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Large deformations of soft metamaterials fabricated by 3D printing

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A B S T R A C T

The aim of this paper is to explore large-deformation responses of hyper-elastic porous metamaterials made by three-dimensional (3D) printing technology. They are designed as a repeating arrangement of unit-cells in parallelogram and hexagonal shapes. Fused deposition modeling is implemented to fabricate metamaterial structures from soft poly-lactic acid. 3D printed metamaterials are tested under in-plane tension-compression in axial and transverse directions. Experiments reveal that unit-cell shape, direction, type and magnitude of mechanical loading have significant effects on metamaterial anisotropic response and its instability characteristics. To replicate experimental observations, a finite element solution is developed adopting the hyper-elastic Mooney-Rivlin constitutive equations and non-linear Green-Lagrange strains. Iterative Newton-Raphson approach is implemented to solve governing equations with material-geometric non-linearities. The accuracy of the computational tool is verified by capturing main features observed in the experiments. It is found that modeling of hyper-elasticity and large strain is essential to accurately predict non-linear responses of the 3D printed soft metamaterials. Due to the absence of similar results in the specialized literature, this paper is likely to advance the state of the art of metamaterial printing, and provide pertinent results that are instrumental in the design of hyper-elastic metamaterial structures and infill patterns for printing purpose.

1. Introduction

Metamaterials are appearing at the frontier of structural engineering owing to their unique mechanical features and extraordinarily properties originated from their structures rather than their constituents [1]. Metamaterials comprise a repeating arrangement of unit-cells with tunable behaviors. Significant examples of metamaterials are pentamodes with vanishing shear modulus [2], mono/multi-stable materials [3,4] and auxetic with negative Poisson's ratio [5]. Recently, three-dimensional (3D) printing technology [6,7] has gained significant attention for processing metamaterials. It has provided flexibility in creating metamaterials with complex structures and shapes, fast and with low cost. 3D printing procedure relies on CAD data and comprises depositing material in consecutive layers. It is worthy to mention that most of 3D printers fill the interior of an object by some infill patterns that are similar to porous metamaterials [8,9]. Although there is a variety of different infills, unit-cells with parallelogram, rectangular and hexagonal shapes are mostly used.

Some researchers have been conducted to explore material properties of metamaterials experimentally and theoretically. For instance, Scarpa et al. [5] calculated in-plane Poisson's ratio and Young's moduli of re-entrant cell auxetic honeycombs for different geometric layout combinations by means of finite element (FE) simulations and experiments. Florijn et al. [10] created metamaterials whose response to uniaxial compression can be tuned by lateral confinement, allowing monotonic, non-monotonic, and hysteretic feature. Using PolyJet 3D printing system, Wang et al. [11] fabricated auxetic metamaterials with elastic joints and stiff beams/walls without buckling issue. They investigated the influence of material selections and stiff material fraction on Young's Modulus, Poisson's ratio, and volume reduction by experiments and FE simulations. Mousanezhad et al. [12] investigated small and large deformation in-plane elastic response of auxetic spiderweb honeycombs fabricated by PolyJet 3D printing under compression through analytical modeling, numerical simulation, and experiments. They also examined the behavior of auxetic metamaterials with structural hierarchy by experimental and computational studies [13]. The results showed that hierarchy-dependent buckling introduced at early steps of deformation decreased the Poisson's ratio as the structure was uniaxially compressed leading to auxeticity in next deformation steps. Ren et al. [14] experimentally and numerically investigated the loss of auxetic feature of buckling-induced metallic metamaterials under compression to understand the mechanism behind this phenomenon. They found that the auxetic performance can be tuned by the microstructure geometry while strength and stiffness can be tuned through

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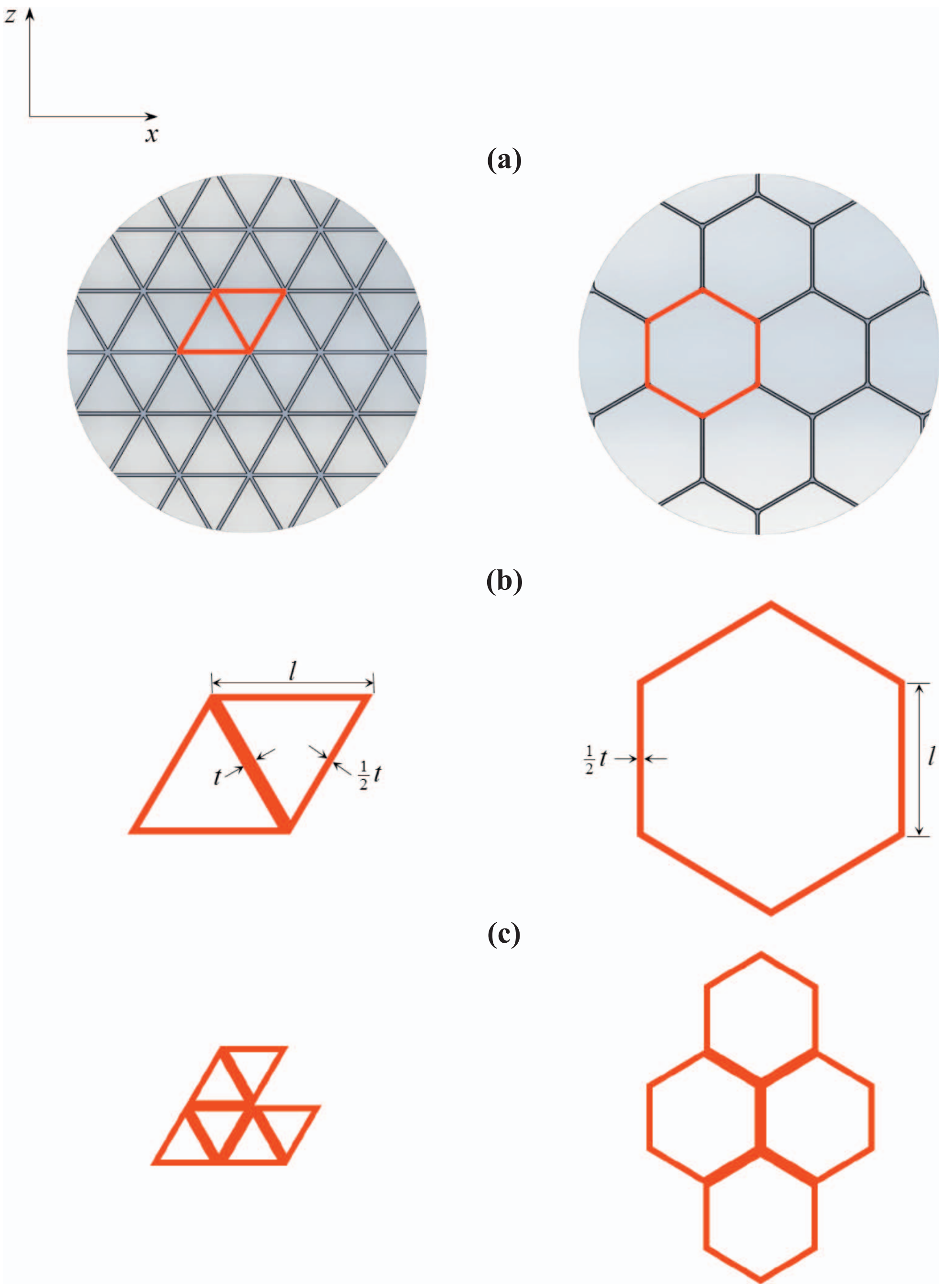

Fig. 1. Metamaterials: (a) schematic sketch; (b) geometries and dimensions of unit-cells; (c) periodicity.

plasticity of the main material. Hedayati et al. [15] derived analytical relationships for elastic modulus, yield stress, buckling stress and Poisson's ratio of 3D printed octagonal honeycombs using linear beam theories of Euler-Bernoulli and Timoshenko. They compared the results from analytical solutions with experiments and those computed by ANSYS FE code. They found that there is a good agreement between the results from Timoshenko beam theory, FE and experiments. In another study [16], they investigated influence of assuming exact apparent density rather than approximate density on the elastic modulus, yield stress and Poisson's ratio. They validated the accuracy of the proposed model by comparing predicted mechanical properties with experimental data. Tang and Yin [17] explored the designs for obtaining extreme stretchability and/or compressibility in auxetic metamaterials by combining line cuts, cut-outs, and hierarchical structures. They verified their results through experiments, geometrical modeling, and FE simulation. Using 3D printing technology, Fu et al. [18] fabricated a 3D auxetic metamaterial on the basis of 2D re-entrant honeycombs and tested it numerically and experimentally. The results showed that the 3D structure can gain a negative Poisson's ratio in two principal orthogonal directions under compression in other principal axis. Recently, Naddeo et al. [19] presented an algorithmic procedure to replace continuous mass of convex solids with a cancellous bone-inspired lattice structure showing curved beams oriented according to the external forces, sharing with its border and boundary conditions. They selected a cubic representative volume element (RVE) and performed FE sensitivity analysis by implementing periodic boundary conditions to investigate structural mechanical behaviors. The computational results were compared with experimental data of compression tests on polymeric 3D printed cubic specimens that confirmed validity of the beam element-based lattice structure.

The literature survey reveals that, most of research works have been focused on the behaviors of polymeric metamaterials under either