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In-plane mechanics of a novel zero Poisson's ratio honeycomb core

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ABSTRACT

This work presents a novel zero in-plane Poisson's ratio honeycomb design for large out-of-plane deformations and morphing. The novel honeycomb topology is composed by two parts that provide separate in-plane and out-of-plane deformations contributions. The hexagonal component generates the out-of-plane load-bearing compression and in-plane compliance, while a thin plate part that connects the hexagonal section delivers the out-of-plane flexibility. The paper illustrates the in-plane mechanical properties through a combination of theoretical analysis, FE homogenization and experimental tests. Parametric analyses are also carried out to determine the dependence of the in-plane stiffness versus the geometric parameters that define the zero-ν honeycomb.

1. Introduction

Honeycomb structures have drawn worldwide attention within the research community for their remarkable lightweight and mechanical properties, which are directly dependent upon the shape, topology and size of their cells [1,2]. Different honeycomb configurations lead to different in-plane Poisson's ratio values. The in-plane Poisson's ratio of a conventional regular hexagonal honeycomb is theoretically equal to 1 when pure bending of the honeycomb ribs is the main deformation taken into account [1]. In general, however, centersymmetric hexagonal configurations exhibit both large positive (PPR) or negative (NPR) Poisson's ratio values [3–7]. The hexachiral [8–11], tetrachiral [9–11], and anti-tetrachiral [12] ones show negative in-plane Poisson's ratios (NPR). Honeycombs with negative Poisson's ratio are also described as auxetic [13,14]. Honeycomb configurations like the SILICOMB [15–18], chevron [19–21] and accordion [22,23] can however achieve a Poisson's ratio (ν) of zero (ZPR). ZPR honeycombs show no lateral mechanical coupling under in-plane deformation when loaded along one direction [16,18]. The out-of-plane deformation of PPR honeycombs exhibits anticlastic or saddle-shape curvature that does not facilitate their use in sandwich structures with complex out-of-plane geometry [24–27]. Structures with NPR behaviour feature synclastic curvature when subjected to out-of-plane bending [9,24,26,28]. On the opposite, no anticlastic or synclastic curvature could be found for structures exhibiting ZPR under out-of-plane bending, which makes zero-ν cellular configurations more suitable for cylindrical sandwich panels and morphing applications in which the structure needs either to undergo pure cylindrical bending or one-dimensional (span) morphing [18,19]. The chevron and accordion honeycombs feature ZPR by balancing the deformation between embedded re-entrant and non-re-entrant structures [19,20,22,23]. The SILICOMB features a zero-ν behaviour by using a geometry inspired to the tessellation of the β-cristobalite lattice [29,30]. One example of application of ZPR honeycombs with accordion-like honeycomb microstructures is biomedical scaffolds [31], and in the field of morphing aircraft flexible sandwich structures with cellular cores and flexible face sheets have been proposed as a promising solution for morphing skins [23,32,33]. ZPR honeycombs have been used in flexible skins undergoing one-dimensional spanwise morphing [22,23,32,33] and have also demonstrated their potential in planar morphing applications [34]. Generally, morphing wing designs could be classified into in-plane and out-of-plane morphing [35–38], and spanwise morphing is a subset of the in-plane category. Moreover, the effect of the zero Poisson's ratio creates very complex and

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sometimes unusual multiphysics properties, like in the case of the strong increase of the longitudinal wave speed in a stressed plate with constrained width when the material has a ZPR behaviour [39].

In this work, a novel honeycomb design exhibiting ZPR for large out-of-plane deformations is proposed and investigated. This honeycomb configuration features a new mechanism to achieve ZPR, which consists in inserting a hexagonal part to bear the out-of-plane compression and to produce in-plane flexibility, and connecting a thin plate for the large out-of-plane flexibility. Thus different parts bring about different mechanical properties leading to a separate design for the in-plane and out-of-plane performances. Analytical models to describe the in-plane elastic constants of the novel honeycomb are developed and benchmarked with the FE homogenization approaches and experimental tests. The sensitivity of the in-plane stiffness versus the honeycomb geometry is further investigated using a combination of analytical analysis and FE homogenization.

2. Models and experimental tests

2.1. Geometry of the novel honeycomb

Fig. 1 shows the representative unit cells of the novel ZPR honeycomb configuration with cell angles $\theta \geq 0^\circ$ and $\theta < 0^\circ$. The parameters l and $h = \alpha l$ are the length of the inclined wall and the vertical wall, respectively. The thickness of the hexagonal section, thin plate and the whole honeycomb are represented by $t = \beta l$, $b_1 = \lambda b$ and b. The dimension $l_1 = \eta l$ represents the length of the thin plate part. The parameter $b = \gamma l$ is used to normalize all dimensions. The width of the unit cell for the case $\theta \geq 0$ is $w = \alpha l + 2l\sin(\theta)$ and becomes $w = \alpha l$ when $\theta < 0$.

2.2. Analytical models

Because the hexagonal structures of the honeycomb are connected by the thin plate and the hexagonal structures are not directly in contact, one can infer that the in-plane Poisson's ratio ν_{12} of the honeycomb is approximately equal to 0. The analytical models for the calculation of the in-plane elastic modulus along 1 (horizontal) direction developed in this work are based on the application of Castigliano's second theorem [40]. The honeycomb ribs are assumed to undergo bending and axial tensile deformations to avoid an infinite value of the homogenized Young's modulus when the internal cell angle equals to zero [1]. The theorem states that when an elastic system is statically loaded, the partial derivative of the strain energy U with respect to any applied force P_i equals the displacement δ_i of the point in which the force is applied:

$$\frac{\partial U}{\partial P_i} = \delta_i \tag{1}$$

For the case of a beam undergoing bending $M(x)$ and axial loading $F_N(x)$ one obtains:

$$U = \int_0^L \frac{M^2(x)}{2EI}\mathrm{d}x + \int_0^L \frac{F_N^2(x)}{2EA}\mathrm{d}x \tag{2}$$

The elastic modulus of the honeycomb is calculated following the loading scheme shown in Fig. 2. One set of cell walls of length l are bent and stretched by the applied stress σ_1 parallel to 1 direction. From the equilibrium equations one can obtain the moment M bending the wall [1]:

$$M = \frac{1}{2}Fl\sin\theta \tag{3}$$

It is worth noticing that the positive bending moment is orientated along the anti-clockwise direction. The bending moment distribution on the single rib is:

$$M(x) = \left(\frac{1}{2}l - x\right)F\sin\theta,\quad F_N(x) = F\cos\theta \tag{4}$$

Substituting Eq. (4) into Eq. (2), one obtains the strain energy of the single bending wall:

$$U = \frac{F^2l^3\sin^2\theta}{24E_sI} + \frac{F^2l\cos^2\theta}{2E_sA} \tag{5}$$

In Eq. (5), E_s is the Young's modulus of the honeycomb material, I and A the second moment of area and the area of the cross-section respectively. Following Eq. (1) it is possible to obtain the horizontal displacement of the free end:

$$\delta_1 = \frac{Fl^3\sin^2\theta}{12E_sI} + \frac{Fl\cos^2\theta}{E_sA} \tag{6}$$

The homogenized stress and strain along the 1 (horizontal) direction for a cell angle $\theta \geq 0^\circ$ can be therefore obtained as:

$$\sigma_1 = \frac{F}{b\left(\frac{1}{2}\alpha l + l\sin\theta\right)} \qquad \varepsilon_1 = \frac{\delta_1}{\eta l + l\cos\theta} \tag{7}$$

The homogenized and non-dimensional Young's modulus along

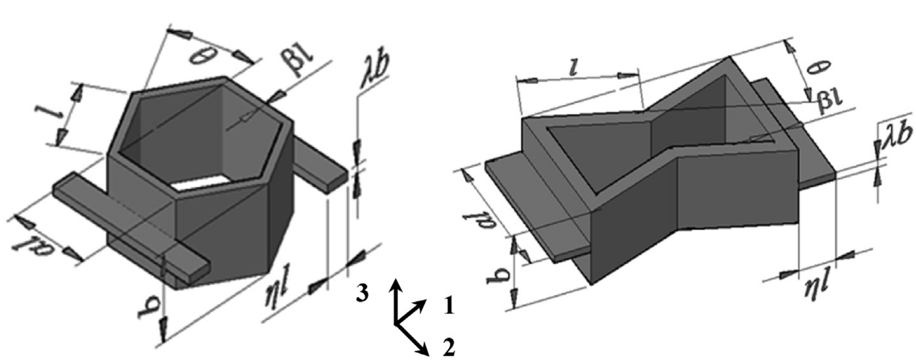

Fig. 1. Geometry of the novel ZPR honeycomb unit cell with cell angle $\theta \geq 0^\circ$ and $\theta < 0^\circ$.