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A novel chiral three-dimensional material with negative Poisson's ratio and the equivalent elastic parameters

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ABSTRACT

In this paper, a new kind of chiral three-dimensional honeycomb material was designed by orthogonal assembling based on chiral two-dimensional honeycomb with four ligaments. The analytical formulae of equivalent Young's modulus and Poisson's ratio are deduced using the beam theory. The calculations of the analytical formulae can be well consistent with those of finite element method. The theoretical and numerical results show that the honeycomb material proposed in this paper is isotropic at the macroscopic scale and its Poisson's ratio is close to −1, which means the material have larger ratio of shear modulus to Young's modulus. Furthermore, the influence of geometries on the equivalent elastic parameters are also discussed.

1. Introduction

Negative Poisson's ratio (NPR) material, also known as auxetic material, gets fatter perpendicular to the applied force when it is stretched, or becomes smaller when it is compressed. This type of materials has long been widespread concern of scholars due to the exceptional mechanical features.

The microstructures of the most common two-dimensional (2D) NPR materials are including re-entrant honeycombs [1], chiral honeycombs [2–6], re-entrant star [7–9], double arrowheads [10] and other forms. The 2D NPR materials are simple in form and easy to process. Therefore, the theoretical and experimental studies are more adequate. In contrast, the three-dimensional (3D) NPR materials are relatively complex and difficult to manufacture, so their research is still insufficient. In recent years, with the industrial technology innovation, especially the development of 3D printing technology, the 3D NPR materials have become a research focus. Based on the bow-tie functional element, Bückmann et al. [11] constructed a 3D periodic auxetic material with 3D direct laser writing technology. Subsequently, Yang et al. [12–21] performed a series of more in-depth analyzes on this 3D auxetic material. Fu et al. [22] also designed a 3D auxetic material based on the bow-tie functional element to maintain the NPR effects over a wide range and avoid buckling of the structure. Shen [23–25] proposed a perforated material containing perfect 3D voids deforms by a rotating cubes mechanism to give NPR. Sun et al. [26] constructed a kind of hierarchical tubes based on a concave hexagon, which also has both NPR effects and high toughness. Lim [27,28] developed a 3D auxetic material using the intersecting double arrowhead structure and deduced the Poisson's ratio of the structure based on the beam theory. A novel unit cell structure with re-entrant hollow skeleton was designed and its Poisson's ratio was studied using the finite element method as a function of the geometric variables and the parent material Poisson's ratio by Li et al. [29].

Chiral structure is a typical 2D honeycomb structure. The common chiral honeycombs having three, four, and six ligaments attached to them, which can also be divided into chiral and anti-chiral honeycombs according to the rotation direction. 3D isotropic chiral lattices that justified Poisson's ratio and isotropy by the cells in each side and aspect ratio were developed by Milton and Ha et al. [30–32] using cubic structure as the center of rotation.

Based on the 2D chiral honeycomb, a new 3D chiral honeycomb was developed by spatial combination. Meanwhile, the equivalent Young's modulus and Poisson's ratio of this structure are analyzed in the range of linear elasticity, and the analytical formulae are achieved. Moreover, the relation between equivalent elastic parameters and geometric variables is also studied.

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2. A new type of 3D auxetic material

2.1. The chiral honeycomb with four ligaments

The structure of chiral honeycomb with four ligaments (tetra-chiral honeycomb) shown in Fig. 1 consists of a circle of radius r, acting as nodes, connected by four ligaments, of length l tangent to the nodes themselves. The thickness and depth of ligament are denoted as t and h, respectively. The depth of the unit cell is not shown. The angle between the imaginary line connecting the node centers and the ligament is defined as θ. For small deformation, the macroscopic equivalent elastic parameters of the structure are as follows [6]

$$E_x = E_s \frac{t/l}{\cos^2\theta + \sin^2\theta/(t/l)^2} \tag{1}$$

$$v_{xy} = 0 \tag{2}$$

Eq. (2) reveals that Poisson's ratio of this chiral honeycomb is zero. Another important property of this material is that there will be shear deformation under axial tension or compression loading, as shown in Fig. 2.

Fig. 2 shows that the inclination angles of the longitudinal line connecting the centers are opposite under the axial tensile or compressive load for tetra-chiral honeycombs with an opposing ligament rotation patterns.

2.2. 3D auxetic material

In the following section, a novel 3D auxetic material shown in Fig. 3 was developed based on 2D tetra-chiral honeycomb. In the manner shown in Fig. 3, the same chiral honeycombs are arranged uniformly in x, y and z directions, respectively., The rotation of the ligaments is in opposite directions for two adjacent honeycombs with the same normal direction (represented by the same color in Fig. 3), and the honeycombs in different directions (represented by the different colors in Fig. 3) are perpendicular to each other and intersect at the midpoint of the ligaments.

When the proposed structure is subjected to a compressive load in the x direction, lateral contraction occurs on the surfaces with y and z directions as the normal directions (represented by the red and yellow) due to the rotation of the circle, which in turn produces a NPR effect. Obviously, the structure has the same properties in x, y and z directions, and is therefore an isotropic.

Although the tetra-chiral honeycombs have a Poisson's ratio of zero in small deformation, the 3D structure formed by them always has a NPR effect.

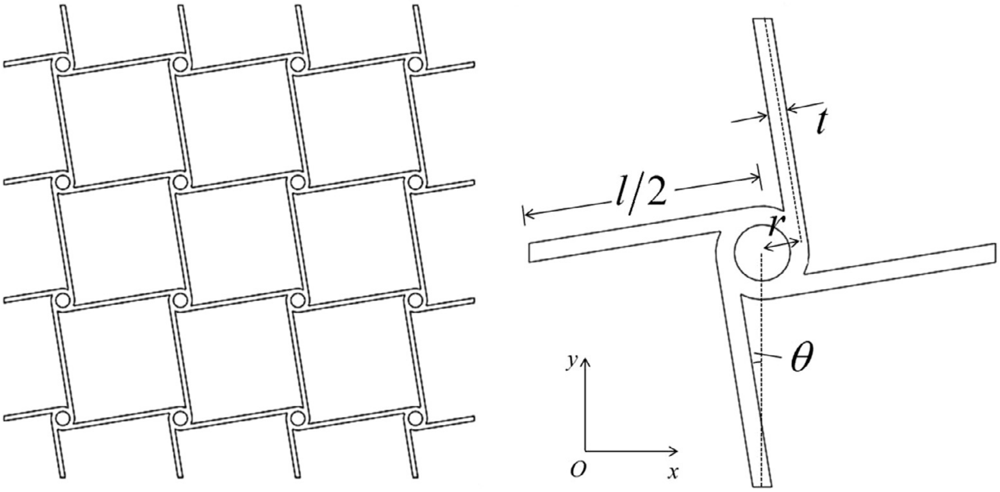
3. Equivalent elastic parameters

Chiral honeycombs are generally equivalent to homogeneous materials for engineering applications. According to the periodic nature of the structure, the equivalent Young's modulus and Poisson's ratio can be obtained only by analyzing its unit cell. The unit cell of the structure proposed in this paper consists of six half-depth 2D unit cells of the tetra-chiral honeycombs, as shown in Fig. 3(b). Taking the centroid of the unit cell as the origin of the coordinate system, the case of loading in x direction is taken as an example for study.

It can be seen from Section 2.1 that the line connecting the centers of the two adjacent circles in the same direction will have the opposite inclination tendency under the unidirectional tensile or compressive load. However, if there are enough number of cells in each surface of the 3D structure, such inclination in each surface does not occur due to the restraint of the vertical honeycombs. In other words, the mutually perpendicular surfaces before deformation are still in a mutually perpendicular state after deformation under unidirectional tensile or compressive load. Therefore, the six surfaces of the unit cell after deformation are still parallel to the initial plane before deformation, and the junctions of the ligaments still fall on the coordinate plane.

To theoretically calculate equivalent elastic parameters of the proposed structure, a mechanical analysis model has been proposed based on the following assumptions:

(i). Each surface of the proposed structure is still parallel to the original plane after deformation.
(ii). The intersections of the ligaments still fall on the coordinate plane, namely $u_{ay} = u_{bx} = u_{b'z} = 0$, similarly other points.
(iii). The circle is considered as rigid body.
(iv). The bending moment and torque at the junction of the ligaments can be neglected.
(v). Ligament is satisfied with Euler beam theory.



(a) (b)

Fig. 1. Geometry of tetra-chiral honeycomb: (a) multiple unit cells; (b) unit cell.