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The in-plane linear elastic constants and out-of-plane bending of 3-coordinated ligament and cylinder-ligament honeycombs

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ABSTRACT

Four novel cylinder-ligament honeycombs are described, where each cylinder has 3 tangentially-attached ligaments to form either a hexagonal or re-entrant hexagonal cellular network. The re-entrant cylinder-ligament honeycombs are reported for the first time. The in-plane linear elastic constants and out-of-plane bending response of these honeycombs are predicted using finite element (FE) modelling and comparison made with hexagonal and re-entrant hexagonal honeycombs without cylinders. A laser-crafted re-entrant cylinder-ligament honeycomb is manufactured and characterized to verify the FE model. The re-entrant honeycombs display negative Poisson's ratios and synclastic curvature upon out-of-plane bending. The hexagonal and 'trichiral' honeycombs possess positive Poisson's ratios and anticlastic curvature. The 'anti-trichiral' honeycomb (short ligament limit) displays negative Poisson's ratios when loaded in the plane of the honeycomb, but positive Poisson's ratio behaviour (anticlastic curvature) under out-of-plane bending. These responses are understood qualitatively through considering deformation occurs via direct ligament flexure and cylinder rotation-induced ligament flexure.

1. Introduction

Honeycombs combine light weight with good through-thickness strength and stiffness properties and find use as the core material in sandwich panel composites for aerospace, automotive and marine applications. The linear elastic properties of conventional hexagonal honeycombs (Fig. 1a) are described well by analytical expressions [1] based on beam theory [2], and this understanding of structure-properties relationships has enabled the development of novel re-entrant hexagonal honeycombs (Fig. 1b) displaying in-plane negative Poisson's ratio (auxetic [3]) response (e.g. [1,4,5].

Auxetic materials can have enhancements in other useful physical properties, including energy absorption, plane strain fracture toughness and the ability to form synclastic (dome-shape) curvatures under out-of-plane bending [6]. Consequently, the potential to use auxetic honeycombs in advanced sandwich panel composites has provided the impetus to develop alternative auxetic honeycombs for optimal mechanical response. An alternative example of an auxetic honeycomb is the chiral cylinder-ligament honeycomb [7]. Cylinder-ligament honeycombs are attractive since the through-thickness shear response is enhanced by the ligaments [8] and the through-thickness compressive modulus and buckling are enhanced by the presence of the cylinders [9]. Hence it is possible to optimize the through-thickness behaviour through careful selection of the cylinder and ligament dimensions.

The first reported cylinder-ligament honeycomb comprised of an array of cylinders interconnected by ligaments: each ligament connecting two cylinders (located on opposite sides and ends of the ligament), with each cylinder having 6 ligaments tangentially attached to it at regular 60° intervals [7]. The system, therefore, has 6-fold chiral symmetry. More recently, alternative chiral connectivities have been reported, comprising cylinders having 3 or 4 tangentially-attached ligaments [10]. The 3-, 4- and 6-connected systems are termed trichiral, tetrachiral and hexachiral honeycombs, respectively. Cylinder-ligament honeycombs in which adjacent cylinders are located on the same side of the interconnecting ligament have also been reported for 3- and 4-connectivities, known as anti-trichiral and anti-tetrachiral honeycombs, respectively [10]. The in-plane and through-thickness linear elastic properties of the 3-, 4- and 6-connected chiral and anti-chiral honeycombs have been reported [11,12]. The hexachiral, tetrachiral and anti-tetrachiral honeycombs are auxetic, but the trichiral honeycomb (Fig. 1c) exhibits positive in-plane Poisson's ratios. The anti-trichiral honeycomb (Fig. 1e) possesses positive Poisson's ratios in the long ligament limit, and undergoes a transition to negative Poisson's ratio response in the short ligament limit.

The 3-coordinated cylinder-ligament honeycombs are attractive from a light weight perspective since they contain fewer ligaments and cylinders than the 4- and 6-connected systems. In order to develop 3-coordinated systems with the added benefits associated

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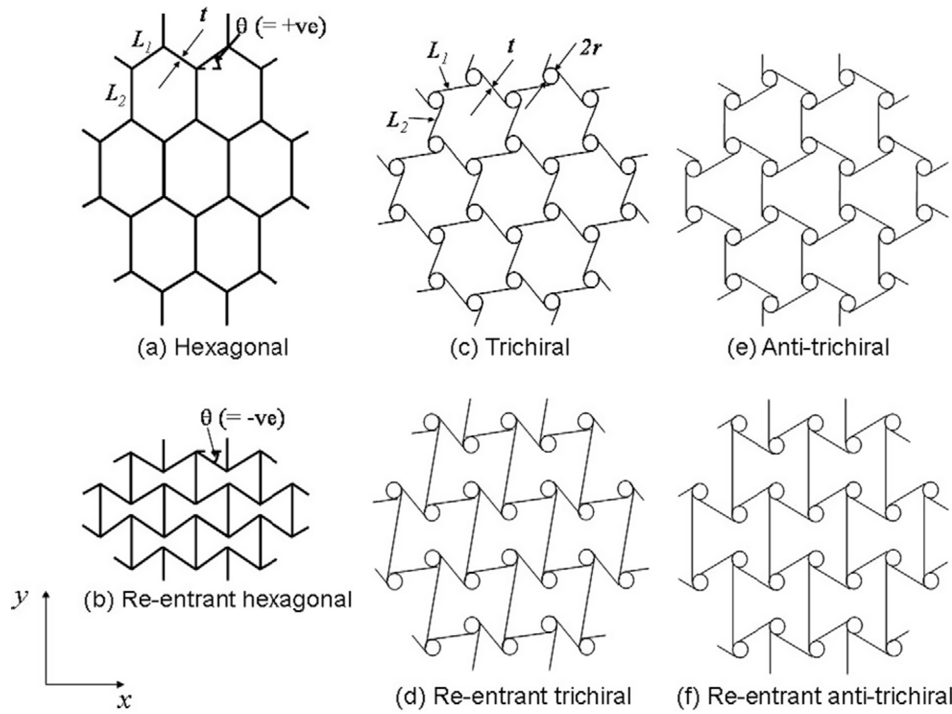

Fig. 1. Honeycombs investigated in this study: (a) hexagonal; (b) re-entrant hexagonal; (c) trichiral; (d) re-entrant trichiral; (e) anti-trichiral; (f) re-entrant anti-trichiral.

with auxetic response, we report here for the first time two new 3-connected cylinder-ligament honeycombs based on the re-entrant hexagonal cell structure. The linear elastic in-plane and out-of-plane bending responses of these new honeycombs are compared with those of the existing trichiral and anti-trichiral honeycombs which are both based on a conventional hexagonal cell structure, and the conventional and re-entrant hexagonal honeycombs (i.e. the 3-coordinated systems in the limit of zero cylinder radius). The responses are considered in terms of the major deformation mechanisms acting in these honeycombs.

2. Honeycomb geometries

The 3-coordinated honeycombs are shown in Fig. 1. The previously reported conventional hexagonal, re-entrant hexagonal, trichiral and anti-trichiral honeycombs are depicted in Fig. 1a, b, c and e, respectively. The new 3-connected cylinder-ligament honeycombs based on the re-entrant hexagonal cell structure are shown in Fig. 1d and f, and are achieved by locating the tangentially-attached ligaments at 60° intervals on each cylinder. The honeycomb containing cylinders located on opposite sides of the connecting ligament (Fig. 1d) is called the re-entrant trichiral system in recognition that the honeycomb is a hybrid of the trichiral and re-entrant hexagonal honeycombs. Similarly, the honeycomb containing cylinders connected on the same side of the connecting ligament (Fig. 1f) is called the re-entrant anti-trichiral system.

The off-axis ligaments have length L_1, the ligaments aligned along/towards the y axis have length L_2, the circular nodes have radius r, and the nodes and ligaments have common wall thickness t and depth d (Fig. 1). Four dimensionless parameters are defined: $\alpha = L_1/r$, $\beta = t/r$, $\gamma = d/r$ [11] and $\delta = L_2/L_1$.

3. Finite element model development

Simulations were performed using the ANSYS FE package, version 10.0.

3.1. In-plane mechanical properties

PLANE2 (linear elastic, solid) elements were employed in the simulations of the in-plane mechanical properties. Simulations were performed for small strains in the linear elastic region on arrays of several (typically 7×7 to 11×11) unit cells. x-directed forces were applied to the ligament nodes on the right-hand edge which were also constrained from displacement in the y direction. Nodes on the bottom and left-hand edges were constrained from in-plane rotation and translation normal to the edge direction, but were allowed to translate along the edge direction. This simulates the uniaxial test employed experimentally, and is shown for the trichiral honeycomb subject to tensile loading in Fig. 2a. The aspect ratio of the honeycomb in Fig. 2a could lead to the presence of Saint Venant effects in the simulations (for loading along x) but was chosen since it approximates the sample aspect ratio achievable experimentally. Forces in the y-direction were applied to the ligament nodes on the top edge which were also constrained from displacement in the x-direction. Nodes on the bottom and left-hand edges were constrained from in-plane rotation and translation normal to the edge direction, but were allowed to translate along the edge direction.

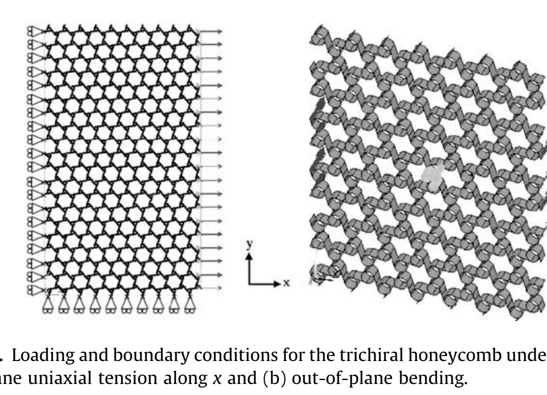

Fig. 2. Loading and boundary conditions for the trichiral honeycomb undergoing (a) in-plane uniaxial tension along x and (b) out-of-plane bending.