Extreme Mechanics Letters 16 (2017) 18–32

Contents lists available at ScienceDirect

Extreme Mechanics Letters

journal homepage: www.elsevier.com/locate/eml

Mechanical properties of hierarchical anti-tetrachiral metastructures

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ARTICLE INFO

Article history:
Received 9 July 2017
Received in revised form 22 August 2017
Accepted 23 August 2017
Available online 1 September 2017

Keywords:
Hierarchical
Anti-tetrachiral
Hierarchical auxetic
Poisson's ratio
Stent

ABSTRACT

Chiral structures consisting of circular ring nodes and tangentially connected ligaments are engineered systems that exhibit excellent flexibility, vibration attenuation, impact resistance performance, etc. In this paper, we proposed an innovative hierarchical anti-tetrachiral structures based on the auxetic deformation behaviors of anti-tetrachiral unit cell at different structural hierarchical levels. The in-plane mechanical properties of hierarchical anti-tetrachiral metastructures are deduced from strain energy analysis, experimental and finite element analysis (FEA) comparisons are employed for verification. The in-plane mechanical properties of hierarchical anti-tetrachiral metastructures can be remarkably enhanced and manipulated through combining the auxetic deformation behaviors of chiral structures and the mechanical benefits of structural hierarchy, and its tunable mechanical properties can be designed within very large range of modulus and Poisson's ratio value. Finally, an innovative hierarchical anti-tetrachiral stent is proposed, and the interaction between stent and artery vessel are studied, demonstrating the promising industrial application potential of hierarchical chiral metastructures. The proposed chiral geometry represents a new family of chiral hierarchical structures, and the extent of auxeticity and its in-plane mechanical properties can be tuned through manipulating node ring size and shape, length and thickness, and the hierarchy level, thus achieving desired extreme mechanical properties. It is believed that this work can greatly expand the potential applications of chiral metamaterials in conformable and stretchable electronics, biomedical devices, electronic skin, stents, and reconfigurable soft robotics, etc.

1. Introduction

In recent years, lightweight flexible multifunctional structures which can bear large global flexibility and large local deformation within elastic limits are becoming a hot research topic and various types of promising industrial applications of innovative lightweight structures are demonstrated, such as: self-expandable antenna, morphing airfoils, flexible electronics, deformable smart phone, expandable vascular metallic stent, etc. [1–9]. As a special class of flexible structures, auxetic mechanical metamaterial with negative Poisson's ratio is becoming a hot research topic, such as: reentrant materials, rigid square rotation materials and chiral structures, etc. Auxetic structures can expand its volume when stretched, enhanced and improved properties conventional materials such as higher shearing modulus, increased indentation resistance, good absorption properties (acoustic absorption), and higher fracture toughness. Chiral metastructures stands for a series of structures which cannot be mapped to its mirror image by rotations and translations alone [10]. Depending on the geometrical spatial relations between ligaments and nodes of 2D chiral structures, structures with nodes on the opposite side of the ligament are called chiral systems, while structures with nodes on the same side of the ligament are called anti-chiral systems [11]. Under external loadings, node rotation and ligament bending will be the main deformation features of chiral and anti-chiral structures, and the elastic ligament forms a half-wave shape in the anti-chiral systems and a full-wave shape in the chiral system [11,12].

In the classical theory of elasticity, the degrees of freedom are not included for describing the mechanical behaviors of continuum deformable solid, and the classical elasticity cannot describe the mechanical behavior of chirality, where non-affine, rotational and non-centrosymmetric degrees of freedom should be considered. Cosserat elasticity [13], also known as micropolar elasticity

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http://dx.doi.org/10.1016/j.eml.2017.08.004

[13–15] 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. [16–21]. For example, based on the micropolar theory and tensor analysis, Liu et al. [17] developed a continuum theory which can describe both the dilatation–rotation coupling and shear–rotation coupling deformation mechanism of chiral lattice structures. Chen et al. [18] proposed a micropolar continuum model for describing the constitutive relation for tetrachiral lattice structure, where 13 independent material constants are employed. Spadoni et al. [19] proposed a micropolar continuum model for analyzing the in-plane properties of hexachiral structures, where deformable-ring node model are employed. Making use of beam-lattice model and continuous model, Bacigalupo et al. [20,21] studied the in-plane elastic properties of anti-tetrachiral cellular structures through adopting the 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. Alternatively, the in-plane mechanical properties of chiral lattice structures can be studied through enforcing equilibrium of externally applied stresses with resulting internal forces [22]. Besides the most widely employed micropolar theory and internal–external force equilibrium analysis methods, kinematic geometrical relation based strain energy approach [23–25] are also employed for analyzing the equivalent elastic mechanical properties of lightweight materials with microstructure, such as granular materials, lattice structures, re-entrant structures, chiral structures, etc.

Hierarchical cellular structures are known to have enhanced mechanical properties when compared to regular cellular structures, and it is important to understand the relations between mechanical properties and structural hierarchy. By replacing the solid cell walls with anisotropic re-entrant or isotropic chiral honeycomb, multifunctional hierarchical honeycomb is constructed for achieving tunable mechanical properties by appropriately adjusting the geometrical parameters [26]. By replacing every three edge vertex of a regular hexagonal honeycomb with a smaller hexagon, hierarchical honeycombs of first and second order are constructed by Alqassim [27], and it is demonstrated that the in-plane stiffness of hierarchical honeycombs of first and second order can be up to 2 and 3.5 times stiffer than regular hexagonal honeycombs with the same relative density. Through replacing each three-edge node with a smaller, parallel hexagonal novel class of self-similar hierarchical honeycombs is proposed by Haghpanah et al. [28], and theoretical models on the mechanical properties of self-similar honeycomb structures are elaborated systematically, which can be employed for the understanding and development of novel materials and structures with desirable and tunable properties. Sun et al. [29] proposed three types of multifunctional hierarchical honeycomb through replacing the solid cell walls of the original regular hexagonal honeycomb with equal-mass isotropic honeycomb sub-structures consisting of hexagonal, triangular and Kagome lattices, it is found that the triangular and Kagome substructures result in substantial improvements by one or even three orders of magnitude on Young and shear modulus, depending on the cell-wall thickness-to length ratio. Tang and Yin [30] proposed the design principles of hierarchical re-entrant metamaterials, hierarchical porous-rotation square-unit metamaterials for achieving both extreme stretchability and compression deformation in auxetic kirigami metamaterials via the combination of line cuts, cut-outs. Gatt et al. [31] proposed a new class of hierarchical auxetic structures based on the rotating rigid units mechanism. Making use of the mechanical properties benefits of structural hierarchy and grading, hierarchy and functional graded hybrid honeycomb structures are proposed by Taylor et al. [32] for improving the comprehensive mechanical performances of honeycomb structures. Besides the above-mentioned hierarchical honeycombs [26–32], various types of alternative hierarchical honeycombs are proposed through the modification of the node or cell wall structural levels for generating enhanced and tunable mechanical properties through structural hierarchy approaches [33–39].

Stents are small, expandable tubes that are placed within narrowed arteries for restores the flow of blood and maintaining the proper functioning of the heart. Coronary artery disease (CAD) caused by the buildup of plaque inside the coronary arteries is a growing death reasons throughout the world. In 2015, CAD affected about 110 million people and resulted in 8.9 million deaths [40,41], and CAD makes up 15.9% of all deaths making it the most common cause of death globally [41]. The treatment solutions for CAD are mainly noninvasive lifestyle modification, bypass surgery, amputation and stent placement, during which stent placement is one of the most important treatment solutions for maintaining the flow of oxygen-rich blood and recovering the functions of artery vessels. Stent is a small expandable tube that is used to treat narrow, weak or blocked arteries, such as cerebral artery stent, carotid stent, coronary stent, peripheral stent, abdominal artery stent, etc. The primary objective of a vascular stent is to maintain luminal clearance so that adequate blood flow can be supplied to downstream body tissues. The mechanical behaviors of stent under tensile, compression, bending, torsion and crushing loadings are important for improving the function reliability of the stent, such as structural support, blood flow adjustment, high drug delivery efficiency, etc. [42–46]. In order to perform the functions of stent properly, the mechanical properties of stent should adapt to the biological environment of blood vessel environment, and its interaction with the plaque and artery vessels should be investigated systematically.

In this paper, an innovative hierarchical anti-tetrachiral metastructures with auxetic mechanical properties are proposed, and analytical formulas for the in-plane mechanical properties of hierarchical anti-tetrachiral metastructures are derived through strain energy analysis. Comparison between finite element simulation (FEA), experimental test and theoretical studies are performed to study the mechanical behaviors of hierarchical anti-tetrachiral metastructures, and its tunable mechanical properties can be realized through appropriately adjusting its hierarchical geometrical parameters for achieving large range of modulus and Poisson's ratio value. Finally, an innovative auxetic hierarchical anti-tetrachiral stent is proposed, and the interaction between stent and artery are studied, demonstrating the promising industrial applications of hierarchical chiral metastructures. The proposed innovative auxetic hierarchical anti-tetrachiral metamaterials represent a class of new structures, and can be used in conformable and stretchable electronics, biomedical devices, electronic skin, and reconfigurable soft robotics etc.

2. Mechanical properties of hierarchical anti-tetrachiral metastructures

In order to describe the geometrical topology and mechanical properties of the hierarchical anti-tetrachiral structures clearly, the symbols for describing the bottom level subordinate chiral structure will be marked as "*", while the symbols for describing the top level superior chiral structure will be marked as "sup", and only two order of hierarchical structures are considered in the current paper. Following Prall and Lakes [24] assumption, the deformation of the hierarchical anti-tetrachiral structures are ligament-bending dominated under in-plane loading conditions, and small linear elastic bending deformation based on Euler–Bernoulli beam theory is employed for studying the in-plane tensile modulus through strain energy analysis.