Two Dimensional Auxetic Metamaterials with Adjustable Values of Poisson's Ratio

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Abstract

In the past decades, mechanical metamaterials have attracted extensive attention due to their unusual mechanical and physical properties with simple structures, as well as their unique potential applications in various fields, including engineering, aerospace, biomedical engineering, robotics, sports equipment, and textiles, etc. Auxetic metamaterials are a class of materials that exhibit negative Poisson's ratio, meaning they contract in the direction perpendicular to the applied force when compressed. In this work, a group of unit cell structures for two-dimensional auxetic metamaterials was designed and fabricated using 3D modeling and printing technology, with the unique feature of adjustable Poisson's ratio. The Poisson's ratios were evaluated experimentally, numerically and analytically, and the results were found to be in agreement each other. Specifically, as the phase shift difference decreased from π to zero, the Poisson's ratios of the materials increased from -2.8 to -0.19. This study provides insights into the design and fabrication of auxetic materials with tunable Poisson's ratios, which could have applications in a variety of fields including engineering and medicine.

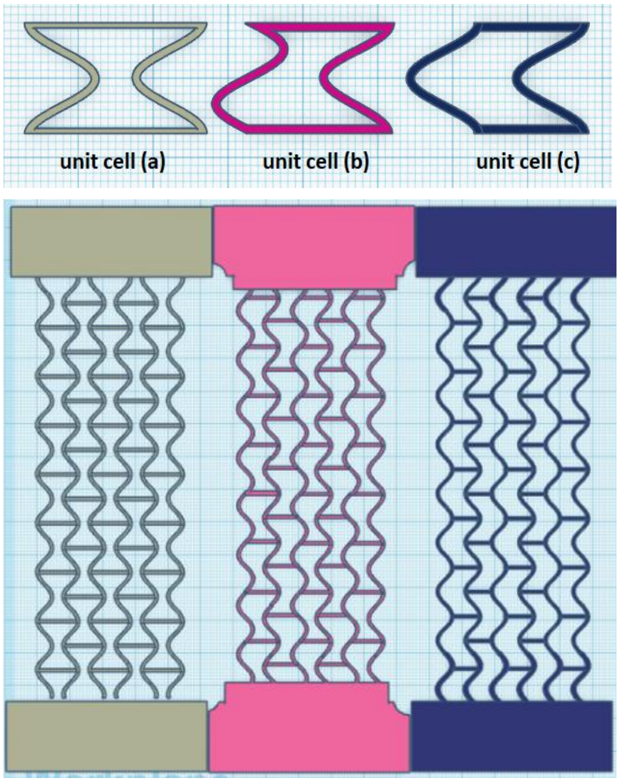
Keywords: Auxetic metamaterials, 3D printing, Negative Poisson's Ratio

Introduction

Mechanical metamaterials are engineered structures that possess unusual mechanical properties and functionalities. The unusual properties include the extraordinary values of familiar mechanical parameters, such as density, Poisson's ratio, and compressibility [1]. The exotic functionalities include pattern and shape transformations in response to mechanical forces, unidirectional guiding of motion and waves, and reprogrammable stiffness of dissipation [2]. Materials and structures with negative Poisson's ratio exhibit uncommon mechanical properties that materials either expand or contract in all directions when a force is applied. Resulting from this uncommon behavior, many desired properties are discovered. Auxetic materials have potential applications in the fields of military, biomedical, aerospace, and textiles. However, there are a limited structures in current literature, which possess negative value of Poisson's ratio, such as re-entrant structure [3], chiral structure, and rigid rotating structure [4]. In addition, there are a few general analytical methods to analyze the relationship of Poisson's ratio, the parameters of geometry, and base material constants. In this study, we designed a group of 3D modelling of unit cell structures with design software. The specimen of the structures based on the units cells were fabricated using 3D printer. Mechanical properties of these structures were analyzed by finite element methods, COMSOL 5.4, Structural Mechanics Module. The Poisson's ratios of the structures were measeured by Instron machine. Furthermore, one model of mechanical properties of these structures was created to estimate the Poisson's ratio of these structures (the details to be published in the other paper). By the comparison of the analytical values of the Poisson ratio with the analytical values from the model, they are found to be in agreement with each other. In particular, the Poisson ratios of the structures are increasing from -2.8 to -0.19 as the phase difference decreasing from π to zero. The insights pave the way for modeling and fabrication of auxetic metamaterials with tunable Poisson's ratio.

Design, Fabricating and Testing

The three two-dimensional cellular structures were designed with TinkerCad and Matlab software. The structures (a), (b), (c) and their unit cells are shown in Fig.1. The shapes of the unit cells are constructed with two straight lines and two curved lines. The sizes of the unit cells are height 11 mm, the width 9 mm, the depth 6 mm, and the thickness 0.5 mm. The two curved lines in each unit cell are sine curve



(a) (b) (c)

Figure 1. Images of a group of two-dimensional cellular materials and their unit cells.

with the attitude of 3.5/2 mm, and the period of 11 mm. The geometries of the unit cells differ in terms of the phase shift of the two sine curves in each unit cell in the vertical direction. In the structure (a), the phase shift of the two sine curves in the unit cell in the vertical direction is π. In the structure (b), the phase shift is π/2 and in the structure (c), the phase shift is zero. The sizes of the structure (a), (b), and (c) are 15 cm X 4 cm with depth 6 mm, respectively.

Matlab was used to draw the sine curves in the unit cells and TinkerCad 3D software was applied to design the structures in 3D modeling. MakerBot Replicator Z18 3D printer was implemented to fabricate the structures with PLA filament. The mechanical and physical properties of the PLA filament (Polylactic Acid) are listed in Table 1. The printed specimens, structures (a), (b), and (c), are shown in Fig.2. Instron 5969 was used to measure the Poisson's ratio of the structures displayed in Fig.3. When bending out of plane, the sample of the structure (a) showed synclastic curvature shape.

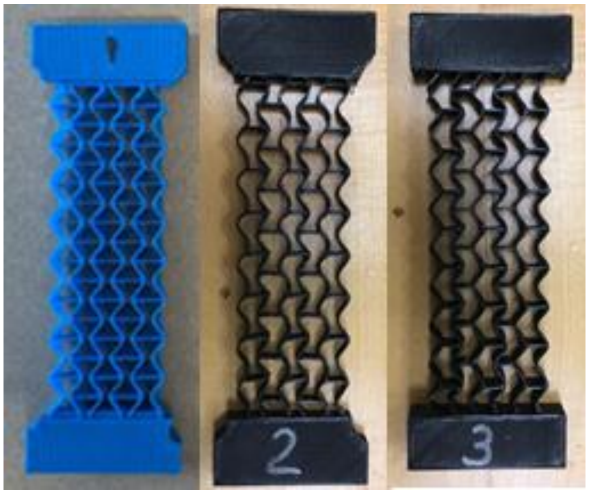


Figure 2. Specimens of a group of two-dimensional cellular materials fabricated by 3D printer

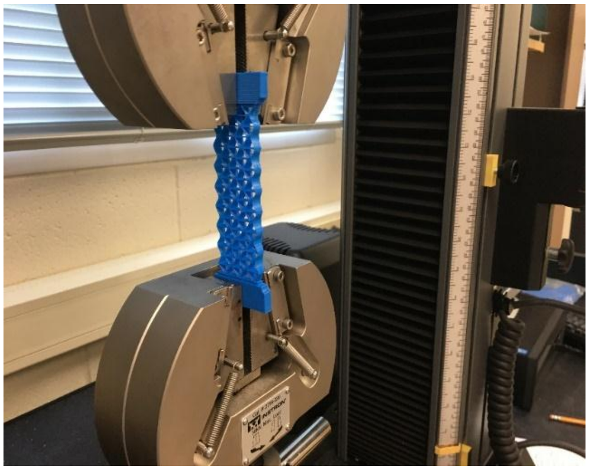


Figure 3. Tensile Testing with Instron machine 5969

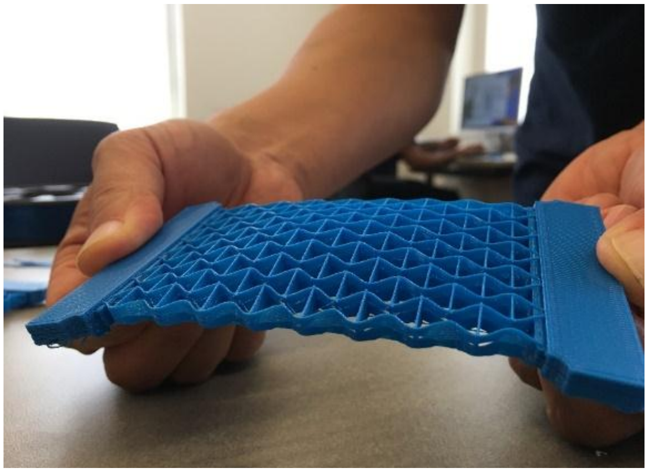


Figure 4. Demonstration of synclastic curvature shape when out-of-plane bending

It indicates experimentally that the sample has negative Poisson's ratio, as shown in Fig.4. Table 1 shows the mechanical and physical properties of PLA filament (Polylactic Acid).

Table 1 Mechanical and Physical Properties of PLA filament (Polylactic Acid)

Mechanical and Physical Properties of PLA filament (Polylactic Acid)	
Mechanical Properties	Physical Properties
Tensile Strength 60 Mpa	Density 1.24 g/cm^3
Young's Modulus 3 GPa	Melting Point 160-180 ^{o}C
Elongation at Break 5-10%	Glass Transition Temperature 55-60 ^{o}C
Poisson's ratio 0.37	

Table 2 Experimental Values of the Poisson's ratio of the Three Structures (a), (b), and (c).

Experimental Values of Poisson's Ratio of the Three Structures			
	Structure (a)	Structure (b)	Structure (c)
Poisson's Ratio	-2.85	-0.85	-0.19

The table 2 displays the experimental values of the Poisson's ratio of the three structures (a), (b), and (c), increasing from -0.28 to -0.19 as the phase difference decreasing from π to zero. The values of the Poisson's ratio were measured using Instron 5969. In the measuring process, mount the specimen between the clamps of Instron machine, stretch out the specimen one millimeter each time and measure the length and the width of the extended specimen several times in different positions. In the elastic deformation region of the specimen, (the elongation of the sample is less than 4 millimeters), the value of the Poisson's ratio was calculated as the negative average values of the transverse strain to axial strain.

Simulation and Calculation

Structural Mechanics Module, COMSOL 5.4 was applied to the unit cell (a) and the structure (a) to simulate the behavior of the structure under an axial load. In simulation, one side of the structures is fixed and the gradually increasing forces are applied to the other side of samples. The deformations and stress distribution of the structure (a) and its unit cell (a) are displayed in Fig.5. The deformation the unit cell (a) demonstrate the obvious extension in the center part of the unit cell (a). This proves the negative Poisson's ratio of the unit cell (a). The deformations of structure (a) also shows auxetic effects.

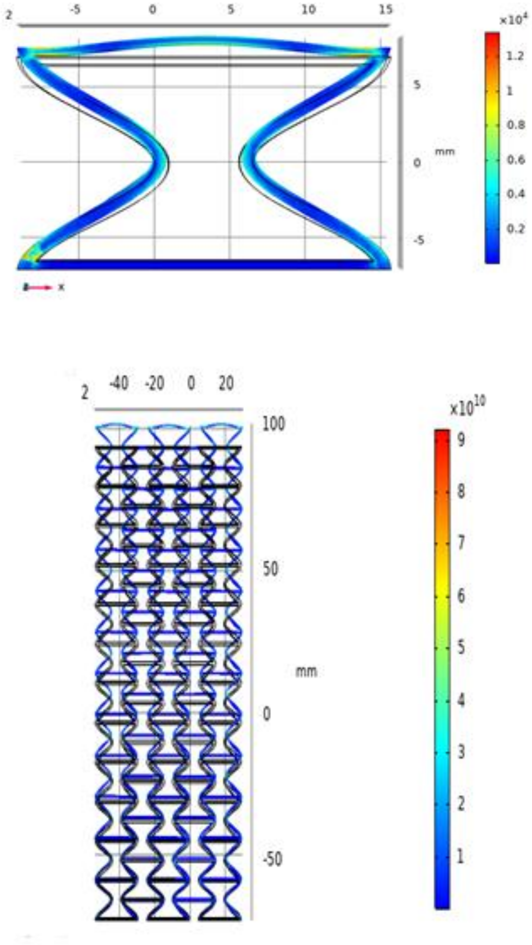


Figure 5. Simulation of structure (a) and its unit cell by Structural Mechanics Module, COMSOL

In addition, one model was created to calculate the Poisson's ratios of the structures and the results shown in Table 3. They share the same trend as the measured Poisson's ratio, increasing from -2.95 to zero as the phase differences decreasing from π to zero. We noted that I.G.Master and K.E.Evans and F.K.Abd-Sayed, etc. methods in the references [5] and [6] were assumed that the sides of cellular materials are linear elastic beams. We used a generalized model to deal with the curved beams in unit cells [to be published].

Table 3 The Analytical Values of the Poisson's Ratio of the Three Structures (a), (b), and (c).

Analytical Values of Poisson's Ratio of the Three Structures			
	Structure (a)	Structure (b)	Structure (c)
Poisson's Ratio	-2.95	-0.96	0

Results

In this study, a group of new auxetic structures was designed and modeled using 3D modeling software. The designs were then fabricated using a 3D printer and the Poisson's ratio of the specimens was measured. The measured values of Poison's ratio ranged from -2.8 to -0.19, indicating that the structures (a) and (b) are auxetics and the Poisson's ratio of the structure (c) is close to zero. The values of negative Poisson's ratio are increasing to zero as the phase difference in the structures decreasing from π to zero. In addition, the results were compared with one analytical model (to be published), and the values of Poisson's ratio were found to be consistent with the prediction of the model, increasing from -2.95 to 0 as the phase shift decreasing from π to zero. Furthermore, COMSOL simulations were performed on the structures, and the results displayed auxetic effects as well.

Conclusions

The results of this work demonstrate the successful design and fabrication of a group of auxetic structures using 3D modeling and printing techniques. The measured values of Poisson's ratio are increasing from -2.8 to -0.19 as the phase differences in the structures decreasing from pi to zero. This indicates that the group of structures exhibit auxetic effects, and COMSOL simulations confirm these results. Moreover, the good agreement between the experimental and analytical results suggests the designed structures are reliable and accurate. These findings have important implications for the development of new materials and structures with unique mechanical properties, which have applications in fields such as aerospace, medicine, and engineering. Overall, this study contributes to the growing body of research on auxetic materials and provides a foundation for future studies in this area.

Acknowledgement

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References

1. Xian Cheng, Yi Zhang, etc, Design and Mechanical characteristics of auxetic metamaterials with tunable stiffness, International Journal of Mechanical Sciences, Volume 223, I June 2022, 107286.
2. Bertoldi, K., Vitelli, V., Christensen, J. *et al.* Flexible mechanical metamaterials. *Nat Rev Mater* **2**, 17066 (2017).
3. Xiangwen Zhang and Deqing Yang, Mechanical Properties of Auxetic Cellular Material Consisting of Re-Entrant Hexagonal Honeycombs, Materials (Basel), 2016 Nov; 9(11):900, Published online 2016 Nov 7.
4. H.M.A.Kolken, A.A.Zadpoor, Auxetic Mechanical Metamaterials, RSC Adv,2017,7,5111-5129.
5. I.G.Maters & K.E. Evans, Models for the elastic deformation of honeycombs, Composite Structures 35 (1996) 403-422.
6. F.K.Abd El-sayed, R.Jones and I.W.Burgers, A theoretical approach to the deformation of honeycomb based composite materials, Composites, October,1979.