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Mechanical metamaterials with 3D compliant porous structures

Kwangwon Kim [a], Jaehyung Ju [b,*]

[a] School of Aerospace and Mechanical Engineering, Korea Aerospace University Goyang, Gyeonggi 412-791, Republic of Korea
[b] Department of Mechanical and Energy Engineering, University of North Texas, Denton, TX 76203-5017, USA

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ABSTRACT

We propose compliant cellular material (CCM), a mechanical metamaterial, with compliant porous structure (CPS) generated from a modified hexagonal topology. The objective of this study is to explore the synthesis of three-dimensional (3D) CCMs with CPSes and to understand the mechanical behaviors of CCMs. An orthotropic constitutive model of CCMs is constructed using the strain energy method, which uses the deformation of hinges around holes and rotation of links. Nonlinear behavior of a finite element (FE) based simulation is conducted to validate the analytical model. The moduli and yield strains of the 3D CCMs with an aluminum alloy are about 1.2 GPa and 0.4% in the longitudinal direction and about 0.08 MPa and 30% in the lateral direction. The CCMs have extremely high positive and negative Poisson's ratios ($\nu_{xy}^{*} \sim \pm 30$) due to the large rotation of the link member in the transverse direction caused by an input displacement in the longitudinal direction. This paper demonstrates that compliant mesostructures can be used for next generation's mechanical metamaterials design in tailoring mechanical properties such as modulus, strength, yield strain, and Poisson's ratios.

1. Introduction

Mechanical metamaterials are engineered materials with properties not observed in nature. Their properties are mainly derived by their geometrical structure, rather than their chemical composition. The unconventional properties include negative Poisson's ratios [1,2], negative thermal expansion [3], etc. The unconventional properties have been explored with granular [4] and tensegrity periodic lattices [5–7], and polyhedral cellular structures [8–10].

Especially, mechanical metamaterials with negative Poisson's ratios were explored by using mechanical instability of lattice structures [11] and by decoupling structure and mechanism in cellular materials [12]. We investigated two-dimensional (2D) hexagonal honeycombs and synthesized 2D mechanical metamaterials with compliant porous structures (CPSes) having extremely high positive (∼50) and negative (∼−50) Poisson's ratios by combining a flexure-hinge based compliant mechanism of mesostructures [2,13,14]. In addition to the extremely high positive and negative Poisson's ratios, other mechanical properties, e.g., modulus, yield strength, and yield strain, can be tailored if the geometry of the holes and slits is properly arranged. For example, a mechanical metamaterial with a CPS made of an aluminum alloy can be tailored to have a high yield strain (∼25%) with a low modulus (∼25 MPa), which are close values in the mechanical properties of elastomers [13,14].

In this study, we propose three-dimensional (3D) CPSes to design compliant cellular materials (CCMs), mechanical metamaterials, with extremely high positive and negative Poisson's ratios while having a high yield strain (Fig. 1). The CCMs consisting of cubic holes and slits in Fig. 1 appear to look similar to each other, yet they generate totally different mechanical properties: the macroscopic mechanical properties of CCMs vary with a geometric arrangement of holes and slits. For example, one of the CCMs in Fig. 1 has an extremely high negative Poisson's ratio. The other CCM in Fig. 1 has an extremely high positive Poisson's ratio. The readers may start noticing how those CCMs in Fig. 1 have different mechanical properties while reading this paper.

The hypothesis set in this paper is that the arrangement of holes and slits can customize mechanical properties – namely, modulus, strength, yield strain, and Poisson's ratio. Nonlinear constitutive equations of mechanical metamaterials with CPSes will be developed including contact between slit surfaces while generating direction dependent mechanical properties by properly arranging cell topologies in the direction targeted to the design. Therefore, the design of materials with CPS in this study will pave the road to develop functional materials with customized anisotropic properties.

* Corresponding author. Tel.: +1 940 565 2118; fax: +1 940 369 8675.
E-mail address: jaehyung.ju@unt.edu (J. Ju).

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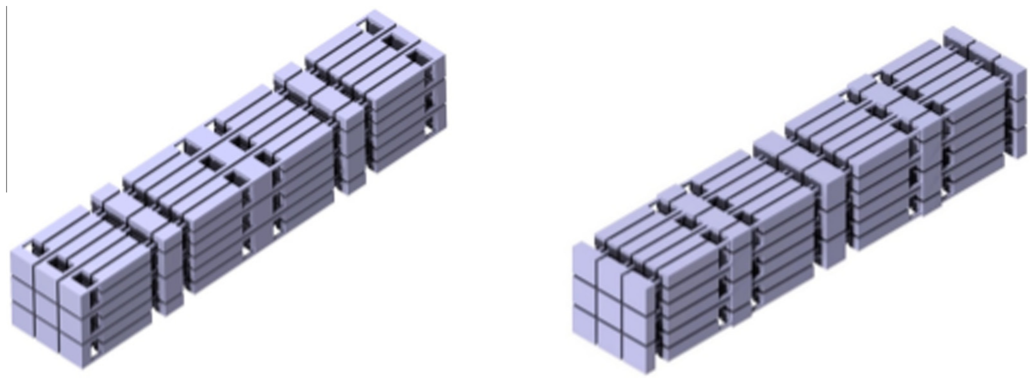

Fig. 1. An example of CCMs with CPSes.

We demonstrate that the mesostructures designed with metals, e.g., an aluminum alloy, have properties of soft materials in modulus ($E \sim 1GPa$) and yield strain ($\varepsilon_Y^* \sim 30\%$). Analytical models on constitutive equations of mechanical metamaterials with CPSes are constructed while observing deformation of CPSes. The constitutive models of the mechanical metamaterials are validated with a finite element based (FE) simulation.

2. Synthesis of 3D compliant cellular materials with compliant porous structures

Mechanical properties of cellular solids are controlled by both constituent materials and cell topologies. The cell topologies can function as either a structure or a mechanism [15–18]. If a cellular solid is used for a structural purpose, it should be stiff. On the other hand, if a cellular solid is used for a mechanism purpose, it should be flexible. A combination of both purposes is also possible depending on the selection and design of cell topologies. Ju et al. designed cellular materials to tailor moduli and strengths (or the yield strains) by modifying hexagonal honeycombs' cell geometry, including the cell wall thickness, the vertical and inclined cell lengths, and the cell angle [19–22]. They found that each cell strut has different functions – structures and mechanisms.

The behavior of hexagonal structures was also investigated from a different view. Murakoa and Sanada suggested a displacement amplifier using a honeycomb link mechanism [23]. They designed a plate having periodic patterns of two holes and a slit, in which rigid links and elastic hinges were defined. Technically, this is a flexure hinge based compliant mechanism [24,25]. From the expansion mechanism of a flexure in the transverse direction for longitudinal loading, which showed a negative Poisson's ratio (NPR), they found its similarity on the deformation of the re-entrant auxetic hexagonal honeycomb. Kim et al. introduced a synthesis of 2D compliant porous structures (CPSes) from regular and re-entrant auxetic honeycombs [13,14] to design compliant cellular materials (CCMs) with high positive and negative Poisson's ratios. Inspired by the synthesis of 2D CPSes, we further explore 3D CPSes by extending the concept of 2D CPSes to the deformation in the out-of-plane direction.

A 3D re-entrant auxetic compliant cellular structure, transversely expanded for a longitudinal load, is synthesized such that a re-entrant hexagonal honeycomb is populated through rotation by 90° with respect to the longitudinal direction (the x-axis in Fig. 2). Considering the location of the elastic hinges and rigid links, the configuration is modified followed by the generation of a 3D re-entrant auxetic CPS, the unit cell of a CCM (Fig. 2).

Similarly, a regular 3D CPS is synthesized such that a hexagonal cellular structure is populated through rotation by 90° with respect

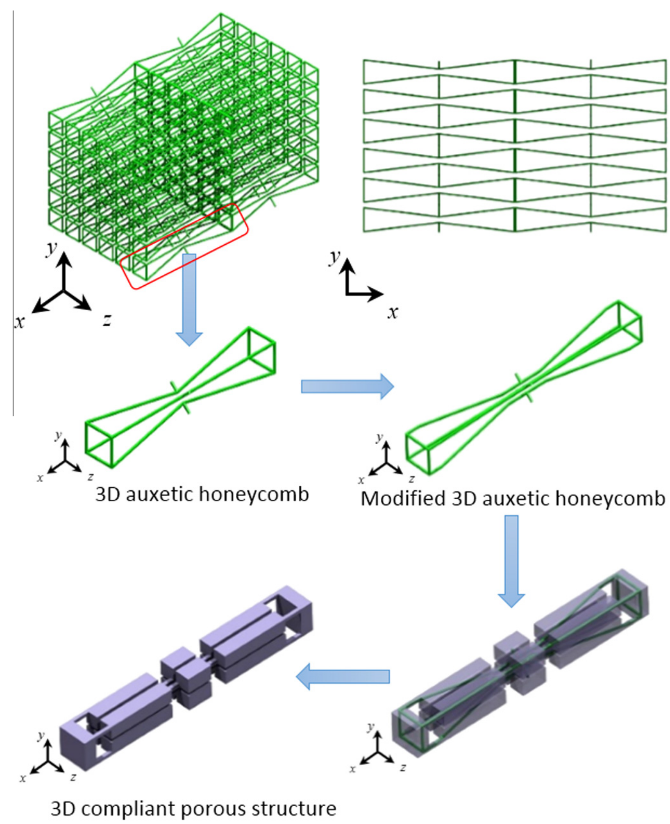

Fig. 2. Synthesis of a 3D auxetic compliant porous structure (CPS-I).

to the longitudinal coordinate (the x–axis in Fig. 3). Again, the configuration of the 3D regular hexagonal structure is modified for a 3D regular CPS considering the location of the elastic hinges and rigid links (Fig. 3). It is worthwhile to note that the regular 3D CPS generated in Fig. 3 shrinks in the transverse direction for a longitudinal load in the x-direction.

3. Constitutive modeling of compliant mesostructures

We build a constitutive model of 3D CCMs while deriving effective moduli and strengths using the stain energy method. A CPS, a unit cell of CCM, is used to construct the constitutive model of CCM with consideration given to periodic boundary conditions.

Fig. 4 shows CPS-I and CPS-II, constructed with flexure hinges using a hexagonal link mechanism based on the re-entrant and regular hexagonal cellular geometries, respectively. The CPSes