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Elastic properties of a cellular structure with in-plane corrugated cosine beams

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ABSTRACT

Cellular structure cores are potential candidates for support structures of flexible skin. The skin requires low in-plane and high out-of-plane stiffness of the support structure. To overcome these problems, a cellular structure with in-plane corrugated cosine beams having close-to-zero Poisson's ratio to significantly reduce unnecessary stress and strain for one-dimensional morphing application was developed. The elastic properties were theoretically analyzed by energy methods, and verified by finite element analysis. Results show that better in-plane morphing and out-of-plane load-bearing capabilities can be obtained with larger height-to-length ratio, spacing-to-length ratio and vertical beam to cosine beam thickness ratio as well as smaller thickness-to-length ratio. Comparisons on properties with conventional accordion honeycomb were carried out. The results reveal that the cellular structure is of lower in-plane elastic modulus, which shows better in-plane property but weaker out-of-plane load-bearing capability. However, the out-of-plane load-bearing capability can be reinforced by increasing the height-to-length ratio and vertical beam to cosine beam thickness ratio.

1. Introduction

Flexible skin plays an important role in morphing aircraft and morphing wind turbine, especially in aerodynamic components such as morphing wing and morphing blade [1–3]. Therefore, quantities of studies were done on flexible skins. In Smart Wing Program, Kudva and Bartley-Cho et al. studied a variable camber wing using flexible silicone rubber as the external skin supported by a through-the-thickness flexible honeycomb structure [4,5]. Daynes et al. fabricated a morphing blade of wind turbine adopting a through-the-thickness aramid honeycomb covered with silicone rubber [6,7]. This kind of support structure is of great load-bearing capability but heavy in weight and difficult to manufacture because of its complicated surface shape. In Morphing Aircraft Structures Program, Andersen also adopted a silicone rubber as the skin with metallic ribbons as the support structure [8]. This kind of simple and reliable structure is intuitively designed based on project experience without too much theoretical guidance. Besides, the conventional metallic material adopted in the study is of high density, which is not suitable enough for the situations where light-weight is needed. Kikuta, Perkins, Reed and Keihl et al. tried to use shape memory polymers for supporting flexible skins in wing morphing applications. This kind of material, which can conduct active morphing, is of light weight, but it was found that there are many challenges associated with the properties of the material because of the complicated process such as heating and cooling during morphing [9–12]. Yokozeki and Thill et al. proposed an out-of-plane corrugated flexible skin and applied it on the wing undergoing one dimensional morphing [13,14]. This skin is of good in-plane morphing behavior but thick in the normal direction, which imposes restriction on the applications where the airfoil thickness is small. Olympio and Gandhi proposed sandwich flexible skins using honeycomb structures as internal support to withstand the aerodynamic load and external flexible skin layer to maintain the smooth appearance [15]. The study shows that internal honeycombs with external smooth sheet is an ideal option of passive flexible skin.

The honeycomb structures are of great physical and mechanical properties and have been already widely used in aircraft structures [16–19]. They are potential candidates for support structures of sandwich flexible skins because of excellent in-plane morphing and out-of-plane load-bearing capabilities. Gibson and Ashby et al. did a lot of research on mechanical properties of conventional

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hexagonal honeycomb, and presented the in-plane equivalent elastic and shear moduli considering internal bending moment, axial force and shear force [20]. A variety of honeycombs with positive/negative/zero Poisson's ratio have been investigated with focus on elastic properties [21–29]. It's worth pointing out that structures of non-zero Poisson's ratio will generate strain and stress at the non-loaded direction because of the Poisson effect, limiting its application in one dimensional deformation such as chord-wise, span-wise and trailing edge morphing. So smart structures of zero or close-to-zero Poisson's ratio need to be developed and studied for one-dimensional morphing applications. Olympio proposed a hybrid honeycomb with zero Poisson's ratio and derived its equivalent moduli by a similar approach to Gibson using Timoshenko beam theory. The in-plane equivalent moduli of accordion honeycomb with zero Poisson's ratio were also analyzed, but the out-of-plane moduli were not involved in this study [30]. Bubert et al. fabricated a skin supported by accordion honeycomb and analyzed the in-plane equivalent moduli of two directions without discussing the modulus in the third direction and the shear moduli [31]. Liu et al. had proposed a cellular structure with in-plane corrugated cosine beams and obtained its in-plane equivalent modulus of the *x*-direction by virtual force method considering internal bending moment and axial force. The preliminary application of the structure was realized on a variable camber wing [32]. However, the internal shear force should be considered in the derivation of the in-plane modulus to make it more accurate. Besides, the analysis of the elastic properties in other directions, some of which are important indicators of the out-of-plane stiffness and load-carrying capabilities for practical application, was not included in the study.

In this paper, the non-dimensional equivalent in-plane elastic modulus in the *x*-direction and the shear modulus in the *x*-*y* plane of the cellular structure are derived by the Castigliano's second theorem considering internal bending moment, axial force and shear force. The upper and lower bounds of the non-dimensional equivalent shear modulus in the *x*-*z* plane are determined by the principle of minimum potential energy and the principle of minimum complementary energy, respectively. In addition, the Poisson's ratios in the *x*-*y* plane, the non-dimensional equivalent in-plane elastic moduli in the *y*-direction and the *z*-direction as well as the non-dimensional equivalent shear modulus in the *y*-*z* plane are analyzed. Numerical calculation and finite element analysis were carried out to verify the theoretical formulas of the six moduli. The effect of structural parameters on the equivalent moduli of the structure is also analyzed. Finally, the superiority of the in-plane property of the structure is proved by comparison with a conventional accordion honeycomb and suggestions on selection of parameters for the design of the structure are provided considering the out-of-plane load-bearing capability.

2. Theoretical model

Fig. 1(a) shows the three-dimensional model of the cellular structure, which consists of two parts: the cosine beams and the vertical beams. A unit cell of the model is selected for analysis because of the symmetry and periodicity of the structure and the loads, as shown in Fig. 1(b). Geometric parameters of the unit cell are shown in Fig. 2. In the figure, l is the wave length of the cosine beam in the *x*-direction, hl is the peak-to-peak value of the cosine curve in the *y*-direction, tl is the beam thickness of the cellular structure, gl is the spacing between the cosine beams in the *y*-direction, l_v is the length of the vertical beam in the *y*-direction, and $t_v l$ is the thickness of the vertical beam. Also, bl is the cell depth in the *z*-direction, which will be used in the derivations of the moduli but is not shown in Fig. 2. The overall mechanical properties (E_x, E_y, ν_{xy}, ν_{yx}, E_z, G_{xy}, G_{xz} and G_{yz}) can be obtained in terms of the following non-dimensional set of cell parameters: h (height-to-length ratio of the cosine beam), t (thickness-to-length ratio of cosine beam), g (spacing-to-length ratio of cosine beams), $\eta = t_v/t$ (vertical beam to cosine beam thickness ratio), and b (non-dimensional cell depth).

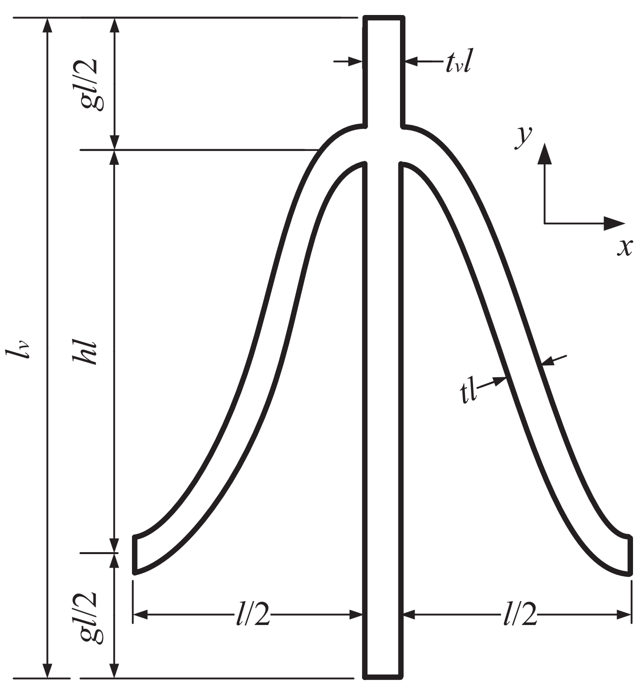

Fig. 2. Cell geometric parameters.

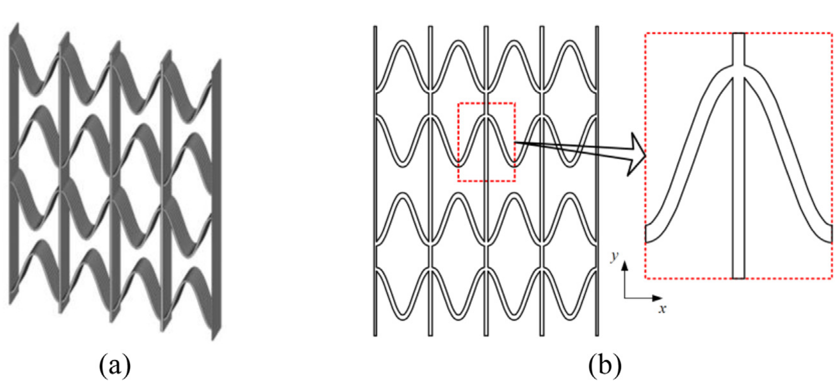

Fig. 1. Geometry of cellular structure: (a) 3 D structure; (b) unit cell.