Designing pattern-transforming metamaterials for soft actuators

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Soft actuators, compared to their hard counterparts, show advantages in safely interacting with human bodies and handling fragile objects, since they are composed of soft materials. Soft actuators are capable of programmable shape reconfiguration or locomotion in response to external stimuli, such as heat, chemicals, electrical fields, or light irradiation. The stimuli-responses of these soft materials are determined by their chemical composition. A general approach to achieving desirable stimuli-responsive properties is through precise chemical synthesis, which, however, takes tremendous efforts.

Metamaterials create a new dimension in designing stimuli-responses of soft materials through architectures. Metamaterials are materials with micro-architectures, which can give rise to advanced acoustic, optical or mechanical properties, difficult to achieve in homogeneous materials. The vast design space of metamaterials in both material constituents and micro-architectures significantly broadens the stimuli-responsive properties that can be achieved.

In this project, we design composite metamaterials composed of a soft elastomer and air. The elastomer has periodic holes filled with air (Fig. 1a). The holes are sealed under a low pressure, and an increase of the external air pressure can actuate the material. Under a critical external pressure, these metamaterials can buckle and undergo a pattern transformation, yielding a large transformation strain (Fig. 1c, d). More importantly, both the transformation strain and the critical pressure of buckling are open to design.

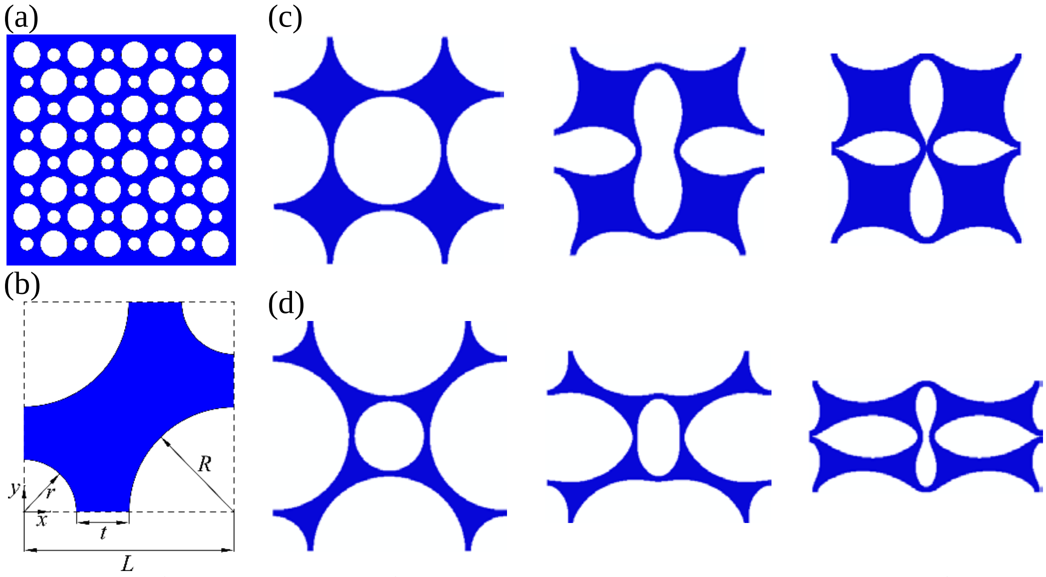

Fig. 1 Overview of the pattern-transforming metamaterials. (a) The schematic figure. (b) The smallest repeated unit cell. (c, d) The simulation results of the pattern transformation in the metamaterials as the external air pressure increases. When the metamaterial has alternating large and small holes (d), it shows an anisotropic pattern transformation, which is different from the isotropic transformation when all the holes have the same sizes (c).

We explore the design space of this pattern-transforming metamaterial, including the geometric parameters (Fig. 1b) such as the two radii R and r, the width of the slenderest wall t and lattice size L, and the material parameters such as the modulus of the elastomer and the pressure of the air when the holes are sealed. We investigate how the symmetry of the lattice affects the anisotropy of the metamaterial. We run finite element simulations for unit cells of the metamaterial, and compute the stress-strain relationship, the critical pressure of the buckling transformation, and the transformation strain. We also establish a simplified 1D model of the metamaterials to understand the mechanics of the metamaterials. Experimentally we fabricate the metamaterial by 3D printing, and characterize the pattern transformation.

We find that simply varying the lattice spacing and the size of the holes allows us to continuously tune both the critical external pressure of bucking and the transformation strain. Fig. 2a, b show the strains of the metamaterials versus the external and internal pressure difference. At a critical pressure difference, the slopes of the curves dramatically increase, which indicates the pattern transformation occurs. When the metamterial forms self-contact, the slopes become flat again. By varying the sizes of the holes R and r, we find that the width of the slenderest wall t is the key factor in determining the critical pressure (Fig. 2a, b), and the critical pressure increases with the width t. When the neighboring holes have the same size $R = r$, the strains ε_1 and ε_2 are always equal, and therefore the pattern transformation is isotropic. When the metamaterial contains alternating large and small holes, i.e. $R \neq r$, the transformation strains ε_1 and ε_2 bifurcate from each other after the pressure reaches the critical value, leading to an anisotropic pattern transformation. If we hold the lattice spacing and the size of the holes constant, the changing of the air pressure when the holes are sealed can further tune the transformation from being abrupt to being continuous over a broader external pressure range.

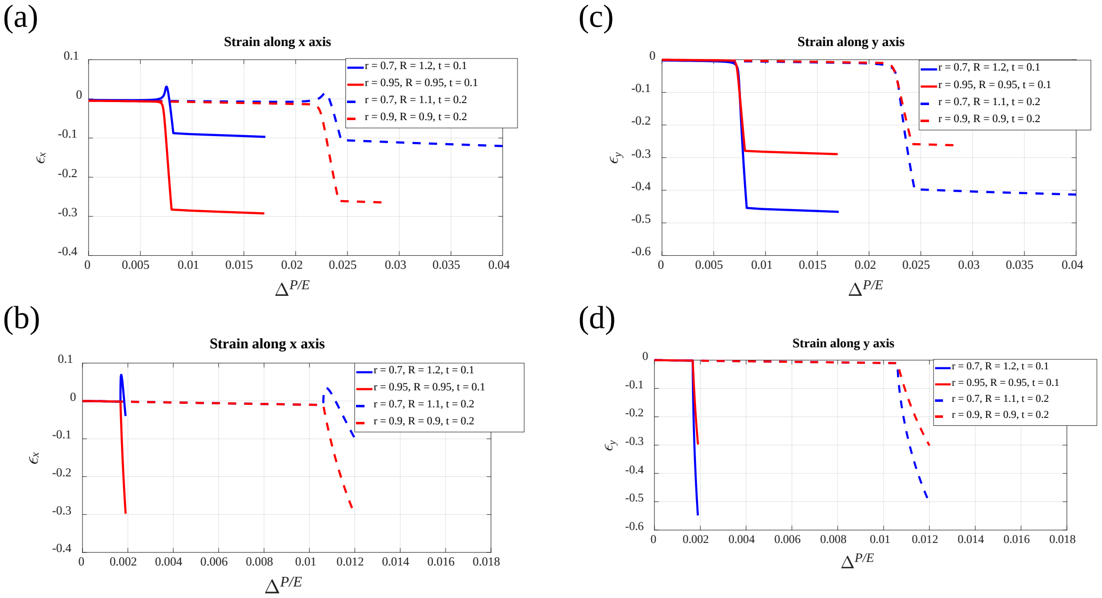

Fig. 2 Dependence of the strains on the external and internal pressure difference from the simulations (a, b) and the simplified model (c, d).

To qualitatively understand the mechanics of this metamaterial, a simplified 1D model is proposed. Since we note that the deformations of the metamaterial mainly occur in the slender regions, the metamaterials could be modeled as rigid rectangles connected by slender beams. The buckling of the beams determine the critical pressure for the initiation of the pattern transformation, and the post-buckling of the beams further determines the strain-pressure difference relations (Fig. 2c, d). The proposed simplified model can qualitatively capture almost all the results observed in the simulations.

Our work provides a new strategy for designing soft actuators by tuning the micro-architectures of metamaterials.