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Compressive Deformation Mechanisms In Auxetic Materials With Re-Entrant And Curved Structures

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***Abstract*—Cellular materials are a new kind of functional and structural material composed of solid skeleton and massive voids, which are developed to achieve the balance of mechanical properties and lightweight. Generally, the mechanical performance of cellular material is strongly related to its microstructure design. In this study, two different cellular materials with negative Poisson's ratio effect are designed and fabricated by 3D printing technique, including the re-entrant structure and the curved sinusoidal beam structure. Then, their compressive properties are investigated by quasi-static compressive tests. The relationships between the compressive stress and the normal strain are presented for the two auxetic structures in the test. The results reveal that the auxetic material with a curved structure has more stable compressive deformation than the auxetic re-entrant material. The former shows obvious layer-by-layer collapse in the compression, rather than the double V fracture mode for the latter. Moreover, the former show higher resistance to compression loading than the latter.**

Keywords—Cellular materials, Auxetic materials, Compression, Deformation mechanism

I. INTRODUCTION

Cellular materials are a new kind of functional and structural material composed of solid skeleton and voids in either two-dimensional or three-dimensional cell configurations [1, 2]. Due to high porosity, cellular materials generally possess some inherent characteristics of low density and high specific stiffness and strength. Typically, some of them exhibit unusual deformation behavior, i.e., they expand laterally when stretched while shrinking when compressed. This characteristic is called a negative Poisson's ratio effect or auxetic effect [3, 4]. Due to the unusual auxetic performance that simple homogeneous materials are often not able to fulfill, auxetic materials have many potential applications in a vast number of engineering fields like construction, machine, sport, medicine or aerospace [5-7].

Among them, two-dimensional auxetic sheets with various perforations exhibit considerable attraction because holes with different geometry can be easily and simply produced. For example, periodic diamond-shaped, star-shaped, rectangular, elliptical or peanut-shaped perforations in the conventional sheet can exhibit negative Poisson's ratio [8-12]. Besides, the beam-dominated two-dimensional auxetic materials are also popular in engineering for the same reason, including the representative re-entrant structure [13], the chiral structure [14], and the newly developed curved sinusoidal beam structure [15]. The curved structure uses perpendicularly sinusoidal curves to generate auxetic deformation caused by the rotation of junctions. In this study, two types of auxetic cellular materials including the re-entrant structure and the curved sinusoidal beam structure are designed and fabricated by 3D printing technique, and then quasi-static compressive tests are conducted to investigate the difference of deformation mode and stress level between them. To the best of the authors' knowledge, such comparison is the first attempt in open literature.

The paper is organized as follows. The geometry configurations of the two auxetic structures are given in Section 2, and Section 3 depicts the compressive test of them and experimental results are analyzed. Some conclusions are given in Section 4.

II. GEOMETRY CONFIGURATION

In this study, two different auxetic configurations are investigated, including the re-entrant structure and the curved sinusoidal beam structure. To make comparisons conveniently, it is assumed that all configurations have the same dimension 50×50×35mm, in which 50mm is the side length of in-plane square cross-section and 35mm is the out-of-plane thickness of the materials. Here, the out-of-plane thickness is set to be sufficiently big (35 mm), so that out-of-plane bending deformation can be fully avoided during the compressive tests.

Firstly, the 2D square auxetic lattice with a re-entrant structure is designed by using AutoCAD, as shown in Fig. 1. For the re-entrant structure, four key sizing parameters are involved: the wall thickness t of each strut, the length L of the inclined struts, the height H of the vertical struts and the re-entrant angle α. Table 1 shows the values of the four parameters and the related porosity is 69.35%.

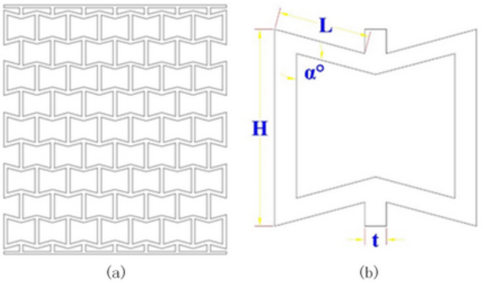

Fig. 1 (a) The ordered auxetic system with re-entrant structure and (b) the corresponding representative unit cell

TABLE I. DESIGN PARAMETERS OF THE RE-ENTRANT AUXETIC STRUCTURE

α (°)	*H (mm)*	*L (mm)*	*t (mm)*
75	6.8603	3.2368	0.75

Similarly, the auxetic material with a curved sinusoidal beam structure is designed, as shown in Fig. 2, in which four key sizing parameters are involved to generate such structure, namely, the amplitude *A*, the wavelength *l*, the curve width *w*, and the inter-curve space *S*. Their values are listed in Table 2. The corresponding porosity is 66.18%.

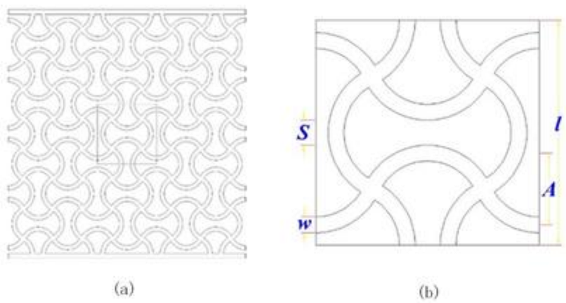

Fig. 2 (a) The ordered auxetic system with curved sinusoidal beam structure and (b) the corresponding representative unit cell

TABLE II. DESIGN PARAMETERS OF THE CURVED SINUSOIDAL BEAM AUXETIC STRUCTURE

A (mm)	*l (mm)*	*w (mm)*	*S (mm)*
4	12.56	0.89	1.39

III. COMPRESSIVE MECHANICAL BEHAVIOR OF MATERIALS

A. *Fabrication of the samples*

Due to the structural complexity of the designed cellular and auxetic materials, the additive manufacturing (3D printing) technique is employed to fabricate the experimental samples in blue polylactic acid (PLA) plastics, which has Young's modulus 3.5GPa and Poisson's ratio 0.36 [16]. Fig. 3 displays the used Wiiboox company II 3D printer purchased from the Wiiboox company (www.wiiboox.com) and the blue PLA wire. Three specimens of each material configuration are fabricated using the same printing material and printing settings. Fig. 4 shows the printed samples for the quasi-static compressive test.

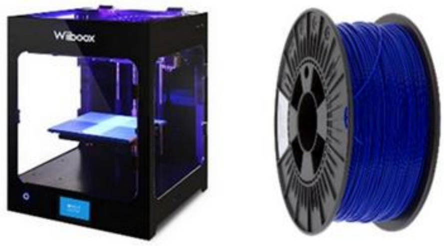

Fig. 3 The 3D printer and the blue PLA plastics

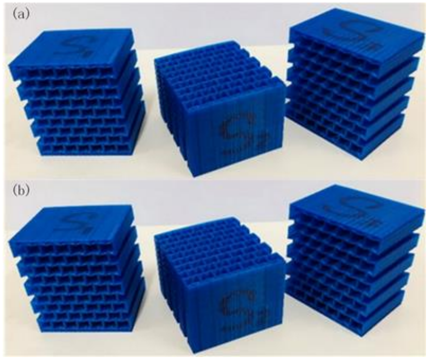

Fig. 4 Printed samples for the compressive test including the re-entrant structure (a) and the curved structure (b)

B. *Quasi-static cimpressive test*

The quasi-static compressive tests are conducted at room temperature on the ETM504C electro-hydraulic universal testing machine with a 50KN load cell in the material testing lab of Henan University of Technology, China. The above crosshead speed is set as 2.0 mm/min and the maximum displacement of the crosshead is 30 mm. The contact surfaces between the specimen and the above and bottom crossheads are oiled to reduce friction. A video camera is employed to capture the deformation behavior and the associated failure mode during compression. The compressive experimental setup of the sample is shown in Fig. 5.

For all samples, the compressive tests are conducted to achieve the displacement-load curves, which can be further treated to obtain the relationship between the compressive stress and the nominal strain. So that for, the normal strain is evaluated by dividing the recorded crosshead's displacement by the height (50 mm) of the sample. Meanwhile, the compressive stress of the experimental sample is evaluated by dividing the recorded crosshead's force by its cross-sectional area (50 mm×35 mm).

Fig. 6 demonstrates the main deformation process of the cellular specimen with irregular cells. Fig. 6(a) shows the unstrained configuration. It is noted that the specimen mainly undergoes an elastic deformation and then local fracture takes place in several cells, as indicated in Fig. 6(b). Subsequently, a more severe fracture is observed in some cells. During the fracture process, the typical horizontal double V deformation modes are firstly observed in Fig. 6(c), and then a layer by layer deformation mode is found in Fig. 6(d). Correspondingly, the stress-strain curves obtained from the three printed specimens, named as S1, S2, S3, are presented in Fig. 7, from which three distinct stages are observed in the evolution of the compressive stress of the re-entrant auxetic structure: linear elastic stage, plateau stage and strain hardening stage.

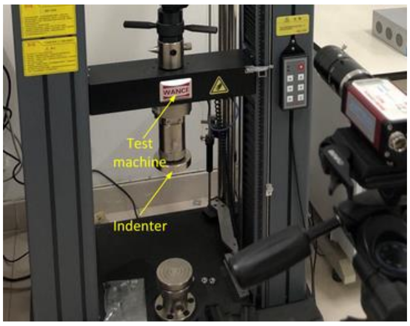

Fig. 5 Experimental setups of quasi-static uniaxial compression of samples

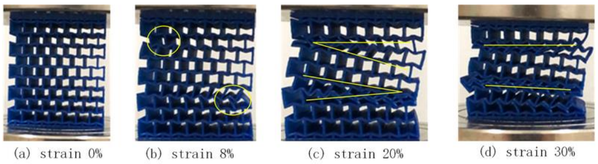

Fig. 6 Compressive deformation of the tested re-entrant auxetic material

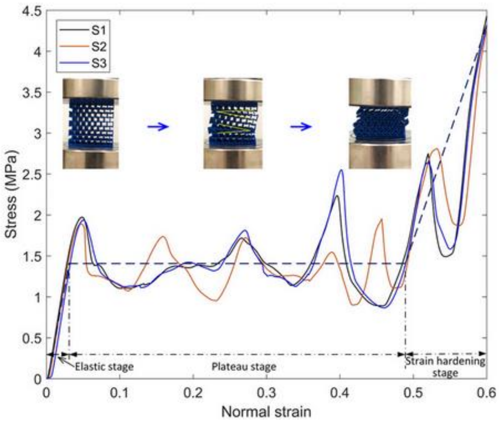

Fig. 7 Experimental results on stress-strain curves of the three specimens with re-entrant structure

Fig. 8 shows the compressive process of the specimen with a curved sinusoidal beam structure. During the compression test, we observe that the curved structure demonstrates a more stable deformation than the re-entrant structure. The gap between some adjacent cells is reduced with the increase of load. Then such cell collapse extends to other cells. Finally, the cells contact each other and the specimen is fully compressed. Besides, as depicted in Fig. 9, the stress-strain curves obtained from the three curved specimens represented by C1, C2, C3 show significantly better deformation behavior, in contrast to the re-entrant specimens. The stress level of the curved specimen is dramatically higher than that of the re-entrant structure under the same compressive strain. At the strain of 0.6, the compressive stress is about 4.5MPa and 14.5MPa for the re-entrant and curved specimens, respectively. It can be attributed to the unstable deformation of the auxetic re-entrant specimens with higher porosity (69.35%), which means the thickness of the cell wall is thin.

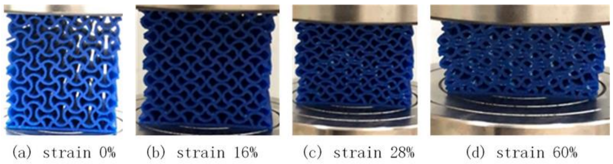

Fig. 8 Compressive deformation of the tested curved auxetic material

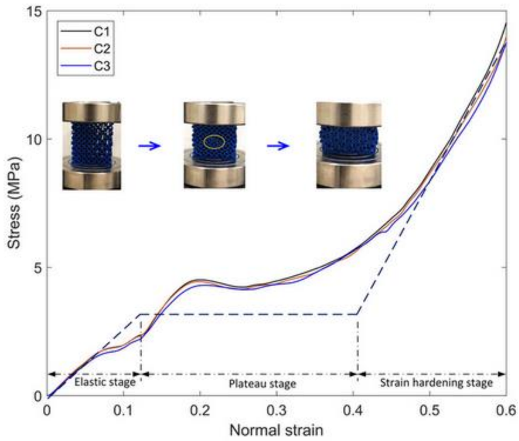

Fig. 9 Experimental results on stress-strain curves of the three specimens with curved structure

IV. CONCLUSIONS

In this work, the mechanical behaviors of auxetic materials with re-entrant and curved structures are studied under the quasi-static compressive test, which mainly focuses on the investigations of the deformation modes and the stress-strain relations of the designed auxetic materials. Based on the experimental results, the obvious difference of their compressive mechanical properties are observed, including both the deformation mode and the stress level. The following conclusions can be drawn:

a) The auxetic re-entrant specimens show unstable deformation mode under compression loading.

b) The double V fracture mode appears for the re-entrant specimen, while it doesn't take place for the curved specimen, which shows obvious layer-by-layer collapse in the compression.

c) The auxetic curved specimens show more stable compressive deformation than the auxetic re-entrant specimens.

d) The auxetic curved specimens show higher resistance to compression than the auxetic re-entrant specimens.

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