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# Mechanical behavior of anti-trichiral honeycombs under lateral crushing

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ABSTRACT

The mechanical properties of anti-trichial honeycombs under quasi-static compression with large deformation are studied by both experiments and theoretical analysis. It is shown that the cells' collapse of the anti-trichiral honeycombs dominated by both the ligaments' rotation around the plastic hinges and the rotation of cylinders. The theoretical analytical models are established to predict both the NPR and the crushing stress of the anti-trichiral honeycombs. The analytical predictions show good agreement with the experimental results. It is shown that the crushing stress of the honeycomb decreases with the ligament's length ratio $L/r$, but increases with the wall thickness. As for the honeycomb's Poisson's ratio, it increases with the ligaments' length ratio and decreases with the honeycomb's deformation, while the wall thickness has no influence on it. The anti-trichiral honeycomb exhibits NPR effect only when the ligament's length ratio less than 5.5. However, when the ligaments' length ratio is more than 10, the anti-trichiral honeycomb shows positive Poisson's ratio during the whole compression. When the ligaments' length ratio is in the range of 5.5 through 10, the anti-trichiral honeycomb appears NPR under small deformation, but positive Poisson's ratio under large deformation. These light up a refer to the design of the anti-trichiral honeycombs.

## 1. Introduction

Auxetic materials possessing a negative value of Poisson's ratio are a new family of cellular materials [1]. Under uniaxial tension or compression, it will result in transverse expansion or contraction, which is contrary to the conventional cellular materials. The plane made from auxetic honeycomb exhibits synclastic curvature behaviors [1,2]. So it makes possible to produce dome-shaped surfaces by out-of-plane bending. Besides, the auxetic materials are believed to have many advantages compared to the conventional materials, including higher shear resistance, hardness improvement, lower fatigue crack propagation [3–6] and so on. Thus, it is expected to be used in various engineering applications.

There are many types of auxetic materials with Negative Poisson's ratio (NPR), such as re-entrant structures [7,8], chiral structures [9,10] and 3D polymer materials with cavities [11,12] etc. The chiral and anti-chiral honeycombs are formed with the cylinders interconnected by ligaments [13,14], which achieve NPR effect by the rotation of cylinders and the bending of ligaments. By theoretical analysis and experiments, Prall and Lakes [14] verified the in-plane Poisson's ratio of hexachiral honeycomb to be equal to −1 in the linear elastic deformation. Alderson et al [15,16] measured the Poisson's ratio of a set of chiral honeycombs and anti-chiral honeycombs (including the chiral honeycombs with 3, 4 and 6 ligaments) under the small deformation through finite element analysis and experiments. It is shown that for the honeycombs with 4 or 6 ligaments, the Poisson's ratio maintained to be −1 regardless of the ligaments' length. The Poisson's ratio of the honeycombs with 3 ligaments depends on the ligaments' length. The trichiral honeycomb always displays positive Poisson's ratio behavior and increases with the ligaments' length. The anti-trichiral honeycomb exhibits positive Poisson's ratio or negative Poisson's ratio response with different ligament's length ratio [17].

Young's modulus is another important mechanical parameter for honeycombs under small deformation, which have been measured for chiral or anti-chiral honeycombs, revealing to increase with the ligament-walls' thinness but decrease with the ligaments' length [15,18]. Chen et al. [2] established the formulas for the elastic modulus of the anti-tetrachiral honeycomb along the two directions ($x$ and $y$). Dirrenberger et al. [19,20] studied the Young's modulus of both hexachiral honeycomb and anti-tetrachiral honeycomb by employing homogenization analysis.

Up to now, most studies on auxetic materials are limited in small deformation as described above. In some applications, the honeycomb core is used to be a structure protection layer in aircraft against collision. The crushing could take place along any direction of the honeycomb and the honeycombs often suffer from large deformation [21,22]. Reported studies of deformation mechanism in the elastic deformation cannot satisfy us in explaining how the chiral honeycomb does work under the large deformation. The studies on the traditional hexagonal honeycombs

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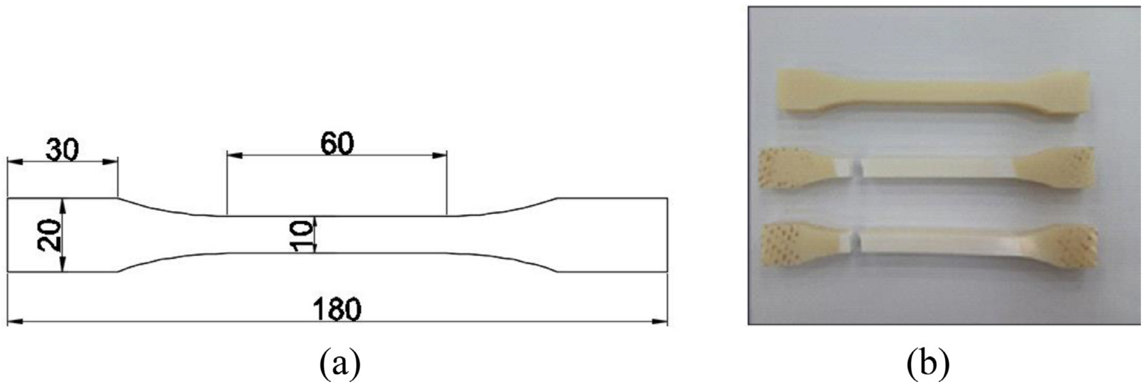


**Fig. 1.** Specimens of base material in the tensile tests. (a). Geometry of dog-bone-shaped specimen. (mm) (b). Specimens before and after tests.

show that the honeycombs' mechanical behaviors, such as deformation mode, deformation mechanism, load-carrying capacity and so on, are very different from those under small deformation [23,24]. Thus, the mechanical behaviors of the auxetic honeycombs under large deformation need to be clarified, however, the studies on which is seldom. Fu et al. [25] deduced the in-plane shear modulus of the re-entrance honeycombs by analyzing the nonlinear behavior under large deformation, showing a nonlinear relationship with the strain. Honeycombs exhibit a plateau stage under the large deformation [26,27], the mechanical properties of the auxetic honeycombs are mainly dominated by both the cells' geometric parameters and the mechanical properties of the base material. Sometimes, the quantitative expression between them is necessary for the design of the honeycombs [28].

In this paper, the mechanical behaviors of the anti-trichiral honeycomb with various ligaments length are studied by both experiments and theoretical analysis under large deformation. The analytical formulas for the Poisson's ratio and the crushing stress of anti-trichial honeycombs are deduced based on the deformation mode revealed from the experiment, showing the relation between deformation properties and its geometry parameters.

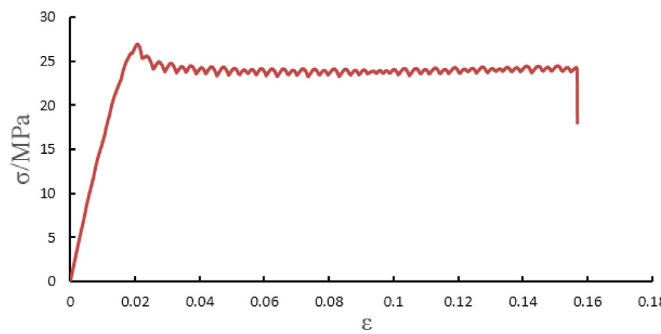


**Fig. 2.** Stress–strain curve of basis material.

## 2. Experiments

### *2.1. Mechanical property of basis material*

The basic material of anti-trichiral honeycombs is ABS polymer with beige color. Dog-bone-shaped specimens were cut for tensile tests to measure the mechanical property of the basic material. The dimensions of the ABS specimen are shown in Fig. 1(a). The total length of the specimen is 180 mm and the thickness is 10 mm. The length and the width of the effective part for the tensile test is 60 mm and 10 mm, respectively.

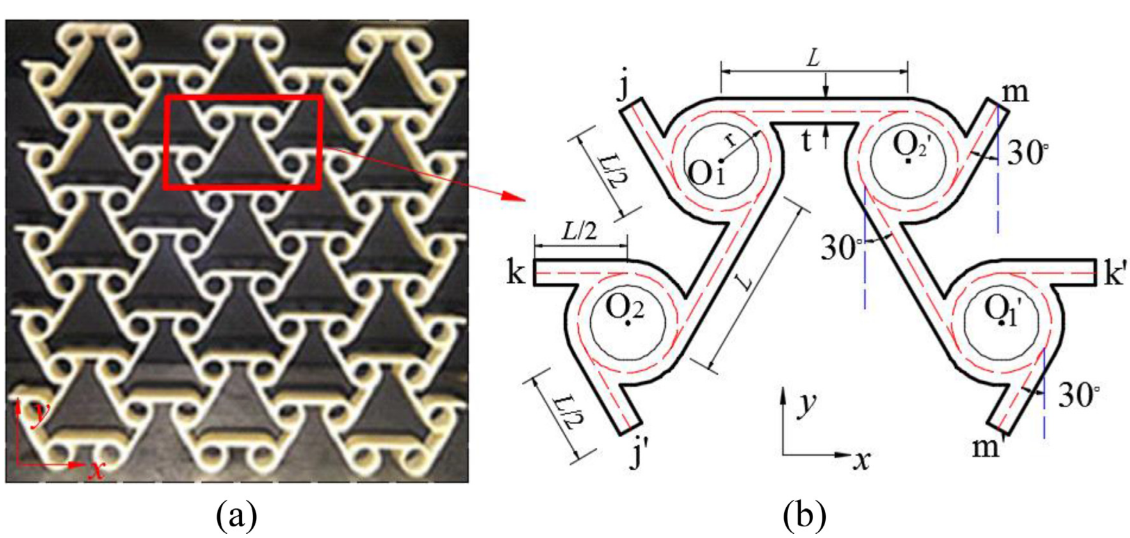


**Fig. 3.** (a) Honeycomb specimen. (b) A cell with dimensions marked.

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