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Compliant cellular materials with compliant porous structures: A mechanism based materials design

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ABSTRACT

Cellular materials have two important properties: structures and mechanisms. These properties have important applications in materials design; in particular, they are used to determine the modulus and yield strain. The objective of this study is to gain a better understanding of these two properties and to explore the synthesis of compliant cellular materials (CCMs) with compliant porous structures (CPSes) generated from modified hexagonal honeycombs. An in-plane constitutive CCM model is constructed using the strain energy method, which uses the deformation of hinges around holes and the rotation of links. A finite element (FE) based simulation is conducted to validate the analytical model. The moduli and yield strains of the CCMs with an aluminum alloy are about 5.8 GPa and 0.57% in one direction and about 2.9 MPa and 20% in the other direction. CCMs have extremely high positive and negative Poisson's ratios ($\nu^*_{xy} \sim \pm 40$) due to the large rotation of the link member in the transverse direction caused by an input displacement in the longitudinal direction. CCMs also show higher moduli after contact of slit edges at the center region of the CPSes. The synthesized CPSes can also be used to design a new CCM with a Poisson's ratio of zero using a puzzle-piece CPS assembly. This paper demonstrates that compliant mesostructures can be used for next generation materials design in tailoring mechanical properties such as moduli, strength, strain, and Poisson's ratios. The proposed mesostructures can also be easily manufactured using a conventional cutting method.

1. Introduction

Cellular materials, often called lattice materials, are made up of an interconnected network of solid struts or plates and have complex architectures with voids (Gibson and Ashby, 1997) . They include two-dimensional (2D) honeycombs, three-dimensional (3D) lattice truss structures, randomly structured foams, and porous materials, and they have received a lot of attention due to their high stiffness to weight ratio. Despite numerous studies on the mechanical properties of cellular materials, there is little understanding of the function of each individual strut for a given deformation mode, especially for a large deformation. This lacuna in understanding is keeping cellular materials from widespread use. By discerning the functions of the individual struts of cellular materials, the overall stiffness (yield strength) and flexibility (yield strain) of cellular materials can be tailored appropriately.

Cellular materials with triangular topologies are known to have high macroscopic stiffness as well as the stretching of the dominant properties of the cell members (Deshpande et al., 2001; Wicks and Guest, 2004; Wang and McDowell, 2004; Hutchinson and Fleck, 2006). On the other hand, cellular materials in which the dominant topologies are bent, such as hexagonal cells, are known to have low macroscopic stiffness and high flexibility (Deshpande et al., 2001; Wicks and Guest, 2004; Wang and McDowell, 2004; Hutchinson and Fleck, 2006). In particular, re-entrant hexagonal honeycombs have negative Poisson's ratios and high flexibility with respect to in-plane shear due to the large bending of vertical cell struts associated with their re-entrant shape (Ju et al., 2012a,b; Ju and Summers, 2011a,b; Berglind et al., 2010; Shankar et al., 2010; Heo et al., 2013). Observing the deformation of hexagonal topologies, some struts are primarily used for a structural purpose (stiffness), and some are mainly used for a mechanism purpose (strain). For example, the inclined cell struts of hexagonal honeycombs function as a mechanism, and the vertical struts function as a structure in axial loading (Ju et al., 2012b). On the other hand, the vertical cell struts of the hexagonal honeycombs function as a mechanism, and the inclined cell struts function as a structure in shear loading (Ju et al., 2012b). The direction dependent mechanical properties of cellular solids

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can also be engineered by properly arranging cell topologies in the desired direction. Therefore, the design of cellular materials provides an opportunity to develop functional materials with customized anisotropic properties.

A functional similarity with the mechanism of the struts of cell topologies can be found in a flexure-hinge based compliant mechanism. A flexure-hinge based compliant mechanism is a single-piece flexible structure that delivers a desired force and motion by undergoing elastic deformation as opposed to having rigid body joints. Compliant mechanisms have received a lot of attention because the hingeless one-piece device has many advantages over linked mechanisms; they experience less friction and wear, they do not require lubrication, and they are easier to manufacture and maintain compared to multiple piece assemblies (Paros and Weisbord, 1965; Howell, 2001; Lobontiu et al., 2002; Lobontiu and Garcia, 2003). Various compliant mechanism synthesis methods have been suggested over the past decade and successfully applied to the design of micro-electro mechanical systems (MEMS), motion amplifiers, and compliant grippers to maximize output displacements (Saxena and Ananthasuresh, 2001; Muraoka and Sanada, 2010; Tanaka and Shbutani, 2009).

Efforts have been made to implement compliant mechanisms in the design of flexible cellular solids with negative Poisson's ratios (Evans and Caddock, 1999; Saxena and Annthasuresh, 2000; Larsen et al., 1997; Mehta et al., 2009; Cirone et al., 2012). Flexible mesostructures were identified using a topology optimization method (Saxena and Annthasuresh, 2000). Using the similarity of re-entrant honeycombs and compliant mechanisms, a new periodic structure was identified (Mehta et al., 2009). A contact aided compliant mechanism was also applied to improve the flexibility of mesostructures (Cirone et al., 2012). To enhance the flexibility of the re-entrant hexagonal honeycombs, curved walls were also used (Shankar et al., 2010; Cirone et al., 2012). The results of these efforts are applicable to designing materials – with a focus on the moduli, yield strength, and yield strain – if the mesostructures are used to tailor macroscopic properties.

Muraoka and Sanada proposed a displacement amplifier using porous geometries with a re-entrant honeycomb mechanism (Muraoka and Sanada, 2010). We synthesized a compliant porous structure with rectangular holes and slits using the re-entrant honeycomb based displacement amplifier to design a compliant cellular material (CCM). We then developed a constitutive model and conducted parametric studies with porous geometries (Kim et al., 2013). Inspired by our previous work on the design of a CCM with a high negative Poisson's ratio (Kim et al., 2013), we may extend our search to CCMs with high positive and negative Poisson's ratios.

In this paper, we propose a new materials design with porous geometry using compliant mechanisms, as shown in Fig. 1. The CCMs consist of circular holes and slits. The macroscopic mechanical properties vary depending on the arrangement of holes and slits. For example, one of the CCMs has an extremely high negative Poisson's ratio. The other has an extremely high positive Poisson's ratio. By arranging the porous geometries, we can customize the mechanical properties – namely, the moduli and the strengths.

When designing compliant cellular solids, two design criteria should be satisfied: (i) they should be flexible enough to satisfy the kinematic requirements, and (ii) they should be stiff enough to support external loads. In this paper, we investigate the in-plane macroscopic properties of mesostructures – the moduli, yield strengths, yield strains, and Poisson's ratios – while implementing compliment mechanisms to design cellular materials. Using analytical and numerical methods, the effective properties of the mesostructures are obtained. A finite element based (FE) simulation followed to validate the effective properties. The designed mesostructures have a Poisson's ratio of down to −82 and a modulus of up to 2 GPa, a strength of up to 9.3 MPa, and a yield strain of up to 28%.

2. Synthesis of compliant cellular materials (CCMs) with compliant porous structures (CPSes)

The 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. If a cellular solid is used for a structural purpose, it should be stiff. 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 in which the moduli and strengths (or yield strains) could be tailored by modifying the geometry of the hexagonal honeycombs; they modified the cell wall thickness, the vertical and inclined cell lengths, and the cell angle (Ju et al., 2012a,b; Ju and Summers, 2011a,b; Berglind et al., 2010; Shankar et al., 2010; Heo et al., 2013). They found that each cell strut has different functions–structures and mechanisms. For example, the vertical cells of hexagonal honeycombs contribute to the overall flexibility (mechanism-purpose) in shear. On the other hand, the inclined struts contribute to the overall stiffness (structural purpose) in shear (Ju et al., 2012b).

The behavior of hexagonal structures was also investigated from a different view. Murakoa and Sanada suggested a displacement amplifier using a honeycomb link mechanism, as shown in Fig. 2 (Muraoka and Sanada, 2010). They designed and tested a plate with periodic patterns of rectangular holes and a slit, in which rigid links and elastic hinges were defined. Basically, they created a flexure hinge based compliant mechanism. After investigating the expansion of a flexure in the transverse direction for longitudinal loading, which showed a negative Poisson's ratio, they found its similarity on the deformation of the re-entrant auxetic hexagonal honeycomb (Muraoka and Sanada, 2010). Considering that the location of the holes functions as an elastic hinge, the unit-cell can be modified to have additional struts in the x-direction to the conventional re-entrant hexagonal honeycomb; this creates a hexagonal bow-tie shape (Fig. 2). The modified configuration still has an NPR. Kim et al. investigated the constitutive behaviors of the CCM with a negative Poisson's ratio and conducted parametric studies on the mechanical properties with varying geometries (Kim et al., 2013).

CCM design can be extended to other cellular geometries. For example, both regular and re-entrant hexagonal topologies can be designed with CPS-I and CPS-II, which are shown in Fig. 2.

In an effort to explore a high positive Poisson's ratio of cellular structures, one can design a compliant cellular structure with a positive cell angle, which is similar to the regular hexagonal topologies (Fig. 2(a)). In order to implement the honeycomb link

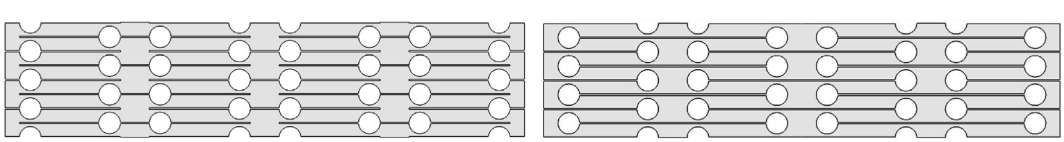

Fig. 1. An example of CCMs with CPSes.