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Developing a new functionally graded lattice structure based on an elliptic unit cell for additive manufacturing and investigation of its properties

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ABSTRACT: The use of additive manufacturing provides the opportunity to create complex geometries at a low cost. This paper introduces a novel nature-inspired additive manufactured graded lattice structure based on an elliptic unit cell. Altering the unit cells' dimensions by the dimension ratios in each repetition results in a graded layer. Linear tessellated layers provide a highly porous, graded structure whose specific properties can be customized at any spatial location. Geometric features were calculated with high accuracy using analytical analysis. Abaqus simulations were utilized to determine the mechanical properties of unit cells, layers, and lattices. A compression test was conducted on a polymer specimen made by digital light processing (DLP) to validate the results. For a conformal model, the elastic modulus along the latitude axis is five times bigger than the value along the longitude axis. An 8.8-fold increase in the elastic modulus is achievable by decreasing the longitude ratio from 1 to 0.75. A reduction of 0.3% in porosity by setting the longitude ratio to 0.75 and a decrease of 2% in porosity by lessening the latitude ratio to 0.75 results in increases of 2.6 and 2.77 folds in the elastic modulus along two directions, respectively. It is possible to tailor geometrical and mechanical properties to meet any design preference by selecting the proper dimension ratios, which can be utilized for medical implant design.

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1- Introduction

Due to growing interest and the vast majority of fields in which cellular materials are necessitated, researchers are trying to introduce new unit cells to provide more efficient mechanical and geometrical properties. The unique properties of these structures are affected by these parameters: unit cell geometry, its topology, materials, and relative density [1].

Porous-graded structures are cellular structures that can provide more customized properties along a particular axis or in different spatial positions. Different characteristics of these structures result from the gradual change in unit cells' geometries through the layers [2]. These structures can be obtained by altering the thickness along any desired axis [3] or changing the size and relative densities simultaneously [4]. Mahbod and Asgari attain double pyramid dodecahedron porous unit cells to form graded structures that get thickened as the layers pile up [5]. As another example, a tessellated radial structure was architected to replicate bone properties [6].

Developing these porous graded structures leads to unique properties. This study introduces new nature-inspired porous uniform and graded structures based on elliptical unit cells, which can provide graded properties in three orthogonal cartesian axes. The parametric study was also conducted to demonstrate the design variable effects on these structure characterizations.

2- Methodology

Unit cells represented in this paper can alter their shape and mechanical properties to form a layer by linear tessellation. Uniform and graded structures are achievable, as shown in Figure 1. Then as the result of the linear array in cartesian coordinates, these layers can form a structure.

Each unit cells consist of two struts and an ellipse that can vary in shape by changing horizontal and vertical radius as follows:

$$\frac{a(2)}{a(1)}=\frac{a(3)}{a(2)}=\frac{a(4)}{a(3)}=L \tag{1}$$

$$\frac{b(2)}{b(1)}=\frac{b(3)}{b(2)}=\frac{b(4)}{b(3)}=H \tag{2}$$

Moreover, the unit cell center determines each unit cell's spatial position, described in cartesian coordinates. These curved beam nature-inspired unit cells overlap each strut to reduce stress concentration.

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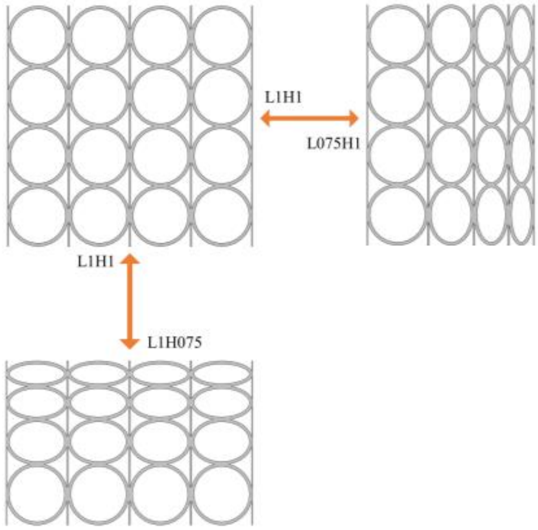

Fig. 1. Sample tessellated layers with different horizontal and vertical dimension ratios

$$xc_i = xc_{i-1} + L^{i-2}a(1) + L^{i-1}a(1) \quad (3)$$

$$yc_j = yc_{j-1} + H^{j-2}b(1) + H^{j-1}b(1) - overlap \quad (4)$$

The surface area and the volume are calculated using the Euler equation to calculate the mid-arc between two intersected volumes.

$$Le_{arc1} = \int_{x0}^{x1} \sqrt{1 + \frac{\partial}{\partial x}(F(i,j))^2}\, dx \quad (5)$$

Furthermore, static general analysis is conducted by placing two plates on both sides of each model regarding the directions of the two study cases. One plate is fixed, and the other has a free translational degree of freedom along the loading axis.

3- Discussion and Results

An experiment test is conducted on an additively manufactured polymeric sample in the elastic region to validate the result, which shows good quantitative agreement with numerical ones. Geometrical properties were calculated. Tables 1 and 2 are an extract from the results of analytical and numerical solutions of surface area (SA) and volume of unit cells, respectively. Calculating these parameters leads to a high-accuracy assessment of the surface-to-volume ratios and porosity percentage.

Table 1. Unit cells' (of L08H08) volume

Unit cell	Volume (mm^3)	Analytical volume (mm^3)	Error%
(1,1)	8.53	8.5712	0.48
(1,4)	6.25	6.1570	0.47
(4,4)	4.14	4.1681	0.68

Table 2. Unit cells' (of L08H08) surface area

Unit cell	SA (mm^2)	Analytical SA (mm^2)	Error%
(1,1)	79.73	78.2368	1.87
(1,4)	63.71	61.6247	3.27
(4,4)	38.36	37.2776	2.82

Figure 2 compares mechanical properties along two loading directions and demonstrates the correlation between these properties and geometrical ones. In addition, the relative mass is calculated for each unit cell to describe the ratio of the unit cell's mass to the bulk cell's mass. Because of the diverse role the struts play as beam and column in two directions, there is a significant difference in the mechanical properties.

As shown in Figure 3, Compared to uniform layers, graded ones exhibit higher geometrical and mechanical properties. The unit cell geometry causes the normalized elastic modulus changes dramatically, while linear tessellation ensures that relative mass changes are kept to a minimum.

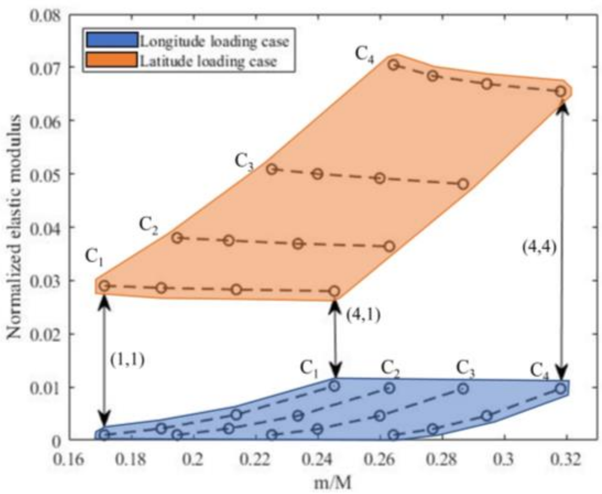

Fig. 2. Normalized elastic modulus-relative mass of unit cells embedded in layer L08H08 in the longitude and latitude loading cases

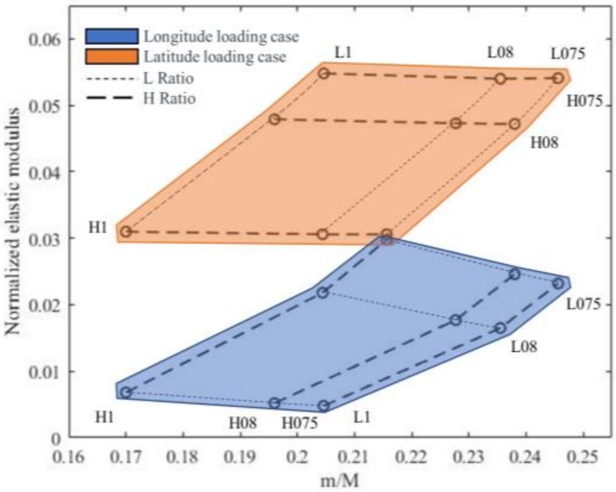

Fig. 2. Normalized elastic modulus-relative mass of layers in the longitude and latitude loading cases

4- Conclusions

This paper represents a cellular porous graded structure inspired by porous wood texture. Mechanical properties in the elastic region and geometric properties, such as porosity percentage and surface-to-volume ratio, were examined for graded and uniform structures. As the dimension ratios (L and H) vary, graded separate structures are formed, resulting in different masses. Cells' relative mass is affected more by reducing the dimension ratio in the longitude direction. Ellipsis's eccentricity and distance between two struts play a vital role in the model's mechanical characteristics in two perpendicular loading cases. The normalized elastic modulus is 2.77 and 2.6 times higher than the uniform structure along L and H directions by increasing relative mass about two times more than the uniform structure's mass. All models can retain high porosity in any dimension ratio, making them a potential candidate for biomaterial or implants.

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