetrachiral systems with less symmetrical design are investigated through analytical and finite element models [64,65]. Mizzi et al. [66] studied the effects of translational disorder on the Poisson's ratio of hexachiral honeycombs. Similarly, elastic properties and Poisson's ratio of anti-chiral structures with stochastic distributions of circular node sizes are investigated using finite element [67]. Besides theses traditional designs of chiral mechanical metamaterials, several novel types of metamaterials with local chiral deformation features are also proposed. Based on moving asymptotes algorithm and solid isotropic material with penalization methods, two-phase anti-tetrachiral structures with adjustable Poisson's ratio and optimized mechanical properties are designed [68]. Through combining independent pointwise density interpolation model and bi-material interpolation method, topology optimization of bi-material chiral auxetic properties is performed for generating multimaterials chiral mechanical metamaterials with optimized negative Poisson's ratio and stiffness [69]. Novel chiral hinge lattice with a marginal in-plane negative Poisson's ratio is designed, where bending and axial deformations provide the main contribution to the elasticity of the chiral hinge lattice [70]. A new series of Abeille's domes constructed from revised Abeille's flat vault in spherical coordinate are proposed for constructing hexachiral topological dome [71]. Flexible chiral metamaterials consisting of interlocked Archimedean spirals are constructed based on relief cutting method, where adjustable stiffness can be controlled through manipulating the local properties of the pattern with intensity of images [72]. Besides, as shown in Figs. 5 and 6, hierarchical and functional graded chiral honeycombs are also proposed [20,73,74]. However, most of the 2D chiral

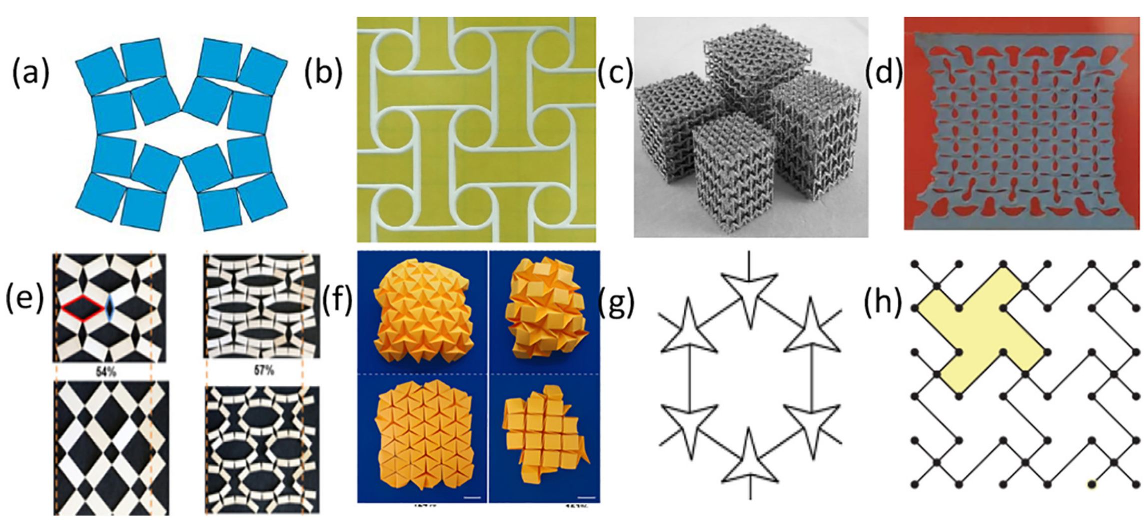

Fig. 1. Classification of auxetics (a), rigid node rotation [33]; (b), anti-tetrachiral [34]; (c), re-entrant lattice [35]; (d), elastic instability [15]; (e), kirigami fractal cut [36]; (f), origami [37]; (g), star shape [38]; (h), missing-rib model [39].

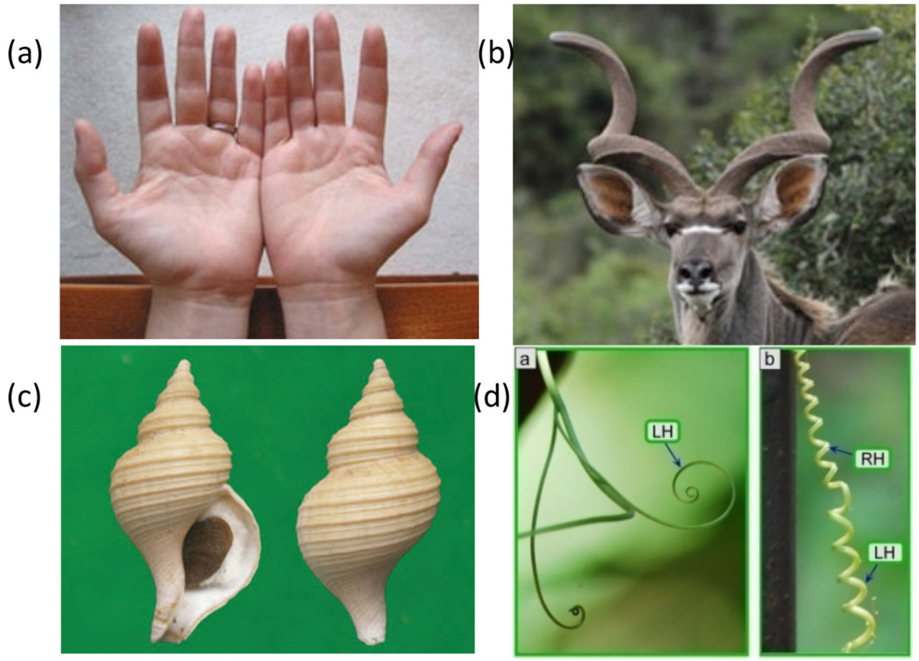

Fig. 2. Chiral in nature: (a), right and left hands [41]; (b), helical goat horns [41]; (c), right-handed and left-handed sea shell; (d), right-handed and left-handed towel gourd tendrils [42,43].

mechanical metamaterials are based on periodic unit cell design, and can be mainly classified into chiral, anti-chiral and meta-chiral configurations, where nodes with circular and polygonal shape are employed, and the ligaments are tangentially connected to the nodes. Moreover, these 2D chiral mechanical metamaterials designs are independent from the feasibility of traditional manufacturing technologies and the manufacturing process constraints of metal additive manufacturing techniques. Thus, advanced design techniques of novel chiral mechanical metamaterials should be performed, such as: machine-learning driven 2D chiral mechanical metamaterials with programmable mechanical properties, topology optimizations of 2D chiral mechanical metamaterials where metal additive manufacturing constraints are considered, etc.

Beside various types of 2D chiral mechanical honeycombs, several types of 3D chiral metamaterials with special mechanical behaviors are also proposed, as shown in Fig. 7. Parametric investigations on the relationships between Poisson's ratio, modulus, porosity, and geometry of the proposed 3D anti-tetrachiral structure are performed through comparisons between experiments and finite element analysis [75]. Compression-twist 3D chiral metamaterials is proposed, and micropolar theory and experimental verification are performed for revealing the underlying deformation mechanisms [21,76]. Chiral 3D isotropic cubic lattices consisting of rigid cubical nodules and deformable ribs are designed, and constitutive equations based on isotropic linear Cosserat elasticity are developed for studying the elastic properties and size effects [28,77]. Duan et al. [78] proposed new 3D chiral lattice material of cubic symmetry, and deduced its elastic constants based on micropolar continuum theory and homogenization method. Novel chiral 3D metamaterials based on orthogonal assembling of tetrachiral elements are proposed, and analytical formulas are deduced using the beam theory [79]. Novel 3D chiral metamaterials based on synergistic deformation of layered 2D chiral honeycombs are proposed for generating 3D auxetic behaviors, and analytical formulas are developed for understanding the underlying deformation mechanisms [80]. Meanwhile, several types of 3D auxetics based on hybrid chiral structural elements are designed [81–83], thus elevated auxetic deformation abilities can be realized. 3D cellular metamaterials with 2D anti-chiral topology are constructed, experimental and simulation comparisons are performed for studying the auxetic behaviors [84]. Xia et al. [85] proposed the design of 3D anti-tetrachiral metastructures, and developed analytical model for predicting its modulus and Poisson's ratio. Novel 3D lattice based on axial symmetrical distributed anti-tetrachiral elements is presented, and its auxetic behaviors and mechanical properties are investigated using experimental, numerical, and analytical methods [86]. Through integrating material-based and boundary representation-based approaches, two-step optimization methods are developed for designing 3D auxetics featuring chiral topological layouts [87]. However, most of these 3D chiral mechanical metamaterials are inspired from periodic 2D chiral mechanical metamaterials, and can be classified into 3D chiral and 3D anti-chiral categories, while designs of 3D meta-chiral mechanical metamaterials consisting of chiral and anti-chiral hybrid elements are still quite limited. Besides, additive manufacturing is one of the most important techniques employed for the fabrication of 3D chiral mechanical metamaterials, while constraints of additive manufacturing process is not considered in the design, such as: anisotropy of 3D printed metals, supporting structures needed for nearly horizontal lattices, etc. Moreover, advanced computational methods should be employed for designing advanced 3D chiral mechanical

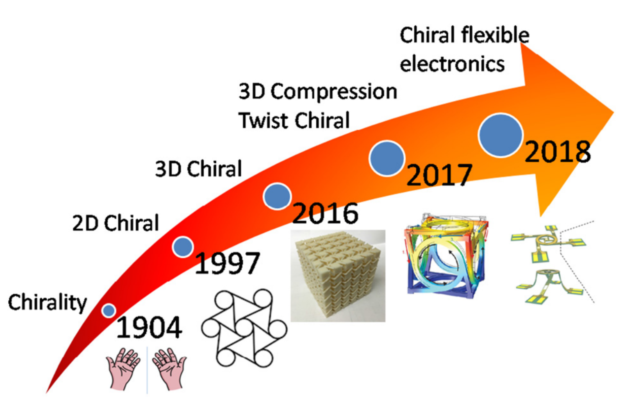

Fig. 3. Important concepts on the development of chiral mechanical metamaterials [6,11,19,21,23].

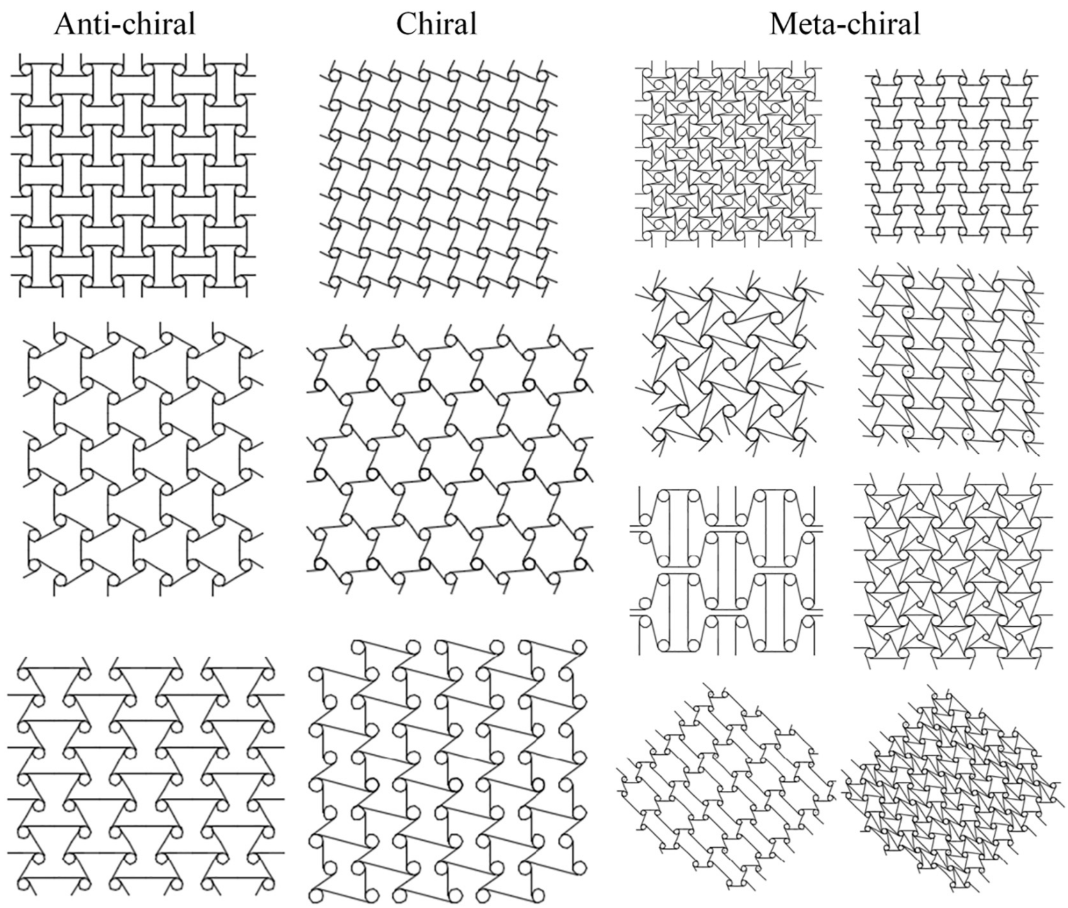

Fig. 4. Classification of 2D chiral mechanical metamaterials.

metamaterials with programmable properties, such as: topology optimization, machine learning, neural-networks, etc.

2.2. Deformation mechanisms of chiral mechanical metamaterials

The mechanical behaviors, deformation mechanisms of 2D and 3D chiral mechanical metamaterials can be investigated through strain energy analysis approach, or equilibrium analysis of unit cell [88–96]. Based on unit cell homogenized distribution of strain energy stored in the bending ligaments, Chen et al. [64] studied the in-plane mechanical properties of anisotropic anti-tetrachiral honeycombs, and analytical relations between elastic properties and dimensionless parameters are constructed. Based on Castigliano's second theorem, closed-form analytical formulas are derived for tri-chiral, tetrachiral, and anti-tetrachiral honeycombs [89]. Making use of classical beam column end-moment analytical expressions, analytical formulas for predicting the in-plane macroscopic buckling strength of 2D trichiral metastructures are developed [90]. Several types of novel hybrid 2D

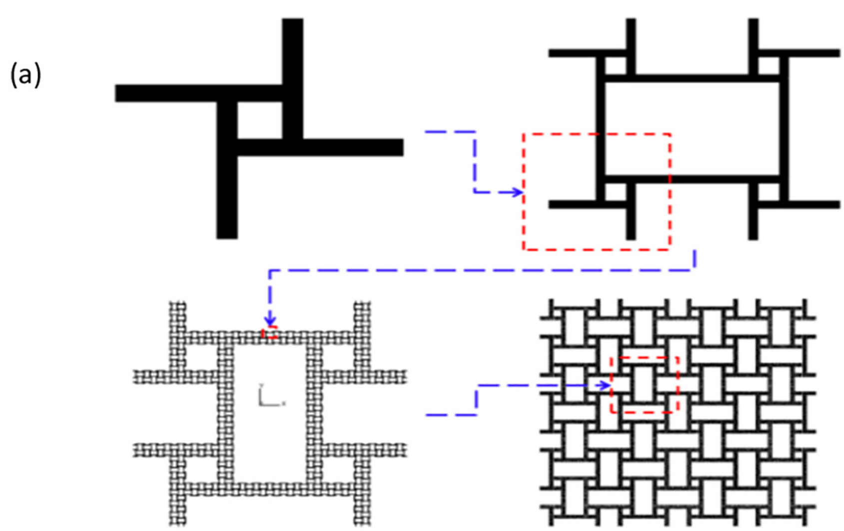

Fig. 5. Hierarchical chiral mechanical metamaterials [20].

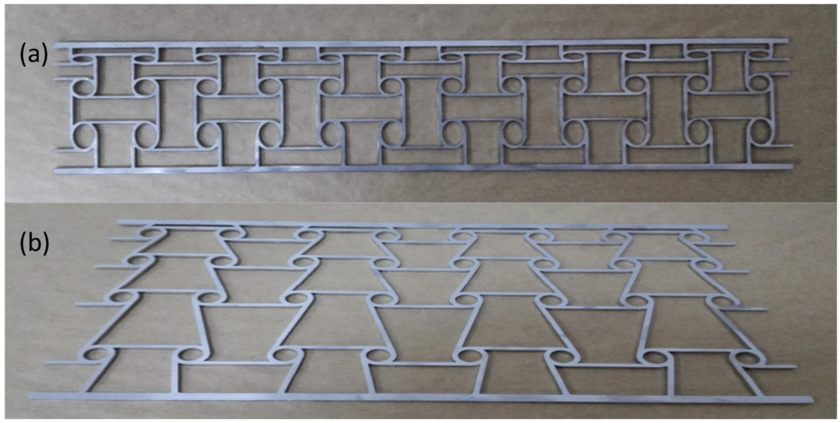

Fig. 6. functional graded chiral mechanical metamaterials: (a), anti-tetrachiral topology; (b), tetrachiral and anti-tetrachiral hybrid metastructures. (Photos prepared by the author.)

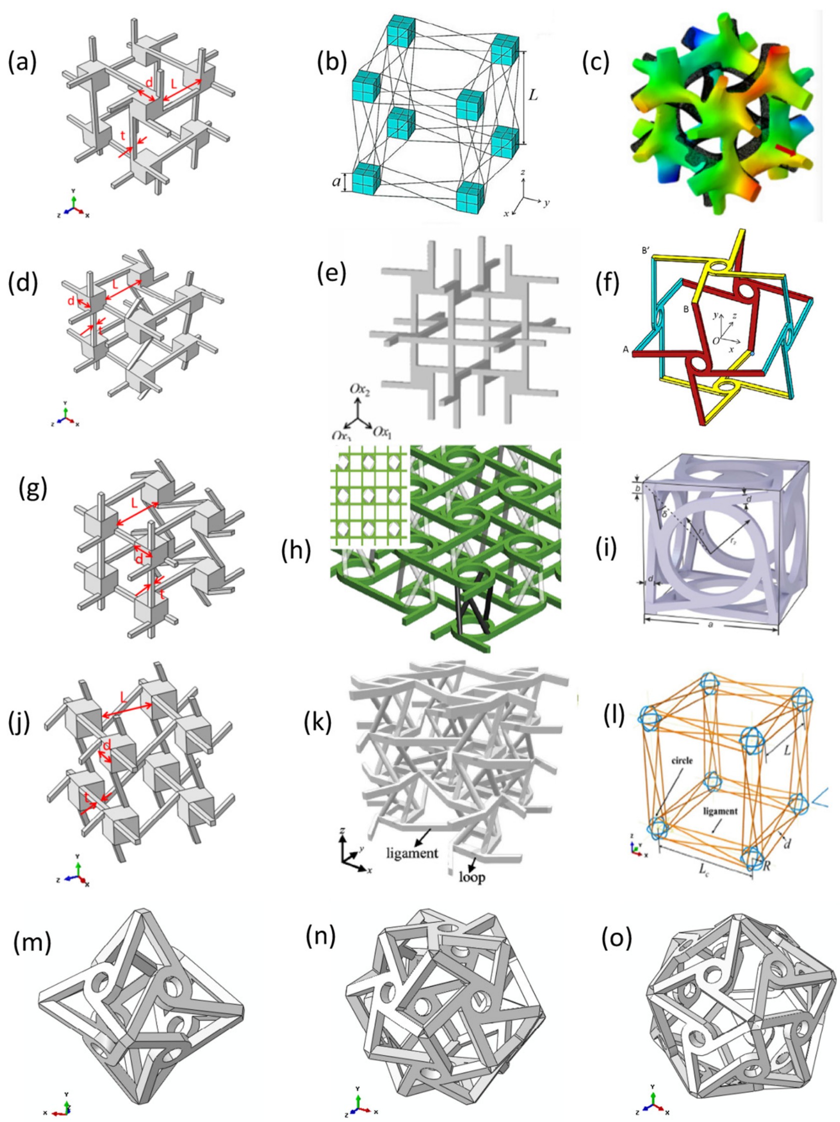

Fig. 7. Various types of 3D chiral mechanical metamaterials designed: (a), 3D anti-tetrachiral mechanical metamaterials [85]; (b), 3D chiral metastructures [86]; (c), computational optimized auxetic lattice with 3D anti-tetrachiral configuration [87]; (d), 3D chiral-antichiral-antichiral mechanical metamaterials [22]; (e), alternative anti-tetrachiral lattices [86]; (f), 3D chiral lattice with negative Poisson ratio [79]; (g), 3D chiral-antichiral-antichiral mechanical metamaterials [22]; (h), 3D cellular metamaterials with planar anti-tetrachiral topology [84]; (i), compression-twist chiral mechanical metamaterials [21]; (j), 3D chiral-chiral-chiral mechanical metamaterials; (k), 3D cellular metamaterials with planar tetrachiral topology [80]; (l), alternative 3D chiral unit cell [78]; (m), 3D chiral pyramid lattice prepared by the author; (n), 3D chiral dodecahedron lattice prepared by the author; (o), 3D chiral regular icosahedrons lattice prepared by the author.

chiral mechanical metamaterials are proposed [91–94], and strain energy based analytical models for predicting the in-plane mechanical properties of tetrachiral and anti-tetrachiral hybrid, chiral re-entrant hybrid 2D mechanical metamaterials are developed. Making use of the mechanical benefits of structural hierarchy, hierarchical chiral mechanical metamaterials are also proposed for generating enhanced mechanical properties, and corresponding analytical formulas in the form of dimensionless structural parameters are deduced [20]. Moreover, composite hexachiral honeycombs with transversally curved ligaments were manufactured and experimentally tested [95]. However, when strain energy method is employed for analyzing the mechanical properties of chiral mechanical metamaterials, following 5 assumptions are adopted: (a) nodes (or circles) are considered rigid; (b) internal forces oriented in a direction perpendicular to the externally applied stress vanish; (c) internal forces are dictated by the observed kinematic behavior; (d) axial and shear deformations of the ligaments are neglected; (e) all deflections are small. It is necessary to quest the relative errors of these assumptions in the future, as the nodes also deforms under external loading, non-linear larger deformation of ligaments should also be considered, and the internal shearing stress components within ligaments also matters. Moreover, theoretical models for exploring the mechanical properties of chiral mechanical metamaterials manufactured with anisotropic carbon fiber reinforced composites are still not available, where anisotropic behaviors of ligaments and manufacturing process influences should be included.

Micropolar elasticity and homogenization methods are efficient alternative approaches for investigating the local deformation mechanisms and mechanical properties of 2D and 3D chiral mechanical metamaterials. Cosserat elasticity [49], also known as micropolar elasticity [49–51] can describe the coupling between local rotation, shearing, bending, and bulk deformation, thus providing institutive explanation for the origin of many unusual mechanical properties (negative Poisson's ratio, high compressibility, etc.) and deformation mechanisms of chiral materials. Based on micropolar elastic theory and tensor analysis, Liu et al. [96] developed a micropolar continuum theory for describing the dilatation–rotation coupling and shear–rotation coupling deformation mechanism of chiral lattice structures. Chen et al. [97] proposed a micropolar continuum model for describing the constitutive relation for tetrachiral lattice structure, where 13 independent material constants are employed. Spadoni et al. [98] proposed a micropolar continuum model for analyzing the in-plane mechanical properties of hexachiral structures, where deformable-ring node model are assumed for comparison. Making use of beam-lattice model and continuous model, Bacigalupo et al. [99,100] studied the in-plane elastic properties of anti-tetrachiral cellular structures based on first-order computational homogenization technique, and also proposed a beam-lattice micropolar equivalent continuum model for hexachiral and tetrachiral structures consisting of rigid circular rings and elastic beam ligaments. Making use of orthotropic chiral micropolar theory, homogenization of chiral honeycomb with deformable circular nodes is performed, where 13 effective material constants are employed [101]. Computations of the homogenized nonlinear elastic response of 2D and 3D auxetic structures based on micropolar continuum models are performed, and discrete asymptotic technique is employed for analyzing the elastic behaviors of hexachiral honeycomb, where all displacement, force, momentum variables are written into Taylor series [102]. Homogenization methods provide the basis for the replacement of the actual heterogeneous microstructure by an equivalent continuum, which is efficient for analyzing the mechanical behaviors of metamaterials, such as chiral honeycombs [103]. Continuum and discrete methods are developed to characterize the homogenized, effective material response of chiral metamaterials, and discrete methods are developed based on the asymptotic expansion of the kinematic and static variables of their inner unit-cell architectures [104]. Making use of discrete homogenization method, Karathanasopoulos et al. [105] analyze the bulk and shear behaviors of 2D architected materials under small strains, and analytical closed-form analytical expressions in the form of inner material structural geometries are proposed for analyzing the mechanical properties of 2D chiral metamaterials. It can be seen from above mentioned literatures on micropolar elasticity and homogenization methods that these models are only valid under linear deformation assumptions. In order to understand the effects of nonlinear deformation, more theoretical investigations should be performed. Moreover, the effects of strong or weak local defects on the mechanical properties of 2D and 3D chiral mechanical metamaterials are still not investigated yet.

3. Multifunctional mechanical properties of chiral mechanical metamaterials

Lightweight materials and structures are widely employed for industrial multifunctional applications, such as: impact energy absorption, vibration attenuation, sound absorption, electromagnetic stealth, thermal isolation, zero thermal expansion, etc. Benefit from its unique structural topology, lightweight chiral mechanical metamaterials with NPRs have the following enhanced dynamic mechanical properties: (a) making use of the local rotation of nodes and bending deformation of ligaments, chiral mechanical metamaterials is able to produce wave mitigation features and adjustable bandgap structures, and the local resonances induced elastic energy storage is benefit for its broadband vibration isolation performances; (b), benefits from the synergistic deformation of ligaments and node rotation, the deformation of chiral mechanical metamaterials will be localized within the contact region due to NPRs effects, thus generate enhanced impact energy absorption abilities; (c), through introducing bi-material structured ligament design, the thermal expansion ability of chiral mechanical metamaterials can be arbitrarily manipulated, thus chiral mechanical metamaterials can be used for designing advanced structures with zero thermal expansion properties for enduring critical environments where temperature changes sharply.

3.1. Vibration and sound attenuation performances

Doubly negative elastic metamaterials consisting of chiral honeycombs with local resonant are proposed for vibration attenuation and sound absorption, where local rotation and bulk deformation are coupled [106]. Lew et al. [107] studied the vibroacoustic behaviors of chiral honeycomb sandwich structures. The dynamic response of chiral truss-core assemblies is investigated numerically and experimentally, and unique vibration deformation characteristics of chiral cantilevered truss-core beam are explored numerically for an airfoil design [108]. Spadoni et al. [109] exploited potential sound-transmission reduction and vibration isolation properties of chiral honeycombs, where in-plane wave propagation in chiral lattices is investigated using Bloch analysis [110]. Mechanical performances of anti-tetrachiral damper with metal rubber particles inclusions are studied through parametric experiments [111]. Making use of the geometrical topological features of chirality, lattice structures integrating the frequency-selective properties of chiral internally resonating elements are proposed for realizing high damping performances [112]. Three types of lightweight honeycomb structures with rubber coatings are proposed for energy absorption and shock wave resistance during underwater explosion, including hexachiral, re-entrant, and circular honeycombs, etc. [113]. Chiral metamaterial based beam with multiple resonators is proposed for broadband vibration suppression by utilizing their individual bandgaps [114]. Making use of coupled uniaxial and rotational deformations, chiral auxetics based composite damper structures are proposed for realizing high dissipation efficiency [115]. Simplified beam-lattice models are proposed for analyzing the acoustic behavior of hexachiral and tetrachiral lattices, corresponding Floquet–Bloch spectrum and occurrence of low frequency band-gaps are analyzed through a discrete Lagrangian model [116]. Making use of Bloch's theorem, vibration transmission and isolation performances of trichiral structures with uniform and gradient geometrical features are investigated [117]. The underwater sound radiation characteristics of free-floating stiffened metal box covered with three different kinds of covering layers are investigated, namely: solid covering layers, chiral covering layers, and chiral covering layers filled with expanded polystyrene (EPS) foams [118]. Rigorous Floquet–Bloch approach is employed for evaluating the wave dispersion and band gaps of chiral honeycombs [119]. Based on stiff rings and unshearable flexible ligaments assumptions, linear parametric model with lumped mass and distributed elasticity is developed for describing the dynamic response of periodic anti-tetrachiral metastructures [120]. Abdeljaber et al. [121] proposed an automated genetic algorithm based optimization approach for obtaining optimized chiral lattice structures with broadband vibration attenuation capabilities, where bandgap location and width can be modulated. Based on the Bloch theorem, the bandgap characteristics of tetra-chiral unit cells filled with and without internal resonators are analyzed and compared; it is found that the internal resonators can obviously enhance the vibration attenuation ability of tetra-chiral lattice coating in the frequency range of the band gap corresponding to the rotating vibration mode of internal resonators [122,123]. Making use of topological optimization technique, optimized anti-tetrachiral meta-materials with the largest band gap amplitudes in the low-frequency spectrum region can be designed [124]. Propagation of elastic waves through tetrachiral metamaterials is studied based on beam lattice model, first-order continuum model and homogenized micropolar continuum model, and parametric analyses of the dispersion spectrum are carried out using a solid Cauchy model [125]. Multi-parameter perturbation technique is employed for solving the spectrum eigen- problem of tetrachiral metamaterials, and explicit parametric model of the band structure governing the free propagation of elastic waves is developed [126]. Lagrangian beam lattice models are proposed for studying the dynamic responses of hexachiral, tetrachiral and anti-tetrachiral metamaterials with periodic microstructures, and multi-objective optimization function is used for achieving the largest stop bandwidth at the lowest center frequency [127]. It can be seen from above mentioned literatures that: the bandgap structures and wave propagation features of 2D periodic chiral and anti-chiral metastructures are studied mainly based on Bloch theorem and Floquet–Bloch wave theories, finite element simulation is frequently employed, while verification experiments are still quite limited. Based on various types of optimization schemes, optimized bandgap structures of chiral metamaterials at low spectrum region can be realized through various types of structural topological optimization approaches. However, research on the bandgap structures and wave attenuation performances of novel 2D meta-chiral metamaterials is still quite limited, and systematical investigations should be performed for understanding the advantages and disadvantages of various types of 2D chiral metamaterials with different frequency spectrum regions, and novel optimization methods should be developed for optimizing the vibration attenuation performances of chiral metamaterials, such as: machine-learning based topology optimization methods, etc. Moreover, investigations on the vibration attenuation performances of 3D chiral mechanical metamaterials are still quite limited.

3.2. Impact energy absorption performance

Spadoni et al. [128] investigated the flat-wise compression behaviors of hexachiral honeycomb based on classical analytical formulas for the linear buckling of thin plates and shells. The compressive strength of auxetic hexagonal chiral honeycombs is analyzed with analytical elastic buckling theory, and finite element simulation approaches are employed for generating theoretical coefficients [129]. The flatwise compressive behaviors of tetrachiral and hexachiral honeycombs are analyzed using analytical and finite element simulations; it is found that ligaments act as mixed stiffeners-elastic foundations, thus providing different buckling mode shapes during deformation [130]. Compression tests on chiral honeycombs made of carbon/composite laminates are performed for studying the crushing performances, and finite element simulations are performed for comparisons [131]. Simplified super folding element theory and plastic hinge energy absorption theory are employed for analyzing the crushing behaviors of anti-tetrachiral honeycombs, and analytical formulas for analyzing the mean crushing stresses, maximum specific energy absorption per mass capacity, and minimum peak crushing stress are developed [132]. The deformation and impact energy absorption performances of 3D anti-tetrachiral ultrathin polymer microlattices under high strain rate loading are investigated, it is found that the failure process of lattice layer is initiated by buckling for the stretch-dominated lattice, and plastic yielding for the bending-dominated lattice [133]. The mechanical properties of anti-trichiral, re-entrant anti-trichiral honeycombs under quasi-static compression with large deformation are studied through experiments and theoretical analysis comparisons, where the deformation dominated by the bending of ligaments, rotation of ligaments around the plastic hinges and the rigid rotation of cylinders [134,135]. Inspired by the interlocking topological microstructures in nacre or tooth enamel through evolution in millions of years, artificial ceramic sandwich panels composed of chiral interlocked blocks are designed for lightweight impact-resistant protecting structures applications [136,137]. It can be seen from above literatures that: the impact energy performances of chiral honeycombs are mainly investigated through finite element simulations, experimental verifications and theoretical investigations based on plastic hinge theories are still very limited, and investigations on carbon fiber and glass fiber reinforced composites based chiral metamaterials are rare, where anisotropy effects should be considered. Moreover, investigations on the crushing impact energy performances of 3D chiral mechanical metamaterials are still quite limited.

3.3. Negative thermal expansion coefficients of bi-material chiral metamaterials

Most of the commonly available engineering materials always present positive coefficient of thermal expansion (CTE). However, precise instruments and structures should maintain thermal dimensional stability and compensation of thermal expansion under harsh service environments. Demands for designing advanced lightweight structures with tunable thermal expansion and Poisson's ratio are of critical importance for temperature-sensitive and mechanical-sensitive devices in satellites, aircrafts, etc. [138]. As shown in Fig. 8, chiral lattice composed of bi-material rib elements is proposed for generating negative CTE, theoretical formulas and experimental verifications are performed for comparisons [10,139]. Yu et al. [140] proposed the design of trichiral, antitrichiral, tetrachiral, anti-tetrachiral and hexachiral with bi-material ligaments for generating adjustable coefficients of thermal expansions (CTE) from negative to positive regions. Wu et al. [141] proposed the design of 3D anti-tetrachiral metastructures with negative CTEs, where the ligaments are composed of bi-material layers with different thermal expansion coefficients. It can be seen from above literatures that: although there are some conceptual designs of chiral structures in 2D and 3D, applications of advanced structures with negative CTEs are still rare, due to manufacturing precision difficulties and material defects. Moreover, advanced design methods are needed for performances optimization of negative CTEs, such as: topological optimization and machine learning driven structural designs, etc.

4. Industrial application potentials

Benefit from the unique structural topology of 2D and 3D chiral mechanical metamaterials, various types of multifunctional industrial applications are proposed, such as: morphing airfoils, smart structures, auxetic stents, flexible electronics, etc.

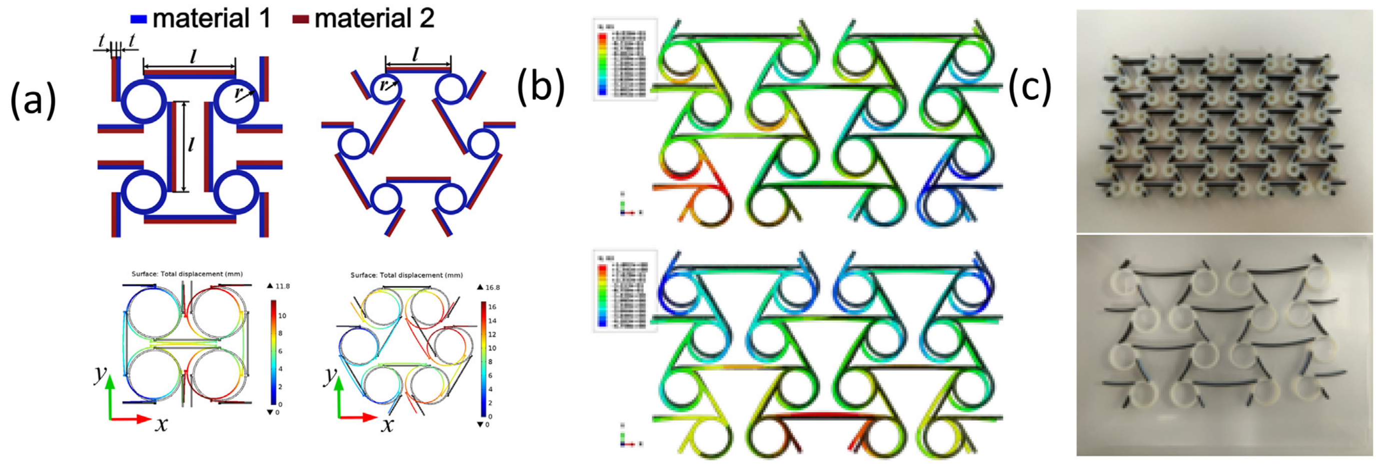

Fig. 8. Chiral bimaterials metastructures with negative thermal expansion coefficient: (a), 2D anti-tetrachiral metamaterials with negative CTEs [141]; (b), novel chiral-re-entrant hybrid metamaterials with negative CTE fabricated by the author, based on bimaterial strips with different CTEs; (c) 3D anti-tetrachiral metamaterials with negative CTEs [141].

4.1. Morphing airfoil application

Morphing airfoil design should be able to change its shape to adaptive between high-speed and low-speed flight or to control flight in different speed regimes, thus enhance the flight efficiency, stability and safety [142]. As shown in Fig. 9, morphing airfoils based on chiral components are proposed and investigated by Scarpa, Spadoni and Betti, and Airoldi et al. [143–152]. Innovative wing profile featuring an internal truss-like structure of chiral topology is proposed for generating large chordwise compliance and large in-plane shear stiffness can through the proper selection of a limited number of geometric parameters of chiral cores [143,144]. Spadoni et al. [145] investigated the static and aerodynamic performances of several types of chiral-core aerofoils, and the entire flow field is resolved using the Euler equations. Metallic glass wing box based on the hexachiral honeycomb concept was designed, and its morphing performances were verified with wind-tunnel testing [146]. Chiral truss-core airfoil is proposed for both passive and active-morphing applications, two different airfoils made with aluminum and carbon fiber material are constructed, and their mechanical stiffness are compared experimentally [147]. The manufacturing process of hexachiral composite airfoil constructed with plain weave carbon fabric plies are developed, and numerical models of the manufactured structures are constructed for evaluating the strength of the proposed configuration [148]. Innovative chiral core airfoil with robust chordwise compliance is proposed for increasing the lift-curve slope and the airfoil efficiency, the contribution of the chiral topology to the torsional and axial stiffness of the wing can be optimized by selecting and possibly grading the most suitable lamination sequence [149]. Carbon fiber based chiral airfoil demonstrator based on the development of chiral ribs was designed, numerical studies of manufacturing trials were performed to assess the technological process applied to small-sized chiral units made of different materials [150–152]. Design

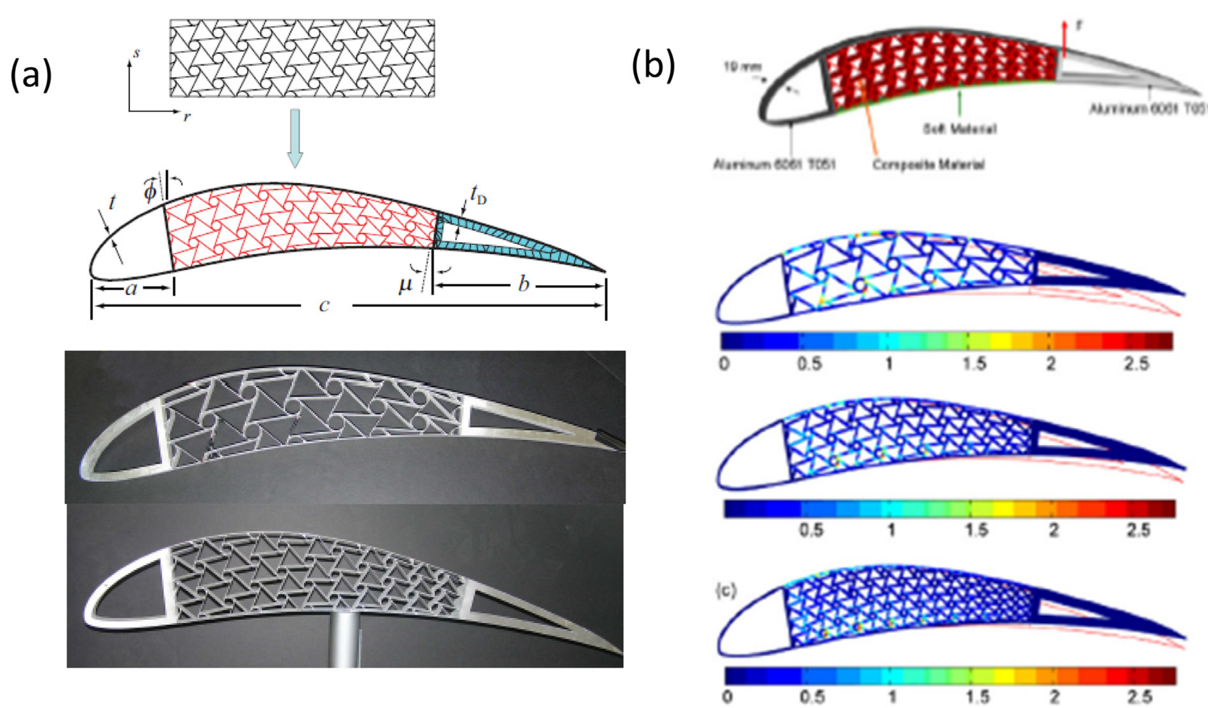

Fig. 9. Chiral airfoil and aerodynamic performance simulation: (a) design and fabricated of chiral airfoil with water-jet cutting techniques [143–145]; (b), axial stress distribution at the limit of the elastic regime of the material for carbon fiber airfoil [148].

of anti-tetrachiral aircraft wing based on the aerodynamics loads is proposed, where elliptical and circular nodes are compared, methods are developed for estimating the shear forces and bending and twisting moments along the wing span based on the distributed loads, and influence of the core design on the overall performance of the airfoil are also studied [153]. It can be seen from above literatures that: chiral honeycomb cores are efficient for generating morphing effects, while research on aerodynamics and vibration attenuation performances optimization is still quite limited. Moreover, fabrication techniques of composite chiral morphing airfoils are still challenging, and industrial applications of chiral morphing airfoil need more experimental verifications.

4.2. Smart structures with chiral topology

Manufacturing and testing of hexachiral shape memory alloy honeycombs are performed, nonlinear finite element models are constructed for simulation, and procedures for fabrication and testing SMA deployable antenna from full packing configuration to deployment are proposed and verified [154–156]. Design of hexachiral honeycombs with magnetic inclusions in the nodes are proposed, where the magnetism can be switched on or off and even controlled electrically. Equilibrium between the magnetic fields and mechanical system on varying the externally applied magnetic field are deduced analytically [157]. Through combining 3D printing technique and shape memory polymers (SMPs), active chiral mechanical meta-materials are designed and fabricated, and maximum area changes up to 200% can be realized [158]. Fabrication and shaping of shape memory polymer hexachiral auxetic structures with tunable stiffness are performed, deployment process and the mechanical properties of the deployed structure can be tailored to meet the application [159]. Utilizing the glass transition behavior in amorphous polymers, thermomechanically triggered two-stage pattern switching of 2D lattices is achieved for tetrachiral metamaterials [160]. Attard et al. [161] proposed the concept of chiral auxetic structures for morphing from flat system to double curved dome-shaped surfaces via simple deformations.

4.3. Chiral auxetic stent application

Coronary artery disease is one of the most common causes of death globally [162,163], and artificial stent placement is one of the most common solutions for coronary artery disease. However, the comprehensive mechanical behaviors of stent are of critical importance for efficient functional recovery of blood vessels. In recent years, auxetics are proposed for designing mechanical adjustable stent [164]. Novel stent based on chiral metastructures with circular nodes are designed, anti-tetrachiral stent with elliptical nodes are proposed for enhancing the radial expansion ability while reduce the axial expansion ability [91]. Making use of the mechanical benefits of hierarchical design, the radial expansion ability can be remarkably enhanced through the introduction of hierarchical anti-tetrachiral unit cell along radial direction of the stent [20,91]. Similarly, novel stent based on chiral and re-entrant hybrid metastructures are also proposed, which can further improve the mechanical performances of stent, especially the radial expansion ability [93]. Although several types of chiral auxetic stents are conceptually proposed, mechanical interactions between chiral stent and three-layered blood vessels should be systematically investigated, clinical experiments on the biocompatibilities of stent are still not performed yet.

4.4. Other miscellaneous application

Flexible electronics, also known as flex circuits, is a technology for assembling electronic circuits by mounting electronic devices on flexible substrates, such as polyimide, PEEK or transparent conductive polyester film. Making use of the buckling assembling features of patterned microstructures under planar retraction of substrate medium, flexible electronics with chiral configuration are designed, and their out-of-plane buckling assembly mechanical performances are investigated through experiments and simulation comparisons [23,165]. Making use of compliant rolling-contact joints, chiral metamaterials with high shape-morphing versatility and extreme ranges of deformation are proposed, and giant guided shape shifting can be generated through circular cam chiral tessellations constructed with alternating compliant rolling-contact joins, and no elevated stress and strain energy are encountered in the structural elements [166]. Dedek et al. [13,167] proposed the design of proposed magneto-mechanical metamaterials for enhanced impact energy absorption, where the performances can be tuned through manipulating the magnitude of magnetic moment associated with magnetic inclusions inserted into the system as well as through the way how magnetic inclusions are distributed within the structure. Sha et al. [168] proposed the design of large-scale chiral metallic glasses with extensive hardening and large ductility properties. Precisely designed Kirigami pattern is proposed for shape transformation applications, nano-kirigami chiral optical metamaterials are fabricated using the topography-guided stress equilibrium, and various types of 3D shape transformation such as buckling, rotation, and twisting of nanostructures are realized [169,170]. Through integrating Miura square-twist origami and local kirigami cutting techniques, structure-guided transformable and foldable metamaterials based on twistable origami structures are proposed for generating multistep transformable feature as well as controllable stimulus-response behavior, where anti-tetrachiral pattern can be formed [171]. Ciobanu et al. [172] analyzed the associated heating effect of Chiral dielectric structures with conductive insertions on high transmission levels at GHz frequency range. Moreover, chiral topological patterns can be employed for designing amazing architectures, and miscellaneous tensegrities, reciprocal frame systems [46,173–177].

5. Perspectives on the future and challenges of chiral mechanical metamaterials

It can be seen from above literatures that researches on different types of chiral mechanical materials are growing rapidly, including: (a), novel design of chiral mechanical metamaterials with unprecedented properties, such as: compression-twist effects, etc. (b), multi-functional applications for potential industrial applications, such as: impact energy absorption, sound absorption, vibration attenuation, adjustable thermal expansion performances, etc. (c), various types of promising conceptual applications are proposed.

However, there are still some problems that should be systematically investigated in the future: (a), advanced manufacturing techniques are needed for fabrication of composites based on chiral metamaterials. (b), research on the design optimizations are still quite limited, especially for 3D chiral metamaterials. (c), the mechanical properties of 2D and 3D chiral mechanical metamaterials under larger deformation conditions should be further investigated. Moreover, mechanical constitutive theories for composite chiral mechanical metamaterials should be developed, where anisotropy of composites should be included. (d), more theoretical models should be proposed for understanding the multifunctional performances of 2D and 3D chiral metamaterials, such as: impact energy absorption theories, etc. (e), more experimental verifications should be performed for potential industrial applications. (f) there are also many other industrial applications that chiral metamaterials should be employed, such as: chiral auxetic nails, chiral composite sportswear, chiral structures for impact, blast, thermal and electromagnetic shielding applications, art, decoration and architecture design, etc.

6. Conclusions

Mechanical design of 2D and 3D chiral mechanical metamaterials are reviewed, and theoretical models for understanding their mechanical behaviors and deformation mechanisms are summarized.

Afterwards, multifunctional properties of chiral mechanical properties are elaborated, such as: vibration attenuation and bandgap features, impact energy absorption and negative coefficient of thermal expansion (CTE). Finally, several successful industrial application of chiral mechanical metamaterials are demonstrated, such as: morphing airfoil with chiral core configuration, shape memorial smart deployable antenna and programmable structures, auxetic stent for biomedical application, chiral flexible electronics and reconfigurable structures with shape shifting abilities, etc.

CRediT authorship contribution statement

Wenwang Wu: Data curation, Formal analysis; Writing - original draft. **Wenxia Hu**: Validation. **Guian Qian:** Conceptualization, Funding acquisition, Project administration, Resources, Software, Supervision, Writing - review & editing. **Haitao Liao**: Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision. **Xiaoying Xu:** Visualization. **Filippo Berto:** Writing - review & editing.

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References

[1] L.J. Gibson, M.F. Ashby, G.S. Schajer, C.I. Robertson, Proc. R. Soc. Lond. A382 (1982) 25–42.
[2] L.J. Gibson, M.F. Ashby, Cellular Solids: Structure and Properties, Pergan Press, London, 1988.
[3] A.G. Kolpakov, Determination of the average characteristics of elastic frameworks, J. Appl. Math. Mech. 49 (6) (1985) 739–745.
[4] R. Lakes, Foam structures with a negative Poisson's ratio, Science 235 (1987) 1038–1040.
[5] K.E. Evans, M.A. Nkansah, I.J. Hutchison, S.C. Rogers, Molecular network design, Nature 353 (6340) (1991) 124.
[6] K. Thomson, B. Kelvin, Baltimore lectures on molecular dynamics and the wave theory of light, CJ Clay & Sons, 1904.
[7] K. Miura, Method of packaging and deployment of large membranes in space, Proc. IAF Congr. 31st Pap. IAF-80-A31 Tokyo, 1980.
[8] R.F. Almgren, An isotropic three-dimensional structure with Poisson's ratio = −1, Journal Elasticity 15 (4) (1985) 427–430.
[9] K.W. Wojciechowski, Two-dimensional isotropic systems with a negative Poisson ratio, Phys. Lett. 137 (1–2) (1989) 60–64.
[10] R.S. Lakes, Cellular solid structures with unbounded thermal expansion, J. Mater. Sci. Lett. 15 (6) (1996) 475–477.
[11] D. Prall, R.S. Lakes, Properties of a chiral honeycomb with a Poisson's ratio of −1, Int. J. Mech. Sci. 39 (3) (1997) 305–314.
[12] J.N. Grima, K.E. Evans, Auxetic behavior from rotating squares, J. Mater. Sci. Lett. 19 (17) (2000) 1563–1565.
[13] R. Mirosław Dudek, B. Grabiec, K.W. Wojciechowski, Molecular dynamics simulations of auxetic ferrogel, Rev. Adv. Mater. Sci. 14 (2) (2007) 167–173.
[14] J.N. Grima, R. Gatt, P.S. Farrugia, On the properties of auxetic meta-tetrachiral structures, Phys. Status Solidi B 245 (3) (2008) 511–520.
[15] K. Bertoldi, P.M. Reis, S. Willshaw, T. Mullin, Negative Poisson's ratio behavior induced by an elastic instability, Adv. Mater. 22 (3) (2010) 361–366.
[16] A. Alderson, K.L. Alderson, G. Chirima, N. Ravirala, K.M. Zied, The in-plane linear elastic constants and out-of-plane bending of 3-coordinated ligament and cylinder-ligament honeycombs, Compos. Sci. Technol. 70 (7) (2010) 1034–1041.
[17] Y. Cho, J.H. Shin, A. Costa, T.A. Kim, V. Kunin, J. Li, S.Y. Lee, S. Yang, H.N. Han, I.S. Choi, D.J. Srolovitz, Engineering the shape and structure of materials by fractal cut, PNAS 111 (49) (2014) 17390–17395.
[18] T. Hewage, K. Alderson, A. Alderson, F. Scarpa, Double-negative mechanical metamaterials displaying simultaneous negative stiffness and negative Poisson's ratio properties, Adv. Mater. 28 (46) (2016) 10323–10332.
[19] C.S. Ha, M.E. Plesha, R.S. Lakes, Chiral three-dimensional isotropic lattices with negative Poisson's ratio, Phys. Status Solidi B 253 (7) (2016) 1243–1251.
[20] L.J. Sun, H.S. Lei, Y. Tao, Y. Xia, J.K. Chen, D.N. Fang, W.W. Wu, Mechanical properties of hierarchical anti-tetrachiral metastructures, Extreme Mechanics Letters 6 (2017) 18–32.
[21] T. Frenzel, M. Kadic, M. Wegener, Three-dimensional mechanical metamaterials with a twist, Science 358 (6366) (2017) 1072–1074.
[22] W.W. Wu, D.X. Qi, H.T. Liao, G.A. Qian, L.C. Geng, Y.H. Niu, J. Liang, Deformation mechanism of 3D chiral metamaterials, Sci. Rep. 8 (1) (2018), 12575.
[23] X. Ning, X. Yu, H.L. Wang, et al., Mechanically active materials in three-dimensional mesostructures, Sci. Adv. 4 (9) (2018) (eaat8313).
[24] Y. Prawoto, Seeing auxetic materials from the mechanics point of view: a structural review on the negative Poisson's ratio, Comput. Mater. Sci. 58 (2012) 140–153.
[25] X.L. Yu, J. Zhou, H.Y. Liang, Z.Y. Jiang, L.L. Wu, Mechanical metamaterials associated with stiffness, rigidity and compressibility: a brief review, Prog. Mater. Sci. 94 (2018) 114–173.
[26] S. Roderic Lakes, Negative-Poisson's-ratio materials: auxetic solids, Annu. Rev. Mater. Res. 47 (1) (2017) 63–81.
[27] C. Körner, Y. Liebold-Ribeiro, A systematic approach to identify cellular auxetic materials, Smart Mater. Struct. 24 (2) (2015), 025013.
[28] N. Novak, M. Vesenjak, Z. Ren, Auxetic cellular materials-a review, Journal of Mechanical Engineering 62 (9) (2016) 485–493.
[29] C.W. Huang, L. Chen, Negative Poisson's ratio in modern functional materials, Adv. Mater. 28 (2016) 8079–8096.
[30] M. Mir, M.N. Ali, J. Sami, U. Ansari, Review of mechanics and applications of auxetic structures, Adv. Mater. Sci. Eng. (2014), 753496.
[31] J. Surjadi, L.B. Gao, H.F. Du, X. Li, X. Xiong, Y. Lu, N. Fang, Mechanical metamaterials and their engineering applications, Adv. Eng. Mater. 21 (3) (2019) 1800864.
[32] X. Ren, R. Das, P. Tran, T.D. Ngo, Y.M. Xie, Auxetic metamaterials and structures: a review, Smart Mater. Struct. 27 (2) (2018), 023001.
[33] A. Slann, W. White, F. Scarpa, K. Boba, I. Farrow, Cellular plates with auxetic rectangular perforations, Physica status solidi B-basic solid state, physics 252 (7) (2015) 1533–1539.
[34] L. Mizzi, K.M. Azzopardi, D. Attard, J.N. Grima, R. Gatt, Auxetic metamaterials exhibiting giant negative Poisson's ratios, Physica status solidi-rapid research letters 9 (7) (2015) 425–430.
[35] A. Rafsanjani, D. Pasini, Bistable auxetic mechanical metamaterials inspired by ancient geometric motifs, Extreme Mechanics Letters 9 (2) (2016) 291–296.
[36] K. Billon, I. Zampetakis, F. Scarpa, M. Ouisse, E. Sadoulet-Reboul, M. Collet, A. Perriman, A. Hetherington, Mechanics and band gaps in hierarchical auxetic rectangular perforated composite metamaterials, Compos. Struct. 160 (2017) 1042–1050.
[37] L. Mizzi, E.M. Mahdi, K. Titov, R. Gatt, D. Attard, K.E. Evans, J.N. Grima, J.C. Tan, Mechanical metamaterials with star-shaped pores exhibiting negative and zero Poisson's ratio, Mater. Des. 146 (2018) 28–37.
[38] K.K. Dudek, R. Gatt, L. Mizzi, M.R. Dudek, D. Attard, K.E. Evans, J.N. Grima, On the dynamics and control of mechanical properties of hierarchical rotating rigid unit auxetics, Sci. Rep. 7 (2017), 46529.
[39] Y.H. Niu, J.R. Ge, J. Liang, et al., Effects of disordered dispersion of circular nodes and missing ligaments on the mechanical properties of chiral structures, Phys. Status Solidi B (2019), 1800586 (Accepted).
[40] L. Yang, O. Harrysson, H. West, D. Cormier, Mechanical properties of 3D re-entrant honeycomb auxetic structures realized via additive manufacturing, Int. J. Solids Struct. 69–70 (2015) 475–490.
[41] Y.C. Tang, J. Yin, Design of cut unit geometry in hierarchical kirigami-based auxetic metamaterials for high stretchability and compressibility, Extreme Mechanics Letters 12 (2017) 77–85.
[42] S.J.P. Callens, A.A. Zadpoor, From flat sheets to curved geometries: origami and kirigami approaches, Mater. Today 21 (3) (2017) 241–264.
[43] C.S. Borcea, I. Streinu, Geometric auxetics, Proceedings Mathematical Physical &Engineering Sciences 471 (2184) (2015).
[44] C.W. Smith, J.N. Grima, K.E. Evans, A novel mechanism for generating auxetic behaviour in reticulated foams: missing rib foam model, Acta Mater. 48 (17) (2000) 4349–4356.
[45] H. Gerlach, Chirality: a relational geometri-physical property, Chairity 25 (11) (2013) 684–685.
[46] D. Avnir, D. Huylebrouck, On left and right: chirality in architecture, Nexus Netw Journal 15 (1) (2013) 171–182.
[47] W.W. Wu, L.C. Geng, Y.H. Niu, D.X. Qi, X.G. Cui, D.N. Fang, Compression twist deformation of novel tetrachiral architected cylindrical tube inspired by towel gourd tendrils, Extreme Mechanics Letters 20 (2018) 104–111.
[48] J.S. Wang, G. Wang, X.Q. Feng, T. Kitamura, Y.L. Kang, S.W. Yu, Q.H. Qin, Hierarchical chirality transfer in the growth of towel gourd tendrils, Sci. Rep. 3 (2013) 3102.
[49] E. Cosserat, F. Cosserat, Théorie des Corps Déformables, A. Hermann Paris, 1909.
[50] A.C. Eringen, Linear theory of micropolar elasticity, J. Math. Mech 15 (1966) 909–923.
[51] A.C. Eringen, Microcontinuum Field Theories I: Foundations and Solids, Springer, 1999.
[52] J.C.S. McCaw, E.C. Urquizo, Curved-layered additive manufacturing of non-planar, parametric lattice structures, Mater. Des. 160 (2018) 949–963.
[53] T. Wang, L.M. Wang, Z.D. Ma, G.M. Hulbert, Elastic analysis of auxetic cellular structure consisting of re-entrant hexagonal cells using a strain-based expansion homogenization method, Mater. Des. 160 (2018) 284–293.
[54] A. Beharic, R.R. Egui, L. Yang, Drop-weight impact characteristics of additively manufactured sandwich structures with different cellular designs, Mater. Des. 145 (2018) 122–134.
[55] S.Q. Yuan, F. Shen, J.M. Bai, C.K. Chu, J. Wei, K. Zhou, 3D soft auxetic lattice structures fabricated by selective laser sintering: TPU powder evaluation and process optimization, Mater. Des. 120 (2017) 317–327.
[56] A. Ingrole, A. Hao, R. Liang, Design and modeling of auxetic and hybrid honeycomb structures for in-plane property enhancement, Mater. Des. 117 (2017) 72–83.
[57] S.Y. Hou, T.T. Li, Z. Jia, L.F. Wang, Mechanical properties of sandwich composites with 3d-printed auxetic and non-auxetic lattice cores under low velocity impact, Mater. Des. 160 (2018) 1305–1321.
[58] T.T. Li, Y.Y. Chen, X.Y. Hu, Y.B. Li, L.F. Wang, Exploiting negative Poisson's ratio to design 3D-printed composites with enhanced mechanical properties, Mater. Des. 142 (2018) 247–258.

[59] J.P. Xiong, D.D. Gu, H.Y. Chen, D.H. Dai, Q.M. Shi, Structural optimization of re-entrant negative Poisson's ratio structure fabricated by selective laser melting, Mater. Des. 120 (2017) 307–316.
[60] M. Kucewicz, P. Baranowski, J. Małachowski, A. Popławski, P. Płatek, Modelling, and characterization of 3D printed cellular structures, Mater. Des. 142 (2018) 177–189.
[61] M. Kaur, T.G. Yun, S.M. Han, E.L. Thomas, W.S. Kim, 3D printed stretching-dominated micro-trusses, Mater. Des. 134 (2017) 272–280.
[62] A. Alderson, K.L. Alderson, D. Attard, K.E. Evans, R. Gatt, J.N. Grima, W. Miller, N. Ravirala, C.W. Smith, K. Zied, Elastic constants of 3-, 4- and 6-connected chiral and anti-chiral honeycombs subject to uniaxial in-plane loading, Compos. Sci. Technol. 70 (7) (2010) 1042–1048.
[63] L. Mizzi, D. Attard, R. Gatt, P.S. Farrugia, J.N. Grima, An analytical and finite element study on the mechanical properties of irregular hexachiral honeycombs, Smart Materials and Structure 27 (10) (2018), 105016.
[64] Y.J. Chen, F. Scarpa, Y.J. Liu, J.S. Leng, Elasticity of anti-tetrachiral anisotropic lattices, Int. J. Solids Struct. 50 (6) (2013) 996–1004.
[65] R. Gatt, D. Attard, P.S. Farrugia, K.M. Azzopardi, L. Mizzi, J.P. Brincat, J.N. Grima, A realistic generic model for anti-tetrachiral systems, Physica Status Solidi B-basic solid state physic 250 (10) (2013) 2012–2019.
[66] L. Mizzi, D. Attard, R. Gatt, A.A. Pozniak, K.W. Wojciechowski, J.N. Grima, Influence of translational disorder on the mechanical properties of hexachiral honeycomb systems, Composites Part B-engineering 80 (2015) 84–91.
[67] A.A. Pozniak, K.W. Wojciechowski, Poisson's ratio of rectangular anti-chiral structures with size dispersion of circular nodes, Physica Status Solidi B-basic solid state physics 251 (2) (2014) 367–374.
[68] E. Idczak, T. Strek, Minimization of Poisson's ratio in anti-tetra-chiral two-phase structure, IOP Conf. Series: Materials Science and Engineering vol. 248 (2017), 012006.
[69] H.K. Zhang, Y.J. Luo, Z. Kang, Bi-material microstructural design of chiral auxeticmetamaterials usingtopology optimization, Compos. Struct. 195 (2018) 232–248.
[70] W.J. Zhang, R. Neville, D.Y. Zhang, F. Scarpa, L.F. Wang, R. Lakes, The two-dimensional elasticity of a chiral hinge lattice metamaterial, Int. J. Solids Struct. 141–142 (2018) 254–263.
[71] M. Brocato, L. Mondardini, A new type of stone dome based on Abeille's bond, Int. J. Solids Struct. 49 (12) (2012) 1786–1801.
[72] S. Zarrinmehr, M. Ettehad, N. Kalantar, N.A. Borhani, S. Sueda, E. Akleman, Interlocked Archimedean spirals for conversion of planar rigid panels into locally flexible panels with stiffness control, Computers & Graphics-UK 66 (2017) 93–102.
[73] Q.Y. Lu, D.X. Qi, Y. Li, D.B. Xiao, W.W. Wu, Impact energy absorption performances of ordinary and hierarchical chiral structures, Thin-Walled Struct. 140 (2019) 495–505.
[74] X. Qi, H.B. Yu, C.W. He, W.W. Wu, Y.B. Ma, Bandgap and wave attenuation mechanisms of innovative reentrant and anti-chiral hybrid auxetic metastructure, Extreme Mech. Lett. 28 (2019) 58–68.
[75] H.H. Huang, B.L. Wong, Y.C. Chou, Design and properties of 3D-printed chiral auxetic metamaterials by reconfigurable connections, Phys. Status Solidi B 253 (8) (2016) 1557–1564.
[76] I. Fernandez-Corbaton, C. Rockstuhl, P. Ziemke, P. Gumbsch, A. Albiez, R. Schwaiger, T. Frenzel, M. Kadic, M. Wegener, New twists of 3D chiral metamaterials, Adv. Mater. (2019), 1807742.
[77] C.S. Ha, M.E. Plesha, R.S. Lakes, Chiral three dimensional lattices with tunable Poisson's ratio, Smart Mater. Struct. 25 (2016), 054005.
[78] S.Y. Duan, W.B. Wen, D.N. Fang, A predictive micropolar continuum model for a novel three-dimensional chiral lattice with size effect and tension-twist coupling behavior, Journal of the Mechanics and Physics of Solids 121 (2018) 23–46.
[79] M.H. Fu, B.B. Zheng, W.H. Li, A novel chiral three-dimensional material with negative Poisson's ratio and the equivalent elastic parameters, Compos. Struct. 176 (2017) 442–448.
[80] M.H. Fu, F.M. Liu, L.L. Hu, A novel category of 3D chiral material with negative Poisson's ratio, Compos. Sci. Technol. 160 (2018) 111–118.
[81] Y.Y. Jiang, Y.N. Li, 3D printed auxetic mechanical metamaterial with chiral cells and re-entrant cores, Sci. Rep. 8 (1) (2018) 2397.
[82] Y.Y. Jiang, Y.N. Li, Novel 3D-printed hybrid auxetic mechanical metamaterial with chirality-induced sequential cell opening mechanisms, Adv. Eng. Mater. 20 (2018), 1700744.
[83] Y.Y. Jiang, Y.N. Li, 3D printed chiral cellular solids with amplified auxetic effects due to elevated internal rotation, Adv. Eng. Mater. 19 (2) (2017), 1600609.
[84] H. Ebrahimi, D. Mousanezhad, H. Nayeb-Hashemi, J. Norato, A. Vaziri, 3D cellular metamaterials with planar anti-chiral topology, Mater. Des. 145 (2018) 226–231.
[85] R. Xia, X.K. Song, L.J. Sun, W.W. Wu, C.L. Li, T.B. Cheng, G. Qian, Mechanical properties of 3D isotropic anti-tetrachiral metastructure, Phys. Status Solidi B 25 (4) (2017), 1700343.
[86] P.S. Farrugia,R. Gatt, J.N. Grima, A novel three-dimensional anti-tetrachiral honeycomb, Phys. Status Solidi B 256 (1) (2019), 1800473.
[87] H.M. Zong, H.Y. Zhang, Y.Q. Wang, M.Y. Wang, J.Y.H. Futh, On two-step design of microstructure with desired Poisson's ratio for AM, Mater. Des. 159 (2018) 90–102.
[88] A. Lorato, P. Innocenti, F. Scarpa, A. Alderson, K.L. Alderson, K.M. Zied, N. Ravirala, W. Miller, C.W. Smith, K.E. Evans, The transverse elastic properties of chiral honeycombs, Compos. Sci. Technol. 70 (7) (2010) 1057–1063.
[89] D. Mousanezhad, B. Haghpanah, R. Ghosh, A.M. Hamouda, H. Nayeb-Hashemi, A. Vaziri, Elastic properties of chiral, anti-chiral, and hierarchical honeycombs: a simple energy-based approach, Theor. Appl. Mech. Lett. 6 (2016) 81–96.
[90] B. Haghpanah, J. Papadopoulos, D. Mousanezhad, H. Nayeb-Hashemi, A. Vaziri, Buckling of regular, chiral and hierarchical honeycombs under a general macroscopic stress state, Proceedings of the Royal Society A: Physical and Engineering Sciences 470 (2167) (2014), 20130856.
[91] W.W. Wu, X.K. Song, J. Liang, et al., Mechanical properties of anti-tetrachiral auxetic stents, Compos. Struct. 185 (2018) 381–392.
[92] B.B. Zheng, R.C. Zhong, X. Chen, M.H. Fu, L.L. Hu, A novel metamaterial with tension-torsion coupling effect, Mater. Des. 171 (2019) 107700.
[93] X.L. Ruan, W.W. Wu, X.K. Song, et al., Design and characterization of the 3D antichiral-reentrant hybrid structure for intravascular stent, Int. J. Appl. Mech. 10 (10) (2018), 1850105.
[94] H.M. Li, Y.B. Ma, W.B. Wen, W.W. Wu, H.S. Lei, D.N. Fang, In plane mechanical properties of tetrachiral and anti-tetrachiral hybrid metastructures, J. Appl. Mech. 84 (8) (2017), 081006.
[95] F. Runkel, G. Ramstein, G. Molinari, A.F. Arrieta, P. Ermanni, Mechanics of curved-ligament hexachiral metastructures under planar deformations, Journal of the Mechanics and Physics of Solids 125 (2018) 145–163.
[96] X.N. Liu, G.L. Huang, G.K. Hu, Chiral effect in plane isotropic micropolar elasticity and its application to chiral lattices, Journal of the Mechanics and Physics of Solids 60 (11) (2012) 1907–1921.
[97] Y. Chen, X.N. Liu, G.K. Hu, Q.P. Sun, Q.S. Zheng, Micropolar continuum modelling of bi-dimensional tetrachiral lattices, Proceedings of the Royal Society A: Physical and Engineering Sciences 470 (2165) (2014), 20130734.
[98] A. Spadoni, M. Ruzzene, Elasto-static micropolar behavior of a chiral auxetic lattice, Journal of the Mechanics and Physics of Solids 60 (1) (2012) 156–171.
[99] A. Bacigalupo, M.L. Bellis, Auxetic anti-tetrachiral materials: equivalent elastic properties and frequency band-gaps, Compos. Struct. 131 (2015) 530–544.
[100] A. Bacigalupo, L. Gambarotta, Homogenization of periodic hexa- and tetrachiral cellular solids, Compos. Struct. 116 (2014) 461–476.
[101] Y. Chen, X.N. Liu, G.K. Hu, Micropolar modeling of planar orthotropic rectangular chiral lattices, ComptesRendusMecanique 342 (5) (2014) 273–283.
[102] K. El Nady, F. Dos Reis, J.F. Ganghoffer, Computation of the homogenized nonlinear elastic response of 2D and 3D auxetic structures based on micropolar continuum models, Compos. Struct. 170 (2017) 271–290.
[103] L. Kaczmarczyk, C.J. Pearce, N. Bicanic, Studies of Microstructural Size Effect and Higher-order Deformation in Second-order Computational Homogenization, vol. 88, Pergamon Press, 2010 23–24 (1383–1390).
[104] F.D. Reis, J.F. Ganghoffer, Construction of micropolar continua from the asymptotic homogenization of beam lattices, Comput. Struct. 112–113 (2012) 354–363.
[105] N. Karathanasopoulos, F.D. Reis, H. Reda, J.F. Ganghoffer, Computing the effective bulk and normal to shear properties of common two-dimensional architectured materials, Comput. Mater. Sci. 154 (2018) 284–294.
[106] X.N. Liu, G.K. Hu, Elastic metamaterials making use of chirality: a review, Strojniškivestnik-Journal of Mechanical Engineering 62 (7–8) (2016) 403–418.
[107] T.L. Lew, A. Spadoni, F. Scarpa, M. Ruzzene, Proc. SPIE 5760 (2005) 559–568.
[108] A. Spadoni, M. Ruzzene, F. Scarpa, Dynamic response of chiral truss-core assemblies, J. Intell. Mater. Syst. Struct. 17 (2006) 941–952.
[109] A. Spadoni, M. Ruzzene, Structural and acoustic behavior of chiral truss-core beams, World Academy of Science Engineering & Technology 128 (5) (2006) 616–626.
[110] A. Spadoni, M. Ruzzene, S. Gonella, F. Scarpa, Phononic properties of hexagonal chiral lattices, Wave Motion 46 (7) (2019) 435–450.
[111] Y.H. Ma, F. Scarpa, D.Y. Zhang, B. Zhu, L.L. Chen, J. Hong, A nonlinear auxetic structural vibration damper with metal rubber particles, Smart Materials and Structure 22 (8) (2013), 084012.
[112] E. Baravelli, M. Ruzzene, Internally resonating lattices for bandgap generation and low-frequency vibration control, J. Sound Vib. 332 (25) (2013) 6562–6579.
[113] F. Xiao, Y. Chen, H.X. Hua, Comparative study of the shock resistance of rubber protective coatings subjected to underwater explosion, Journal of Offshore Mechanics and Arctic Engineering 136 (136) (2014), 021402.
[114] R. Zhu, X.N. Liu, G.K. Hu, C.T. Sun, G.L. Huang, A chiral elastic metamaterial beam for broadband vibration suppression, J. Sound Vib. 333 (10) (2014) 2759–2773.
[115] F. Agnese, C. Remillat, F. Scarpa, C. Payne, Composite chiral shear vibration damper, Compos. Struct. 132 (2015) 215–225.
[116] A. Bacigalupo, L. Gambarotta, Simplified modelling of chiral lattice materials with local resonators, Int. J. Solids Struct. 83 (2016) 126–141.
[117] S.Y. Xu, X.C. Huang, H.X. Hua, A study on the isolation performance of trichiral lattices with gradient geometry, J. Vib. Control. 21 (16) (2015) 3465–3475.
[118] D.W. Zhu, X.C. Huang, Y. Wang, F. Xiao, H.X. Hua, Experimental and numerical research on the underwater sound radiation of floating structures with covering layers, Proc IMechE Part C: J Mechanical Engineering Science 229 (3) (2015) 447–464.
[119] R.C. Zhong, M.H. Fu, Q.Y. Yin, O.T. Xu, L.L. Hu, Special characteristics of tetrachiral honeycombs under large deformation, Int. J. Solids Struct. 169 (2019) 166–176.
[120] A. Bacigalupo, M. Lepidi, High-frequency parametric approximation of the Floquet-Bloch spectrum for anti-tetrachiral materials, Int. J. Solids Struct. 97–98 (2016) 575–592.
[121] O. Abdeljaber, O. Avci, D.J. Inman, Optimization of chiral lattice based metastructures for broadband vibration suppression using genetic algorithms, J. Sound Vib. 369 (2016) 50–62.
[122] S.Y. Xu, X.C. Huang, et al., Study on the application and optimization of trichiral raft in a floating raft system, Proc. Inst. Mech. Eng. C J. Mech. Eng. Sci. 230 (11) (2015) 1819–1829.
[123] D.W. Zhu, X.C. Huang, H.X. Hua, H. Zheng, Vibration isolation characteristics of finite periodic tetra-chiral lattice coating filled with internal resonators, Proc. Inst. Mech. Eng. C J. Mech. Eng. Sci. 230 (16) (2015) 2840–2850.
[124] A. Bacigalupo, G. Gnecco, M. Lepidi, L. Gambarotta, Optimal design of low-frequency band gaps in anti-tetrachiral lattice meta-materials, Compos. Part B 115 (2017) 341–359.
[125] F. Vadalà, A. Bacigalupo A, M. Lepidi, L. Gambarotta, Bloch wave filtering in tetrachiral materials via mechanical tuning, Compos. Struct.201(2018) 340–351.

[126] M. Lepidi, A. Bacigalupo, Multi-parametric sensitivity analysis of the band structure for tetrachiral acoustic metamaterials, Int. J. Solids Struct. 136–137 (2018) 186–202.
[127] A. Bacigalupo, M. Lepidi, G. Gnecco, F. Vadala, L. Gambarotta, Optimal Design of the Band Structure for Beam Lattice Metamaterials, Frontiers in Materials 6 (2019) 2.
[128] A. Spadoni, M. Ruzzene, F. Scarpa, Global and local linear buckling behavior of a chiral cellular structure, Phys. Status Solidi B 242 (3) (2005) 695–709.
[129] F. Scarpa, S. Blain, T. Lew, D. Perrott, M. Ruzzene, J.R. Yates, Elastic buckling of hexagonal chiral cell honeycombs, Compos. Part A 38 (2007) 280–289.
[130] W. Miller, C.W. Smith, F. Scarpa, K.E. Evans, Flatwise buckling optimization of hexachiral and tetrachiral honeycombs, Compos. Sci. Technol. 70 (7) (2010) 1049–1056.
[131] A. Airoldi, P. Bettini, M. Zazzarini, et al., Failure and energy absorption of plastic and composite chiral honeycombs, WIT Transactions on The Built Environment 126 (2012) 101–114.
[132] Q. He, D.W. Ma, Z.D. Zhang, L. Yao, Mean compressive stress constitutive equation and crashworthiness optimization design of three novel honeycombs under axial compression, Int. J. Mech. Sci. 99 (2015) 274–287.
[133] L.C. Quan, D. Chiara, Highly porous microlattices as ultrathin and efficient impact absorbers, International Journal of Impact Engineering 120 (2018) 138–149.
[134] L.L. Hu, Z.J. Wu, M.H. Fu, Mechanical behavior of anti-trichiral honeycombs under lateral crushing, Int. J. Mech. Sci. 140 (2018) 537–546.
[135] L.L. Hu, Z.R. Luo, Z.Y. Zhang, M.K. Lian, L.S. Huang, Mechanical property of re-entrant anti-trichiral honeycombs under large deformation, Composites Part B 163 (2019) 107–120.
[136] M. Mohammad, Z. Tao, B. Francois, Simultaneous improvements of strength and toughness in topologically interlocked ceramics, Proc. Natl. Acad. Sci. 115 (37) (2018) 9128–9133.
[137] M. Mohammad, S. Amanul, A. Behnam, F. Barthelat, Toughness by segmentation: fabrication, testing and micromechanics of architectured ceramic panels for impact applications, Int. J. Solids Struct. 158 (2019) 52–65.
[138] W. Kai, P. Yong, Z.L. Qu, Y.M. Pei, D.N. Fang, A cellular metastructure incorporating coupled negative thermal expansion and negative Poisson's ratio, Int. J. Solids Struct. 150 (2018) 255–267.
[139] C.S. Ha, E. Hestekin, J.H. Li, M.E. Plesha, R.S. Lakes, Controllable thermal expansion of large magnitude in chiral negative Poisson's ratio lattices, Phys. Status Solidi B 252 (7) (2015) 1431–1434.
[140] H.B. Yu, W.W. Wu, J.K. Chen, et al., Drastic tailorable thermal expansion chiral-reentrant hybrid planar and cylindrical tube structures, Compos. Struct. 210 (2019) 327–338.
[141] L.L. Wu, B. Li, J. Zhou, Isotropic negative thermal expansion metamaterials, ACS Appl. Mater. Interfaces 8 (27) (2016) 17721–17727.
[142] D.C. Li, S.W. Zhao, et al., A review of modelling and analysis of morphing wings, Prog. Aerosp. Sci. 100 (2018) 46–62.
[143] A. Spadoni, Application of chiral cellular materials for the design of innovative components, Dissertations &Theses-Gradworks, 2008.
[144] A. Spadoni, R. Massimo, Numerical and experimental analysis of the static compliance of chiral truss-core airfoils, J. Mech. Mater. Struct. 2 (5) (2007) 965–981.
[145] A. Spadoni, M. Ruzzene, Static aeroelastic response of chiral-core airfoils, J. Intell. Mater. Syst. Struct. 18 (10) (2007) 1067–1075.
[146] J. Martin, J.J. Heyder-Bruckner, C. Remillat, F. Scarpa, K. Potter, M. Ruzzene, The hexachiral prismatic wingbox concept, Phys. Status Solidi B 245 (3) (2008) 570–577.
[147] D. Bornengo, F. Scarpa, C. Remillat, Evaluation of hexagonal chiral structure for morphing airfoil concept, Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering 219 (3) (2005) 185–192.
[148] P. Bettini, A. Airoldi, G. Sala, L. Di Landro, M. Ruzzene, A. Spadoni, Composite chiral structures for morphing airfoils: numerical analyses and development of a manufacturing process, Compos. Part B 41 (2) (2010) 133–147.
[149] A. Airoldi, M. Crespi, G. Quaranta, G. Sala, Design of a morphing airfoil with composite chiral structure, J. Aircr. 49 (4) (2010) 1008–1019.
[150] A. Airoldi, P. Bettini, P. Panichelli, M.F. Oktem, G. Sala, Chiral topologies for composite morphing structures – part I: development of a chiral rib for deformable airfoils, Phys. Status Solidi B 252 (7) (2015) 1435–1445.
[151] A. Airoldi, P. Bettini, P. Panichelli, et al., Chiral topologies for composite morphing structures – part II: novel configurations and technological processes, Phys. Status Solidi B 252 (7) (2015) 1446–1454.
[152] A. Airoldi, P. Bettini, M. Boiocchi, G. Sala, Composite elements for biomimetic aerospace structures with progressive shape variation capabilities, Advances in Technology Innovation 1 (1) (2016) 13–15.
[153] P.R. Budarapu, S.Y.B. Sudhir, R. Natarajan, Design concepts of an aircraft wing: composite and morphing airfoil with auxetic structures, Front. Struct. Civ. Eng. 10 (4) (2016) 394–408.
[154] M.R. Hassan, F. Scarpa, M. Ruzzene, N.A. Mohammed, Smart shape memory alloy chiral honeycomb, Mater. Sci. Eng. A 481 (1) (2008) 654–657.
[155] F. Scarpa, M.R. Hassan, M. Ruzzene, Modeling and testing of shape memory alloy chiral honeycomb structures, Proceedings of SPIE-The International Society for Optical Engineering 6170 (2006) 0277–786X.
[156] M.R. Hassan, F. Scarpa, N.A. Mohamed, M. Ruzzene, Tensile properties of shape memory alloy chiral honeycombs, Phys. Status Solidi B 245 (11) (2008) 2440–2444.
[157] J.N. Grima, R. Caruanagauci, R. Gatt, Smart metamaterials with tunable auxetic and other properties, Smart Materials & Structures 22 (22) (2013), 084016.
[158] M. Wagner, T. Chen, K. Shea, Large shape transforming 4D auxetic structures, 3D printing and additive manufacturing 4 (3) (2017) 133–141.
[159] J. Rossiter, K. Takashima, F. Scarpa, P. Walters, T. Mukai, Shape memory polymer hexachiral auxetic structures with tunable stiffness, Smart Mater. Struct. 23 (4) (2014), 045007.
[160] C. Yuan, X.M. Mu, C.K. Dunn,J. Haidar, T.J. Wang, H.J. Qi, Thermomechanically triggered two-stage pattern switching of 2D lattices for adaptive structures, Adv. Funct. Mater. 28 (2018), 1705727.
[161] D. Attard, D. Calleja, J.N. Grima, Out-of-plane doming behaviour from constrained auxetics, Smart Materials and Structure 27 (2018), 015020.
[162] G. Disease, I. Incidence, P. Collaborators, Global, regional, and national incidence, prevalence, and years lived with disability for 310 diseases and injuries, 1990–2015: a systematic analysis for the Global Burden of Disease Study 2016, Lancet 390 (10100) (2017) 1211–1259.
[163] GBD Mortality and Causes of Death Collaborators, Global, regional, and national life expectancy, all-cause mortality, and cause-specific mortality for 249 causes of death, 1980–2015: a systematic analysis for the Global Burden of Disease Study 2015, Lancet 388 (10053) (2015) 1459–1544.
[164] S.K. Bhullar, H.A.T. Mawanane, A. Alderson, A. et al., Influence of negative Poisson's ratio on stent applications, Adv. Mater. 2 (3) (2013) 42–47.
[165] H.R. Fu, K.W. Nan, W.B. Bai,et al., Morphable 3D mesostructures and microelectronic devices by multistable buckling mechanics, Nat. Mater. 17 (2018) 268–276.
[166] L.A. Shaw, S. Chizari, M. Dotson, Y.P. Song, J.B. Hopkins, Compliant rolling-contact architected materials for shape reconfigurability, Nat. Commun. 9 (2018) 4594.
[167] K.K. Dudek, W. Wolak, R. Gatt, J.N. Grima, Impact resistance of composite magnetic metamaterials, Sci. Rep. 9 (2019) 3963.
[168] Z.D. Sha, C.M. She, G.K. Xu, Q.X. Pei, Z.S. Liu, T.J. Wang, H.J. Gao, Metallic glass-based chiral nanolattice: light weight, auxeticity, and superior mechanical properties, Mater. Today 20 (10) (2017) 569–576.
[169] Z.G. Liu, H.F. Du, J.F. Li, L. Lu, Z.Y. Li, N.X. Fang, Nano-kirigami with giant optical chirality, Sci. Adv. 4 (7) (2018), eaat4436.
[170] J.F. Li, Z.G. Liu, Focused-ion-beam-based nano-kirigami: from art to photonics, Nanophotonics 7 (10) (2018) 1637–1650.
[171] L.C. Wang, W.L. Song, D.N. Fang, Twistable origami and kirigami: from structure-guided smartness to mechanical energy storage, ACS Appl. Mater. Interfaces 11 (2019) 3450–3458.
[172] R. Ciobanu, C. Schreiner, R. Damian, High frequency electromagnetic energy phenomena in chiral dielectric structures with distributed and localized conductive insertions, Compos. Part B 160 (2019) 241–248.
[173] P. Song, C.W. Fu, Goswami P, J.M. Zheng, N.J. Mitra D. Cohen-Or, Reciprocal frame structures made easy, ACM Trans. Graph. 32(4) (2013) 94.
[174] C. Douthe, O. Baverel, Design of nexorades or reciprocal frame systems with the dynamicrelaxation method, Comput. Struct. 87 (21—22) (2009) 1296–1307.
[175] T. Kohlhammer, A.A. Apolinarska, F. Gramazio, et al., Design and structural analysis of complex timber structures with glued T-joint connections for robotic assembly, International Journal of Space Structures 2 (3–4) (2017) 199–215.
[176] R. Mesnil, C. Douthe, O. Baverel, T. Gobin, Form finding of nexorades using the translations method, Autom. Constr. 95 (2018) 142–154.
[177] J.P. Rizzuto, Experimental investigation of reciprocally supported element (RSE) lattice honeycomb domes structural behaviour, Eng. Struct. 166 (2018) 496–510.