Extreme Mechanics Letters 20 (2018) 81–90

Contents lists available at ScienceDirect

Extreme Mechanics Letters

journal homepage: www.elsevier.com/locate/eml

Deformation and pattern transformation of porous soft solids under biaxial loading: Experiments and simulations

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ARTICLE INFO

Article history:
Received 26 December 2017
Received in revised form 20 January 2018
Accepted 20 January 2018
Available online 31 January 2018

Keywords:
Porous soft materials
Instability
Finite element analysis
Pattern transformation

ABSTRACT

In this work, we combine both experiments and numerical simulations to study the large deformation mechanics of two-dimensional patterned porous silicone rubber under biaxial loading, by focusing on the combined compressive and tensile loading. Particularly, we design a loading apparatus to impose the biaxial loading and fabricate patterned porous silicone rubbers through 3D printing. Although the pattern transformation with alternating elliptic voids has been observed under uniaxial compression before, our results show that the pattern transformation can be promoted by biaxial compression, while biaxial compression/tension can delay it. When the ratio between tension and compression is larger than a critical value, a new pattern transformation has been observed. In addition, if the imposed tension in one direction is larger than the compression in the other direction, the pattern transformation with alternating elliptic voids cannot occur. Biaxial loading provides new opportunities to fabricate the tunable devices and imprint complex patterns with soft solids.

1. Introduction

Cellular or porous solids, such as foams and honeycombs of polymeric materials and metals, have been widely used in many engineering applications. The relationship between the porous microstructure and macroscopic properties has been studied by many researchers and summarized in the book by Gibson and Ashby [1]. The cellular structure has been designed to satisfy different objectives such as high stiffness to weight, high strength to weight or high energy absorption. To satisfy these objectives, the materials are usually elastic–plastic or elastic-viscoplastic materials such as polycarbonate, polyester urethane and copper etc. For example, when polymeric honeycombs or open cell foams made by polycarbonate or polyester urethane under uniaxial or biaxial compression, the buckling of a member or a wall of the cellular structure can lead to localized deformation bands. The mechanical response of these cellular materials starts with a nearly linear elastic regime and terminates into a limit load followed by an extensive load plateau [2–7]. Thus, larger energy absorption can be achieved. The similar response has also been observed for metallic materials such as inconel 600 alloy, a nickel based super alloy [8] and copper [9]. Simultaneously, the material is damaged after the large deformation and cannot recover to its original shape.

To design the porous materials with exceptional properties, theoretical and numerical methods have been developed to predict their behaviors, especially for the microscopic and macroscopic instabilities. Schraad and Trantafyllidis [10] proposed a mathematical framework to address the influence of length scale on the macroscopic properties of microstructural nonlinearly elastic materials. The scale parameter is unambiguously defined as the ratio of the unit cell size to the overall size of the representative volume. In their following work, a general mathematical framework for micro and macro failure surfaces (instability) of microstructural solids is also presented, which is defined as the locus of first instability point found along radial loading paths through macroscopic strain space and the locus of point corresponding to the loss of ellipticity in the macroscopic (homogenized) moduli of the model [11]. Michel et al. [12] performed an in-depth study on the connections between microstructural instabilities and their macroscopic manifestations for porous polymers through the second-order homogenization technique. Recently, Combescure et al. [13] and Combescure and Elliott [14] employed the analytic group theory to study the honeycomb's bifurcation behavior under three different far-field loadings.

With the advancement of experimental techniques such as micro-fabrication, interference lithography, and thermodynamically driven self-assembly and 3D printing, it has created many new opportunities to design the materials with complex microstructures [15–18]. Based on these new techniques, new

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https://doi.org/10.1016/j.eml.2018.01.008
2352-4316/

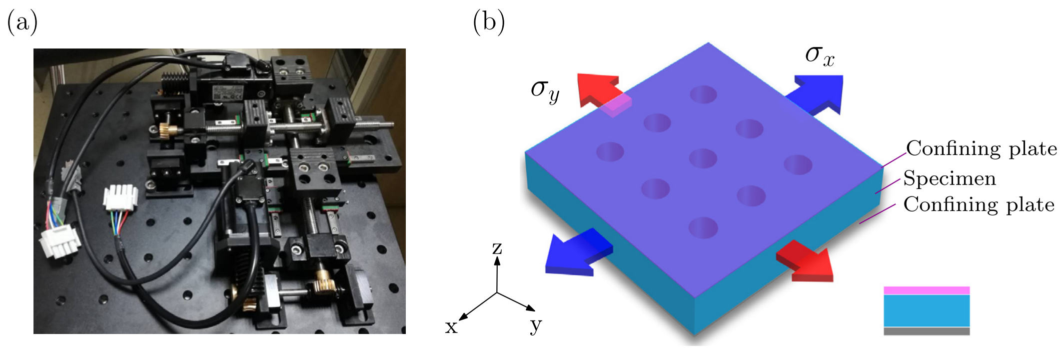

Fig. 1. (a) Photograph of the testing facility for biaxial loading. (b) Schematic of biaxial testing under plane strain condition. The specimen is confined between two close fitting 5-mm-thick transparent sheets (made by polymethyl methacrylate) to eliminate out-of-plane buckling.

research fields such as the flexible electronics are originated and show great potentials to be applied in biomedical engineering or health monitoring [19–22]. Although cellular structures provide the unique energy absorption opportunities and shows the great potential as aforementioned, it should be noted that the cellular structures can provide many other functions or attributes, which can be applied in these new fields. An example towards this goal is demonstrated in the experiments of Mullin et al. [23] and Michel et al. [12] in their unit cell analysis. They reported pattern transformation in porous polymers with periodic void structures under uniaxial compression. Pattern transformation is found to be a result of elastic instability with homogeneous deformation defined by the absence of localized deformation bands observed in more random cellular polymers. Therefore, instability in the form of pattern transformation opens a new avenue for fabrication of soft solids with tunable acoustic, electric and optical properties by designing a microstructure such that the material experiences pattern transformation under certain types of operational loading [24–29]. In these applications, the materials usually are required to respond fast to the mechanical stimulus and recover to their original configurations after the unloading, different from previous works aiming at high stiffness to weight, high strength to weight or high energy absorption.

In the most of above studies, the porous materials are set to be under uniaxial compression. Papka and Kyriakides [3,4] designed a new experimental facility to carry out the biaxial crushing of polycarbonate towards the goal to design porous materials with large energy absorption. Nevertheless, their facility is not easy to impose the combined compression/tension loading. The impact behavior of honeycombs under the combined compression and torsion has been studied by a commercial machine [30,31]. In this work, we aim to understand the pattern transformation under biaxial loading in porous silicone rubber through combined experiments and simulations, especially under combined tension/compression. The porous silicone rubber can experience the large deformation, respond to the mechanical loading fast and recover to its initial shape without any damage. As discussed in many previous works, pattern transformation usually has been realized under the uniaxial compression. We are curious whether pattern transformation occurs under biaxial loadings, especially when one axis is under compression and the other is under tension. This study is organized as follows. Section 2 discusses the experimental facility, testing method, material models and modeling strategy. In Section 3, the material parameters are calibrated by matching observed effective properties with the finite element simulations. With the calibrated material model at hand, we further study the buckling and post-buckling behaviors of porous silicone rubber under biaxial loadings. A short summary in Section 4 concludes this paper.

2. Experiments and computational methodology

2.1. Experimental facility and testing

For the experimental setup, an in-house testing facility for biaxial loading is designed, as shown in Fig. 1a. We did not use the commercial machines of biaxial loading because the specimen is required to be very large and most of them are designed for metals and alloys. The testing facility is also different from that developed by [3]. Their creative facility can accurately impose the biaxial compression for crushing. However, the biaxial compression/tension loading is difficult to be imposed because the platens cannot grip the specimen [32,33]. The schematic for testing under biaxial loading is shown in Fig. 1b. All the specimens are placed between two close fitting 5-mm-thick (made by polymethyl methacrylate) sheets to eliminate out-of-plane buckling. The sheets are transparent and the deformed shapes of voids can be photographed. Washing-liquid is slightly introduced on the surface of specimen homogeneously to reduce potential frictions.

The experiments are conducted under the displacement control with a biaxiality ratio

$$\gamma = \frac{\dot{\epsilon}_y}{\dot{\epsilon}_x} \tag{1}$$

where $\epsilon_x = \delta_x/L_x$ and $\epsilon_y = \delta_y/L_y$. L_x and L_y are the initial dimensions of the test specimen in x and y directions, respectively. $\{\delta_x, \delta_y\}$ are the applied changes in these dimensions and $\dot{\delta}$ denotes a velocity, with the same definitions as Papka and Kyriakides [3]. The strain rate is low and approximately 1×10^{-3} in both x and y axis to avoid the viscoelastic effects. Then a test is defined by parameters $\{L_x, L_y, \gamma\}$. It should be noted that for the convenience of explanation, we use $\gamma = 0$ to represent the uniaxial compression later in this paper. However, it is not consistent with the definition in Eq. (1). Under the uniaxial compression in one direction, the strain in other direction is not zero. The applications of compressive and tensile strains are accomplished by a platen and a designed fixture, respectively. The imposed strain can then be easily measured by the length of the specimen during deformation in both directions.

2.2. Fabrication of silicone rubber and porous specimen

A specimen for biaxial loading is shown in Fig. 2a, following the usual design [34,35]. The specimen has 15 columns by 15 rows of voids created at the central part. The exact dimension of the specimen is given in Fig. 2a. To fabricate these samples, we start by fabricating a negative mold using a 3D printer with epoxy materials. The specimens are then casted by using the silicone rubbers. Our silicone rubber is prepared by mixing vinyl silicone