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Analysis, Fabrication and a Biomedical Application of Auxetic Cellular Structures

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Abstract*— *Light weight, high strength, impact damping capabilities and controllable stiffness of cellular structures offers it potential applications in thermal and sound insulation, automotive and biomedical fields. There are two main characteristics of cellular structure, the first is structure relative density and the second is the cellular architecture of the structure. Studying the mechanical behavior of cellular material in 3D and find methods to fabricate is very challenging. In this paper, 3D FEA using ANSYS software is presented to evaluate mechanical properties and response of different designs of open-cell 3D metallic conventional and auxetic cellular structures. Samples of 3D complex cellular structures are also fabricated to highlight the ability of Additive manufacturing techniques to produce cellular structures having intricate architecture. The study shows that unit cell geometry and relative density have a significant effect on structure mechanical properties. Structure relative density and cell geometry can be controlled to give customized mechanical properties for biomedical applications.

***Index Terms*—Additive Manufacturing, cellular solids, Functionally Graded Auxetic, Orthopedic Implants.**

I. INTRODUCTION

Materials in form of 3D cellular solid are found in many natural structural elements like bone, cork, and wood. Currently, man-made cellular solids such as foams and honeycombs had increasingly used in different Engineering applications that requires light weight, customized stiffness and impact resistance. Numerous research efforts have been made to analyze the mechanical response of periodic and non-periodic cellular solids in 2D and 3D under different loading conditions. In their book, Gibson and Ashby [1] introduced a comprehensive and fundamental work on the behavior and applications of cellular solids. During the last two decades, an increasing interest can be observed for auxetic cellular materials which are a class of materials with negative Poisson's ratio (NPR). The auxetic cellular structure shows an opposite behavior to the behavior of bulk material as it is transversely expands when tensioned and transversely contracted when compressed. This unusual interesting behavior expected to open the door to potential application such as fasteners [2], Plast Damping [3] and biomedical applications [4]. Considerable investigations have been carried out to study the behavior of auxetic structures. Detailed reviews about recent research work related to auxetic structures are reported by Prawoto [5], Alderson et al. [6] and Scarpa [7]. Little research in the literature has been done in the area of 3D FEA and fabrication of functionally graded auxetic structure [8, 9]. So, it is of great significance to study the behavior of regular (non-inverted), re-entrant (inverted) honeycombs in addition to functionally graded Auxetic (FGA) structure that combine both structures and to explore how these structures can be fabricated using Additive manufacturing and what are their potential usages in biomedical implants field.

In this research, a 3D FEA using ANSYS® software [10] is presented to evaluate effective stiffness and strain behavior of periodic regular hexagonal, periodic auxetic re-entrant hexagonal and FGA honeycombs with different structure porosities. We started with the analysis of periodic hexagonal under compression then the analysis of periodic auxetic re-entrant hexagonal under tension and finally the analysis of FGA honeycomb under cantilever bending. Afterwards, we'll examine the possibility to fabricate these structures using additive manufacturing and describe the potential of using the auxetic structure in biomedical implants.

II. GEOMETRICAL MODELS

Fig. 1 shows three different configurations of 3D open-cell structure models having both uniform and gradient porosities designed using SolidWoks (Dassault Systèmes SolidWorks Corp.) software. Model 1 shown in Fig. 1a consists of conventional periodic hexagonal unit cells having vertical struts and diagonal struts at an angle of -60° with respect to horizontal y-axis while the second model (Fig 1b) consists of re-entrant hexagonal unit cells having vertical struts and diagonal struts at an angle of 60° with respect to horizontal y-axis. For both models, the specimen size was a 21.5 mm cube and unit cell sizes were fixed at 2.5 mm .However, relative densities of simulated structures were calculated based on change in strut diameter from 0.3 mm to 0.95 mm to give porosity values ranging from 56.5% to 94 %. The structures porosity are calculated as:

$$Porosity = \frac{V_{bulk} - V_{cellular}}{V_{bulk}} \times 100\%$$

Where, V_{bulk} is the bounding box volume (9.938E+3 mm^3), $V_{cellular}$ is cellular structure volume. The geometrical relationship between strut diameter and structures porosity of hexagonal and re-entrant structures is shown in Fig. 2. For

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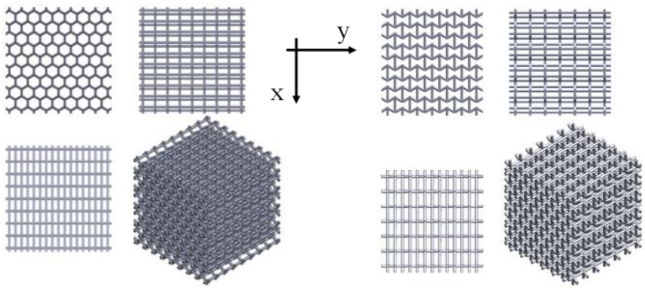
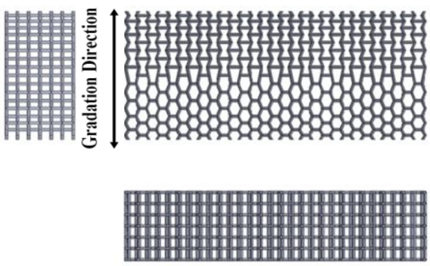
both models, the porosity increases when the strut diameter decrease. However, the increase in porosity is larger for conventional hexagonal structure than re-entrant one at the same strut diameter especially at lager strut diameters. The third model (Fig 1c) is a FGA model consists of both conventional and re-entrant hexagonal structures. FGA has a linear gradual increase in cell size distribution from outside of the structure to the interior of the structure along the height direction. The model size is 54mm in length, 22.9mm in height and 12.5mm in width and will be analyzed as a cantilever under bending. The area in the tension side consists of graded re-entrant hexagonal unit cells. However, the area in the compression side consists of graded conventional hexagonal unit cells.



a. Model 1: periodic regular hexagonal

b. Model 2: periodic Auxetic re-entrant hexagonal



c. Model 3: Functionally Graded Auxetic (FGA)

Fig.1 The 3D open-cell structure models

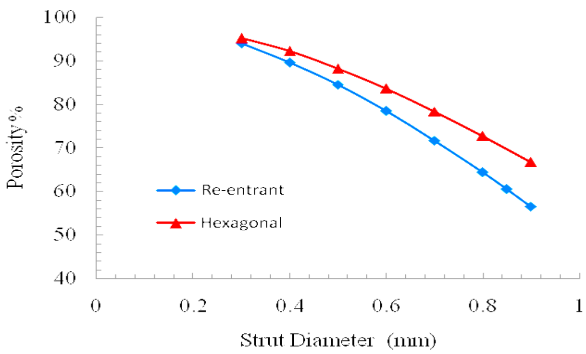


Fig. 2 A Plot of strut diameter versus structure Porosity of 2.5 mm unit cell size specimens

III. Finite Element Analysis

Finite element modeling (FEM) is one of the most effective techniques for the prediction of the mechanical behavior of structures [11]. The described 3D-models were imported into a FE analysis software package ANSYS®. The results of the analysis allow for calculation of Effective Elastic Modulus and Poisson's ratio in compression and tension for model 1and model 2 respectively and the expansion in height direction for the third model 3 under cantilever bending. A linear elastic model with Isotropic material properties is employed. Ti-6Al-4V alloy was assigned as the structures material with a bulk elastic modulus of 114 GPa and Poisson's ratio of 0.34. Ti-6Al-4V is widely used as a biocompatible material for biomedical implants and can be processed in additive manufacturing techniques such as electron beam melting (EBM) or selective laser melting (SLM). Ti-6Al-4V has been selected in this research because we focus on using the proposed structures in biomedical applications as we will discuss in a following section. A high quality mesh consists of 3D 10-node tetrahedral elements (SOLID 187) was used for all models.

A. Prediction of Effective Elastic Modulus and Poisson's ratio for model 1 and model 2

For the conventional hexagonal model 1 and the auxetic re-entrant hexagonal model 2, the lower surface of each structure was completely fixed. However, a compression displacement of 0.043 corresponding to strain of 0.2% was imposed evenly on the top surface of conventional hexagonal model 1 to simulate compression testing and a tension displacement of 0.043 also were imposed evenly on the top surface of auxetic re-entrant hexagonal model 2 to simulate tension testing. The reaction forces were calculated at the fixed bottom layer's nodes for specimens with different strut diameters. The resultant transverse displacement in horizontal y-direction had also estimated during the analysis. Reaction forces and transverse displacements were exported to a text file and effective stiffness and Poisson's ratio of the models were calculated. The calculation approach is similar to the approach introduced by Parthasarathy et al. [12].

The directional effective stiffness E_{XX} was calculated by using of Hook's equation:

$$E_{xx} = \frac{\sigma_x}{\varepsilon_{xy}} = \frac{\dfrac{F_x}{A_o}}{\dfrac{\Delta L_x}{L_x}} = \frac{F_x}{0.002 A_o}$$

, where F_x is the calculated reaction force at fixed bottom surface and A_o is the surface area (21.5x21.5) mm^2 corresponding to the volume's top surface area.

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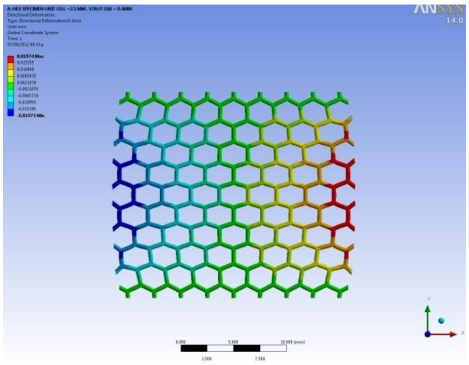
The Poisson's ratios were calculated using the equation:

$$\nu_{xy} = -\frac{\varepsilon_y}{\varepsilon_x}$$

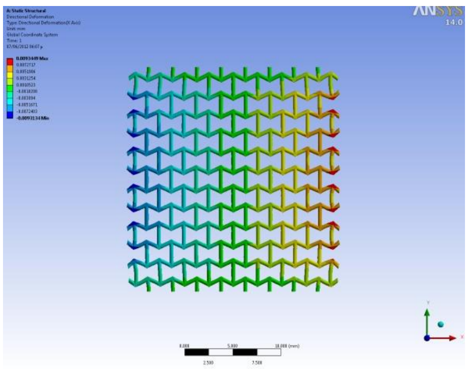
, where, ε_y is the resulting strain normal to the acting force and ε_x is the strain in applied displacement x-direction.

Fig. 3 shows the deformation in transverse direction for 0.5 mm strut diameter samples. Different color shows the different deformation levels where red indicates the highest deformation in positive transverse y-direction, blue indicates the highest deformation in negative transverse y-direction.

The predicted effective modulus as a function of structure porosity for different structures porosities is shown in Fig. 4 and the Poisson's ratio result are shown in Fig. 5.



a. Deformation of model 1 under compression



b. Deformation of model 2 under tension

Fig3. Deformation in transverse direction of 0.5 mm strut diameter structures

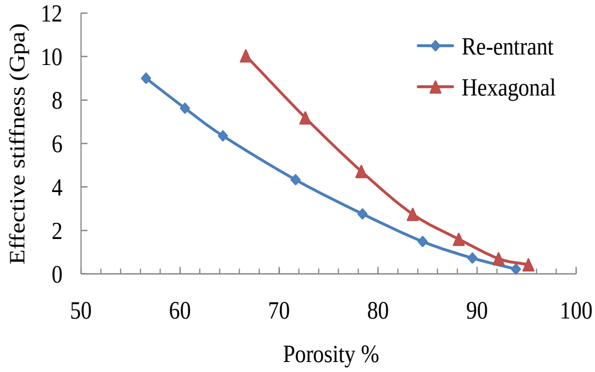


Fig. 4 Effect of porosity on effective stiffness of auxetic re-entrant and regular hexagonal cellular structures

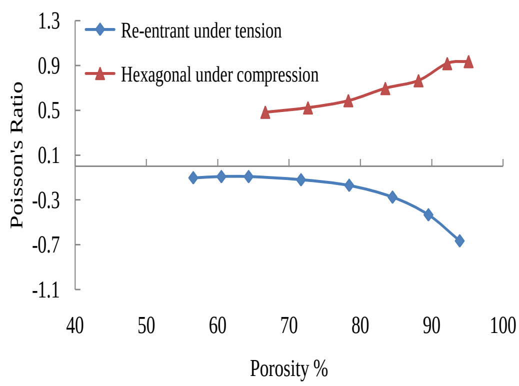


Fig. 5 Effect of porosity on Poisson's ratio of auxetic re-entrant and regular hexagonal structures

B. Evaluation of lateral expansions of the FGA cantilever under bending

From the previous section, we found that when conventional and re-entrant hexagonal structures subjected to compression and tension respectively, both of them are laterally expanded. So, to obtain a lateral expansion through the height of the functionally graded auxetic (FGA) structure beam under bending, the area in the cantilever tension (convex) side would consist of graded re-entrant unit cells. However, the area in the lower compression (concave) side would consist of graded conventional hexagonal unit cells as shown in Fig. 1c. The structure is simulated as a cantilever beam under bending. One sample with porosity of 85% is simulated in this analysis. One end of the cantliver was completely fixed and a shear force of 1000 N was applied in the other free end. In ANSYS®, the directional displacements in length and height directions for any point can be estimated. The transverse (lateral) expansions in height direction along

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the FGA cantilever length can be calculated using the following geometrical calculations with refer to Fig. 6:

$$\tan\alpha = \frac{y_1 + y_2}{w_1},\; w_1 = w_o + x_2 - x_1 \therefore \alpha = \tan^{-1}\frac{y_1 + y_2}{w_o + x_2 - x_1}$$

$$\therefore w_2 = \frac{y_1 + y_2}{\sin\alpha}$$

,where w_o, x_1, y_1, x_2, y_2 represents un-deformed cantilever height and directional displacements of points A and B in x,y directions respectively which can be obtained from ANSYS after analysis completed. Expansion in height direction equals $w_2 - w_o$ where w_2 is the cantilever height after deformation. Fig. 7 shows deformation distribution along structure length and Fig. 8 shows the comparison of change in cantilever height for both FGA and a solid beam having the same overall dimensions.

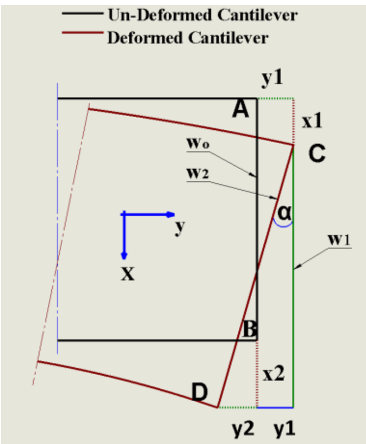

Fig.6 Geometrical relations of deformed cantilever under bending

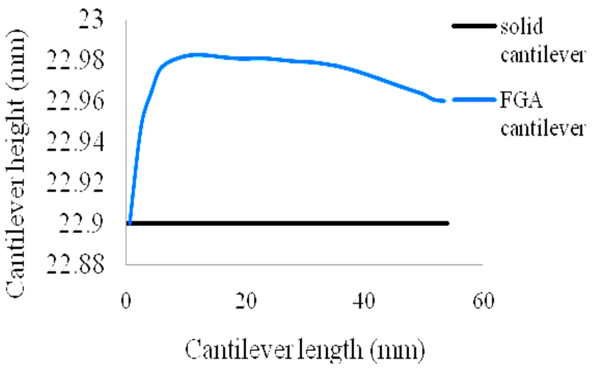

Fig. 8 Change in cantilever height along cantilever length of Ti-6Al-4V solid beam and FGA structure beam under same loading condition

IV. Fabrication of Functionally Graded Auxetic (FGA) Structure Using Additive Manufacturing

Fabrication of complex functionally graded cellular structure with controlled gradation in all spatial directions is a challenge task. However, the advances in computer aided design (CAD) and Additive manufacturing (AM) techniques offer a fast and low cost solution of production problems. AM, is a group of advanced manufacturing processes in which objects can be built layer by layer in additive manner directly from (CAD) data [13]. Fig.9 shows 3D samples fabricated by 3-Dimensional Desktop Printer (envisionTEC, Inc.) from a polymer material. Magics (Materialise NV, Leuven, Belgium) software was used to prepare the build files. Samples are virtually sliced to 50µm layers thickness. Fig. 9a shows a 0.5mm strut diameter auxetic re-entrant sample and Fig. 9b shows the fabricated FGA sample having strut diameter of 0.5 mm and unit cells gradation along sample height and length.

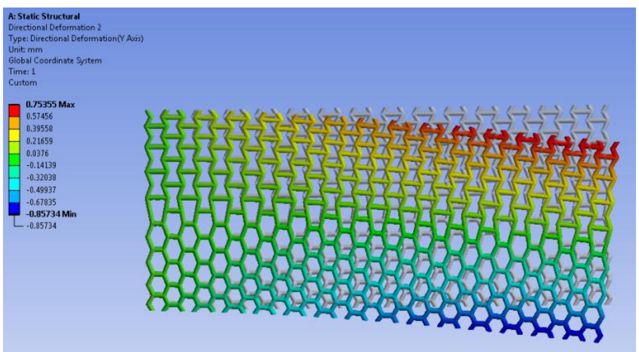

Fig.7 Deformation distribution along FGA structure length

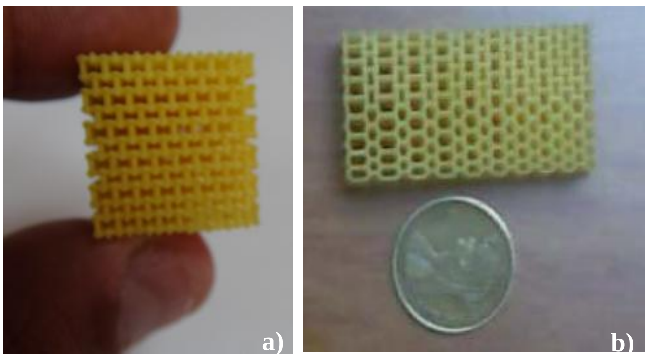

Fig.9 a) 0.5mm strut auxetic re-entrant sample and b) 0.5 mm strut diameter FGA sample having unit cells gradation along sample height and length

V. Potential Application of Auxetic Structure in Biomedical Implants

In this section we will explore the potential application of auxetic structure in femoral component of total hip replacement. It is well known that the bone stress in the proximal femur region is reduced by the presence of the implant [14] due stiffness mismatching between bone and implant materials. This reduction on bone stress in the proximal femur is shown in Fig. 10 [15]. This effect, will lead to stress shielding phenomenon. Stress shielding causes implant loosening, hence, implant failure. To eliminate stress shielding problem, it is better for implant structural and mechanical properties to mimic the bone's stiffness and architecture. Here, we propose to use the advantages of the behavoir of FGA structure that we estimated in the previous sections in addition to its inter-connectivity and custom porosity to enhance bone fixation and osseointegration. The bone load in the proximal region is expected to increase by using auxetic structure due to the continuous contact between stem and bone. Complete Biomedical implants having cellular structure can be successfully processed using AM techniques such as electron beam melting or laser beam melting techniques using Ti-6Al-4V and other biomaterials [16],[17].

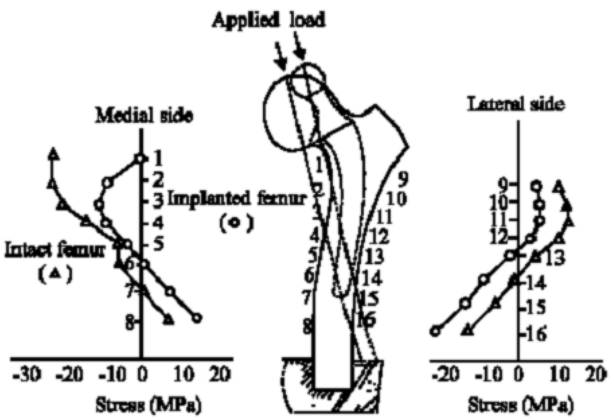

Fig. 10 Stresses distribution along medial and lateral sides when 4,000 N applied load was given onto proximal femur head [15]

VI. Results and Discussion

It was observed that structure unit cell geometry and relative density have a significant effect on structure mechanical properties. As illustrated in Fig. 4, for model 1and model 2, effective elastic modulus increases with the decrease of porosity but this increase is larger for model 1. Both models also show the same lateral expansion behavior although they have opposite loading conditions as shown in Fig.3.

The effect of increasing porosity on Poisson's ratio is illustrated in Fig. 5. The increase in structures porosity leads to an increase in Negative Poisson's ratio of model 2 and positive Poisson's ratio of model 1. The FGA produce a negative Poisson's ratio in tension side and positive Poisson's ratio in compression side when subjected to bending as shown in Fig. 7. This effect yields a significant importance result in which a remarkable transverse expansion had occurred in FGA beam compared to solid one as shown in Fig 8. The designed samples in this research are fabricated from polymer resin using 3-Dimensional Desktop Printer. The results shown in Fig. 9 indicate that AM techniques are a promising method to fabricate regular and FGA structures. The designed geometries can be also fabricated from metal powers such as Ti-4Al-6V biomaterial using other AM techniques.

VII. Conclusions and Future Work

The aim of this research was to understand the unusual behaviour of Auxetic structure under different loading condition by FEM, to examine the possibility to fabricate this type of structure using advanced AM techniques and to propose a novel design of femoral component of total hip replacement using Auxetic structure.

It is clear that, the geometrical and mechanical properties of Auxetic structure can be customized to fit certain applications and femoral component is one of these potential applications. Additive manufacturing techniques offers a promising alternative to fabricate cellular structures with intricate architecture. So, in future, we'll emphasis on design, analysis and fabrication of biomedical implants using additive manufacturing of Auxetic structures.

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