ASSEMBLED 3D PERIODIC AUXETIC CELLULAR STRUCTURE AND ITS MECHANICAL PROPERTIES

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Keywords: Auxetic cellular materials, Manufacture method, Interlocking assembly method, Mechanical properties

Abstract
3D periodic auxetic cellular structures (PACSs) have attracted great interest in recent years as they have superior properties of mechanics and potential application in the filed of aviation, shipping and transportation et al.. However, they usually consist of intricate geometries which make the fabrication of them a significant challenge. The present paper is focused on introducing the interlocking assembly concept into the fabrication of 3D PACSs. There are distinct advantages of the proposed method compared with the additive manufacturing methods mainly used before. The auxetic performance of proposed structures is investigated theoretically and numerically and the effects of re-entrant angle of 3D PACSs on its auxetic performances are discussed.

1. Introduction

Auxetic means that the material or structure possesses negative Poisson's ratio. That is, they will expand in lateral direction when stretched and contract when compressed, which is contrary to common materials and structures.There is a large amount of work devoted to auxetic structures over the past two decades because of the fascinating properties introduced by the negative Poisson’s ratio effect, such as increased shear modulus, indentation resistance, fracture toughness, energy absorption, porosity/permeability variation with strain, synclastic curvature et al.. Due to these excellent properties, auxetic materials have great potential for many applications fields such as aerospace, protection, biomedical, sensors and so on.

3D periodic auxetic cellular structures (PACSs) have attracted considerable interest and become a focus of auxetic material research in recent years. From these researches, it can be found that nearly all 3D PACSs were manufactured by additive manufacturing methods due to their complicated structure, e.g. Selective Electron-Beam Melting (SEBM) by Schwerdtfege et al. [1], Selective Laser Sintering (SLS) by Andreassen et al. [2], Selective Laser Melting (SLM) by Li et al. [3], dip-in direct-laser-writing optical lithography by Bückmann et al. [4], 3D printer [5] and so on. However, additive manufacturing method will introduce defects to the structure such as rough surface, irregular cross sections, and defects caused by stair stepping effect [1, 6]. Additionally, mass production and cost are also problems for additive manufacturing method, and the materials can be used as well as the scale of the structures are also limited by the additive manufacturing equipment.

In this paper, a novel manufacturing method which adopts the interlocking assembly concept is proposed. The auxetic performance of proposed structures is investigated theoretically and numerically. The effects of re-entrant angle of 3D PACSs on its auxetic performances were discussed.

2. Interlocking assembly manufacture method for 3D PACS

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The detailed interlocking assembly manufacture process for 3D PACS can be found in our previous paper [7] and as schematically described in Figure 1. Part-3 and Part-4 are set as the basis of the structure, and they were set parallel and alternately, and the distance between the prior component part and the next component part is determined by the horizontal distance between adjacent interlocking slots. After the basis being set, Part-1 and Part-2 were used to carry on the construction, and they are also set parallel and alternately, the interlocking of the component parts is indicated by the arrows. After one layer being interlocked, the next layer can be interlocked on the basis of the completed layer with the same method. When the structure has been constructed to the number of layers (number of unit cell in the height direction) needed, Part-3 and Part-4 need to be inversed to seal the top, and the interlocking process is the same as former layers. During the interlocking process, adhesive or welding flux should be smeared in the interlocking slots. After being interlocked, waiting for the curing of the adhesive or the finish of braze-welding process, the component parts interlocked will become a complete 3D auxetic structure.

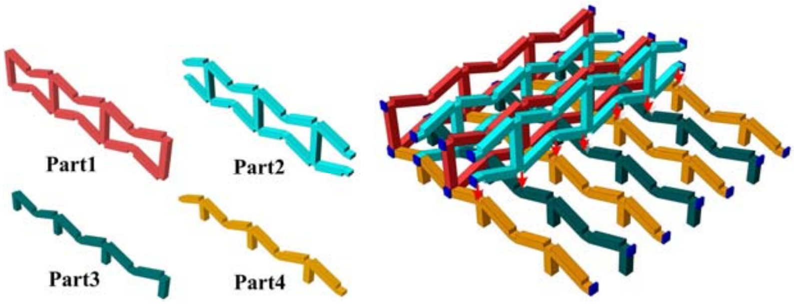

Figure 1. Schematic of interlocking process of 3D re-entrant auxetic structure

It should be mentioned that, the number of the unit cell in any of the three directions is not restricted. Theoretically, arbitrary size 3D auxetic structure can be manufactured using this interlocking process. Additionally, each component part used in this method can be individually qualified [8] so that the whole 3D auxetic structure will avoid the defects caused by additive manufacturing method. The novel method is suitable for any kind of material that can be adhesively bonded or welded such as polymer, metal and fiber reinforced composite materials.

3. Auxetic performance of 3D PACS

The unite cell of proposed 3D auxetic structures can be shown in Figure 2. The geometry can be described in terms of following parameters, length of the vertical struts (H), length of the oblique struts (L), the re-entrant angle (θ), width of the vertical struts (t_1) and width of the oblique struts (t_2), the depth of the vertical strut (t_3) and oblique strut (t_4). In this study it is supposed that the struts both vertical and oblique have the same square cross section, so it can be assumed that $t_1 = t_2 = t_3 = t_4 = t$.

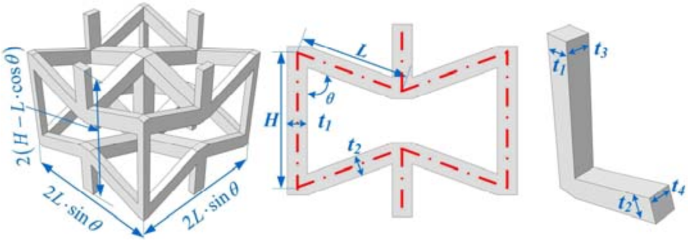

Figure 2. Unit cell and geometry parameters of proposed 3D auxetic structures

The relative density of lattice truss is the ratio of the unit density to the solid from which it is made, or equivalently the volume fraction of truss members occupying the unit cell. The relative density ρ_r of the 3D re-entrant structure can be deduced from the geometry of its unit cell, and it could be expressed

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by the design parameters as

$$\rho_r = \frac{4t^2\left[H + \frac{(1-\cos\theta)}{\sin\theta}t\right] + 16t^2\left(L - \frac{t}{\sin\theta}\right)}{2(H - L\cos\theta)\cdot(2L\sin\theta)^2} = \frac{\left[\alpha + 4 - \frac{(3+\cos\theta)}{\sin\theta}\frac{t}{L}\right]t^2}{2(\alpha - \cos\theta)\cdot(L\sin\theta)^2} \tag{1}$$

where $\alpha = H/L$ is the ratio of the vertical strut length to oblique strut length. The denominator in Equation (1) calculates the volume of the unit cell; the first term of the numerator calculates the volume of the vertical struts in the unit cell, and the part added to H represents the elongation of the vertical strut due to the thickness t; the second term of the numerator calculates the volume of the oblique struts in the unit cell, and the part subtracted from L represents the reduction of the oblique struts due to the overlap of the vertical struts and oblique struts.

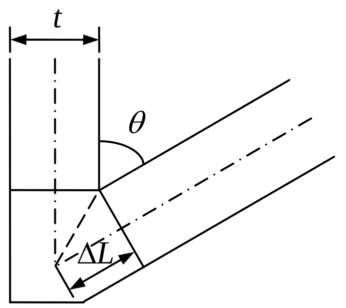


Figure 3. Overlap of truss member

Consider the the overlap of the tips of the truss member as shown in Figure 3, the Young's modulus and Poisson's ratio can be expressed as follows.

$$E = \frac{\sigma_z}{\varepsilon_z} = \frac{H - L\cos\theta}{4L^2\sin^2\theta(\Delta z_1 + \Delta z_2)} \tag{2}$$

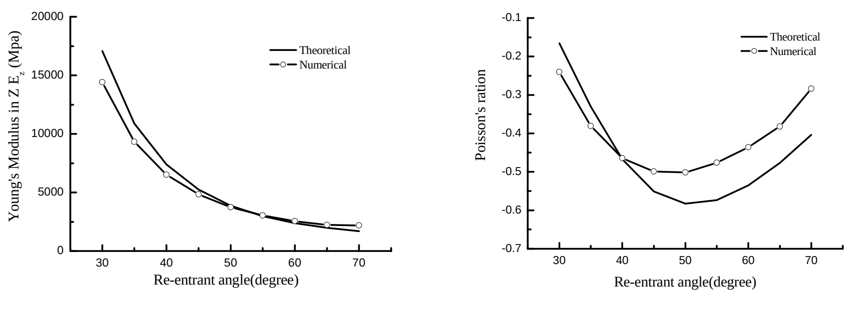
$$\upsilon_{zx} = -\frac{\varepsilon_x}{\varepsilon_z} = \frac{(L\cos\theta - H)\Delta x}{(\Delta z_1 + \Delta z_2)L\sin\theta} \tag{3}$$

Where,

$$\Delta x = \left[\frac{1}{48EI}(L-2\Delta L)^2 - \frac{1}{4EA} + \frac{3}{10GA}\right]\sin\theta\cos\theta(L-2\Delta L),$$

$$\Delta z_1 = \frac{1}{48EI}\sin^2\theta(L-2\Delta L)^3 + \frac{1}{4EA}\cos^2\theta(L-2\Delta L) + \frac{3}{10GA}\sin^2(L-2\Delta L),$$

$$\Delta z_2 = \frac{1}{2EA}(H-2\Delta L).$$



(a) (b)

Figure 4. Auxetic responses of 3D re-entrant auxetic structure

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The auxetic responses of proposed structure were investigated theoretically and numerically. The Young's modulus of the PACSs will monotonic decreasing with the increase of re-entrant angle can be observed from Figure 4(a). There exists an extreme value for Poisson's ratio with the re-entrant angle can be observed from Figure 4(b). Poisson's ratio values will increase (less auxetic) with the increase of the re-entrant angle when the angle is larger than the extreme point, conversely Poisson's ratio values will also increase with the decrease of the re-entrant angle when the angle is smaller than the extreme point. This phenomenon can be interpreted as follows: when the angle is larger than the extreme point, with the increase of the angle the structure will become less re-entrant, though the re-entrant character is the source of auxetic, so with the increase of the angle the structure will become less auxetic. When the angle is smaller than the extreme point, with the decrease of the angle the oblique struts will bear more axial load and less bending load, though the main mechanism causing the auxetic character of the structure is the flexure of the oblique struts, so with the decrease of the angle the structure will become less auxetic.

4. Conclusions

A novel method which adopts the interlocking assembly concept was proposed to manufacture 3D periodic auxetic cellular structures in present work. This manufacturing method will overcome the defects of additive manufacturing method and has the potential for mass production and automatic manufacturing, at the same time it will greatly reduce the manufacturing expenses. In addition, the method is suitable for any kind of material that can be adhesive bonded (e.g. plastic and fiber reinforced composite) or welded (e.g. metal). The auxetic responses of these structures were investigated theoretically and numerically. The effects of re-entrant angle of 3D PACSs on its auxetic performances were discussed.

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