Composite Structures 185 (2018) 381–392

Contents lists available at ScienceDirect

Composite Structures

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

Mechanical properties of anti-tetrachiral auxetic stents

Wenwang Wu[a,b], Xiaoke Song[c], Jun Liang[a,b], Re Xia[c,*], Guian Qian[d,*], Daining Fang[a,b]

[a] Institute of Advanced Structure & Technology, Beijing Institute of Technology, Beijing 100081, China
[b] Beijing Key Laboratory of Lightweight Multi-functional Composite Materials and Structures, Beijing 100081, China
[c] Key Laboratory of Hydraulic Machinery Transients (Wuhan University), Ministry of Education, Wuhan 430072, China
[d] Laboratory for Nuclear Materials, Paul Scherrer Institute (PSI), Villigen 5232, Switzerland

ARTICLE INFO

Keywords:
Hierarchical
Anti-tetrachiral structures
Auxetic
Stent
Mechanical properties

ABSTRACT

The mechanical properties of artery stent are of key importance to the mechanical integrity and biomechanical performance reliability of stent-plaque-artery system. In this paper, making use of auxetic deformation features of chiral structures and mechanical benefits of structural hierarchy, two types of innovative chiral stents with auxetic properties are proposed: (a) anti-tetrachiral stent with circular and elliptical nodes; (b) hierarchical anti-tetrachiral stents with circular and elliptical nodes. Firstly, the in-plane mechanical properties of anti-tetrachiral structures are investigated theoretically, and uniaxial tensile experiments are performed for verification; Secondly, design procedures of anti-tetrachiral stent and hierarchical anti-tetrachiral stent with circular and elliptical nodes are elaborated. Effects of stent geometrical parameters on the tensile mechanical behaviors of these stents are studied with finite element analysis (FEA). It is found that the mechanical behaviors of anti-tetrachiral stent can be tailored through adjusting the levels of hierarchical structures and unit cell design parameters. Finally, the deformation of anti-tetrachiral and hierarchical anti-tetrachiral stents during stenting process are investigated with FEA. It is found that the proposed anti-tetrachiral and hierarchical anti-tetrachiral stents exhibit remarkable radial expanding abilities while maintaining axial stability, thus show promising performances for practical clinical applications.

1. Introduction

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 [1–2], making up 15.9% of all deaths globally [2]. With the progress of medical device technology, stent placement becomes one of the most important treatment solutions for CAD. Stents are small, expandable tubes that are placed within narrowed arteries for vessel tissues supporting and restoring the flow of oxygen-rich blood through artery vessels, thus the proper functions of the heart can be maintained. The mechanical behaviors of stent under tensile, compression, bending, torsion and crushing loadings are important for the functional reliability of the stent, such as structural support, blood flow adjustment, drug delivery efficiency improvement, etc. Thus, an ideal stent should have large radius expanding deformation ability to reopen the narrowed vessels, high radial strength to provide good arterial support post expansion, high flexibility for easy maneuverability during deployment, minimal injury to the artery when being expanded, and small axial recoiling deformation for avoiding shearing damage to the vessel materials.

Traditionally, stent design is a tradeoff between radial strength and bending flexibility. García et al. [3] developed a geometrical parametric model for studying the mechanical performances of stent, and proposed a variable radial stiffness stent design procedures to improve the mechanical interaction between stent and artery vessel. Making use of finite element analysis (FEA) method, Migliavacca et al. [4] studied and compared the mechanical behaviors of stainless steel balloon-expandable and shape memory alloy self-expandable stents, it is found that self-expandable stent induces fewer stresses and causes less damage to the artery vessel than the balloon-expandable stent. Making use of quantitative finite element analyses (FEA), Kumar et al. [5] studied and compared the arterial stresses and vessel deformation during stent deployment process of bulk metallic glasses (BMGs) based self-expandable stent and Nitinol-based stent in a patient specific descending aorta, it is found that the proposed BMGs stent can be safely deployed in the artery without vessel overstretching and mechanical failure, thus preventing unexpected vessel injuries and resultant pathological responses. Migliavacca et al. [6] studied the effects of different geometrical parameters on the mechanical performances of a typical diamond-shaped

* Corresponding authors.
E-mail addresses: xiare@whu.edu.cn (R. Xia), guian.qian@psi.ch (G. Qian).

https://doi.org/10.1016/j.compstruct.2017.11.048
Received 30 July 2017; Received in revised form 7 November 2017; Accepted 16 November 2017
Available online 20 November 2017

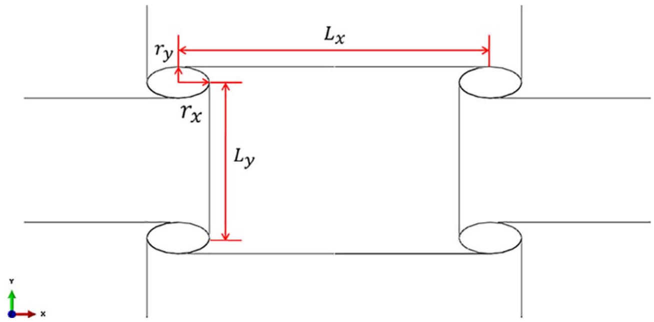

Fig. 1. Geometry of the anti-tetrachiral anisotropic unit cell with elliptical node.

coronary stent, it is found that stent with a low metal-to-artery surface ratio has a higher radial and longitudinal recoil, but lower dogboning effects.

Auxetic structures with negative Poisson ratio can expand its volume when stretched, and exhibit enhanced and improved mechanical properties over conventional materials, such as higher shearing modulus, increased indentation resistance, good absorption properties (acoustic absorption), and higher fracture toughness, thus offering unique features for industrial application. Kolken and Zadpoor [7] made a review on the topology–property relationship of three main types of auxetic mechanical metamaterials, namely re-entrant, chiral, and rotating (semi-) rigid structures. In recent years, auxetic materials with negative Poisson's ratio are proposed for stent application. Bhullar et al. [8] pointed out that arterial endothelium has a negative Poisson's ratio when subjected to both wall shearing and circumferential strain due to pressured blood flow, thus designing stents with axial tension (or compression) and transverse expansion (or contraction) features would match the native tissues of the blood vessel, reduce the deformation incompatibility, and promote the clinical tissue regeneration. Bhullar et al. [9] designed and fabricated an auxetic stent composed of rotating-square unit cells, it is found that the mechanical performances of the stent are improved through mechanical design with tailored negative Poisson's ratio, and stent migration inside vessels can be remarkably reduced. Kuribayashi et al. [10] proposed an Ni-rich TiNi shape memory alloy (SMA) auxetic origami stent graft, which can be deployed at near body temperature or through superelasticity deformation. Li et al. [11] proposed a tetrachiral and anti-tetrachiral hybrid stent with negative Poisson's ratio to reduce the shearing stress due to axial shortening effects.

Hierarchical cellular structures are known to have enhanced mechanical properties when compared to regular cellular structures [12–18]. Parametric model is proposed by Taylor et al. [12] for studying the effects of structural hierarchy and functional grading on the mechanical properties of honeycomb structure, and tradeoff/compromise between structural hierarchy and functional graded design is advantageous for improving the performances of honeycomb structures. Multifunctional hierarchical honeycomb is constructed by Sun et al. [13] through replacing the solid cell walls of regular hexagonal honeycomb with re-entrant or chiral honeycombs, and tunable mechanical properties can be achieved by appropriately adjusting the geometrical parameters at different hierarchical structural levels. By replacing every three edge vertex of a regular hexagonal honeycomb with a smaller hexagon honeycomb unit cell, hierarchical honeycombs of first and second order are constructed by Alqassim [14], it is showed 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. A novel class of self-similar hierarchical honeycombs is proposed by Haghpanah et al. [15], which can be employed for designing novel materials and structures with desirable and tailorable properties. Sun et al. [16] 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 sub-structures result in substantial tensile and shear modulus improvements by one or even three orders of magnitude, depending on the cell-wall thickness-to length ratio. Tang and Yin [17] proposed the design principles of hierarchical re-entrant and hierarchical porous-rotation square-unit metamaterials for achieving both extreme stretchability and compression deformation abilities in auxetic kirigami metamaterials via the combination of line cuts, cut-outs. Gatt et al. [18] proposed a new class of hierarchical auxetic structures based on the rotating rigid units mechanism, which can generate enhanced mechanical properties compared to normal auxetic structures. Wu et al. [19] proposed the design of hierarchical anti-tetrachiral structures with square and circular nodes on different structural levels, and analytical models are proposed for describing its in-plane mechanical properties and auxetic deformation abilities.

Chiral structures consisting of circular, polygonal nodes and tangentially connected ligaments are attracting the interest of researchers throughout the world in recent years [20–24]. Depending on the geometrical spatial relations between ligaments and nodes, structures with cylinders on the opposite side of the ligament are called chiral systems, while structures with cylinders on the same side of the ligament are called anti-chiral systems [20–24]. In this paper, we studied the in-plane mechanical properties of anti-tetrachiral structures with elliptical nodes through experimental, FEA simulation and theoretical comparison. Making use of the auxetic deformation features of chiral structures and the mechanical benefits of structural hierarchy, design procedures for anti-tetrachiral stent and hierarchical anti-tetrachiral stent with circular and elliptical nodes are proposed: (a) anti-tetrachiral stent with circular and elliptical nodes; (b) hierarchical anti-tetrachiral stent with circular and elliptical nodes. The coupled mechanical behaviors of stent-plaque-artery vessels system are investigated for both anti-tetrachiral stent and hierarchical anti-tetrachiral stent. It is found that the proposed anti-tetrachiral and hierarchical anti-tetrachiral stents exhibit

Table 1
Geometrical parameters and uniaxial tensile mechanical properties of the tensile specimens through theoretical, experimental and FEA studies.

Sample No.	L_x (mm)	L_y (mm)	r_x (mm)	r_y (mm)	t (mm)	Theo. (MPa)	Exp. (MPa)	FEA (MPa)
A	40	40	3.5	7	2	233.7261	225.21	226.7812
B	60	40	3.5	7	2	294.8585	277.36	283.856
C	80	40	3.5	7	2	358.4144	330.82	322.148
D	40	60	3.5	7	2	118.8268	115.35	120.8751
E	60	60	3.5	7	2	141.0864	139.41	137.6607
F	80	60	3.5	7	2	164.9617	155.21	161.616
G	40	60	7	3.5	2	754.8377	735.21	739.307
H	60	60	7	3.5	2	812.6574	800.95	779.221
I	80	60	7	3.5	2	910.4929	875.26	850.629
J	40	80	3.5	7	2	77.8538	70.95	79.860
K	60	80	3.5	7	2	88.9153	82.14	93.750
L	80	80	3.5	7	2	101.1887	96.52	103.649