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Modeling of honeycombs with laminated composite cell walls

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ABSTRACT

Honeycombs are versatile structures. They have been widely employed in industries where the characteristics of high stiffness, high buckling resistance, large shock absorption and light weight are required. To explore the potential of honeycombs in various mechanical applications, this paper proposes a novel honeycomb with composite laminate cell walls in order to provide wider selection of constituent materials, improved specific stiffness and distinct cell wall surfaces. Analytical homogenization model of this special type of honeycombs is established by modeling the locally heterogeneous honeycomb as a homogeneous orthotropic bulk. Both full-detailed and homogenized models are built and tested using finite element analysis, and the results showed that the analytical model has excellent accuracy in property prediction at a relatively small computational cost. Parametric studies are also conducted to investigate the effect of thickness and elastic moduli of the cell wall plies on the structure's overall mechanical response. Based on the results, suggestions on property optimizations are discussed.

1. Introduction

The blooming of honeycomb-shaped products began with Hugo Junkers patented the first honeycomb weight-saving sandwich panel core for aircrafts wing boxes in 1915. The work marked the initial understanding of this biomimetic structure's favorable property–high out-of-plane compression resistance at a relatively low density. With further study and understanding, more structural characteristics of honeycombs have been revealed and the applications of honeycomb structures have also been expanded to numerous new fields such as anti-bending beam, energy absorber, catalyst supports, heat insulation, noise barrier, etc [1]. The in-plane properties of honeycombs have also been investigated and utilized on some leading-edge products such as morphing wings [2–4], non-pneumatic tires [5] and energy absorption structures for dynamic crushing [6–9].

The most widely recognized fundamental work that thoroughly described the mechanical behaviors of honeycomb and its analogues was done by Gibson and Ashby in 1990[10]. Based on their model, Masters and Evans [11] concluded that the in-plane elastic response of honeycombs is not only the accumulated effects of cell walls' bending but also their stretching and hinging behaviors. Besides the orthotropic stiffness parameters, Chen [12,13] derived a detailed honeycomb out-of-plane bending and torsion model by investigating the 3-D displacement and twisting on each edge of the cell walls. Catapano and Montemurro [14] presented a new numerical approach of honeycomb homogenization by extracting the force-deformation response of a representative volume elements (RVE) model through finite element simulations.

In addition to deriving the reliable homogenization models, the modification and improvement of honeycomb structures for tailored properties has also attracted significant attention. Some researchers seek higher specific stiffness and specific strength while others aim at achieving certain properties with minimum material cost. Conventionally, there are two approaches to achieve these goals: 1) changing the cell walls' arrangement, such as cell wall length, angle and thickness; 2) replacing the cell walls with substructures. The first approach is mostly based on Gibson and Ashby's honeycomb model and is already widely employed in design of honeycomb products [15,16]. Wang and McDowell [17] compared the in-plane stiffness and yield of seven different periodic lattices and provided geometry selection strategy for in-plane mechanical properties. Ju et al. [15] conducted a series of functional designs on honeycombs with various unit cell geometries to reach a target shear modulus. Hou et al. [18] presented an optimized geometry design of aluminum honeycomb sandwich panels for high crashworthiness resistance. Larsen et al. [19] used computer aided topology optimization to design the unit cell of compliant micromechanisms and demonstrated a greatly reduced design cycle of new honeycombs. All of the above optimization approaches are both straightforward in calculation and easy to be realized in manufacturing, but the range of material properties that can be achieved are limited.

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On the other hand, many researches have already proven that regular hexagonal is the optimum unit cell geometry for honeycombs to attain the maximum out-of-plane specific buckling resistance and out-of-plane specific shear stiffness [11]. Regular hexagonal unit cells can also provide isotropic homogenized in-plane moduli, which is an important characteristic in many applications. Hence, there are very few options for cell wall arrangement design.

The second approach is relatively novel and drawing more and more attentions in the recent decades. Observing the non-uniform thickness of natural bee hive cell walls, Chen et al. [20] designed and analyzed a novel cylindrical-joints honeycomb structure with in-plane Young's moduli and fracture strength 76% and 303% higher than those of the conventional honeycombs, respectively. Ajdari et al. [21] and Oftadeh et al. [22] developed honeycombs with multi-order fractal-appearing cell wall networks; Chen and Pugno [23] proposed and analyzed a novel honeycomb by replacing the original cell walls with second-order hierarchical hexagonal cellular. As a comprehensive work, Sun's group [24,25] later conducted systematic investigations on honeycombs with different hierarchical geometries in the cell walls. Almost all of those studies reported remarkable improvement in specific stiffness and buckling resistance (some of them can even increase by 300%–400%), but they suffer from a common disadvantage for being difficult to fabricate due to their unusually complicated geometries. Currently, most of them can only be produced via 3-D printing, which greatly prevents the extensive use of those structures in industry.

Inspired by the literature above and considering the manufacturing feasibility, this paper proposed a new approach to modifying the honeycomb property by introducing laminated composite in the cell walls. The composite cell wall honeycombs can provide special cell wall surfaces and a wider material options to achieve a desired effective property. Fan et al. [26] presented a similar work on honeycomb with sandwich cell walls consist of two surfaces separated by a light middle core. They have assumed that the middle core functions only as a spacer and all of the in-plane loads are carried by the surface sheets. The effect of surface spacing on the homogenized in-plane moduli was investigated, but the effect of employing multi material laminates was not discussed.

Most commercially available honeycombs are produced by the bonding-expanding or corrugation-welding process. With these processes, composite cell walls honeycombs can be fabricated by simply replacing the single layered cell wall with composite laminates. Due to the bonding process, the cell walls in the bonding area will have twice the thickness as shown in Fig. 1. This characteristic is considered and discussed in the following sections.

A comprehensive study on honeycombs with composite cell walls is presented in this paper. In the following sections, hexagonal honeycombs with n-layer cell walls are homogenized as orthotropic solids. Based on the n-layered cell wall model, in the second half of this paper, the properties of a regular hexagonal honeycomb with double-layer cell walls (four layers in the bonding region) as shown in Fig. 1 are modeled and evaluated using commercial finite element code Abaqus. With the verification of the derived analytical homogenization model, a parametric study is conducted. To narrow down the scope of this research and avoid the influence of trivial factors, the presented research focuses only on thin wall honeycombs (cell wall thickness-to-length ratio is less than 1/15) under static or quasi-static homogenous external loads. The mechanical responses discussed are within elastic range and free from adhesive debonding, and the solid materials used in the cell walls are isotropic and homogeneous with a Poisson's ratio of 0.3.

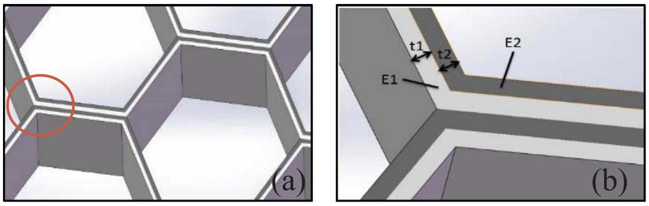

Fig. 1. (a) Honeycomb with laminate cell walls. (b) Ply structure in junction area.

2. Homogenization model

Although many new methods have been developed to obtain analytical homogenization of honeycombs, Gibson and Ashby's fundamental honeycomb model has never been significantly challenged. Considering the accuracy and the corresponding computational cost, their model is still the most efficient one for thin-wall honeycombs [10]. Therefore, the homogenized stiffness matrix of composite cell wall honeycombs is derived by combining Gibson and Ashby's model and the classic laminated beam theory (CLBT) model. Solutions for the general case honeycomb with n-layer composite cell walls are presented.

2.1. In-plane elastic moduli

Per Gibson and Ashby's model, the thin cell walls' axial strain energy is negligible comparing to their bending strain energy when the honeycomb is subject to homogenous global in-plane loads, hence the deformation of honeycombs under this condition becomes the accumulated effect of the cell wall bending deflections, as depicted in Fig. 2. Due to the symmetry of the unit cell, the deflection angles at the two ends must be zero, which leads to a moment M_0 at these locations. With the above boundary conditions, the effective in-plane elastic moduli $E_1{}^*$ and $E_2{}^*$ are given by Gibson and Ashby's model as:

$$E_1^* = \frac{12cos\theta E_s I}{(h + lsin\theta)l^2 sin^2\theta}, \quad E_2^* = \frac{12(h + lsin\theta)E_s I}{l^4 cos^3\theta} \tag{1}$$

where h, l and θ are the unit cell geometry parameters as shown in Fig. 2, E_s is the elastic modulus of the solid material used as the cell walls and I is the moment of inertia of the cell walls.

For honeycombs with laminated cell walls, the macroscopic geometry parameters h, l and θ remain unchanged, but the flexural rigidity E_sI must be replaced by the corresponding effective parameter of the laminated cell walls. Thus, CLBT is introduced. Note that X_1, X_2 and X_3 in Fig. 2 are the global honeycomb coordinate; x, y and z in Fig. 3 are the local cell wall coordinate. By applying CLBT, the bending moment M and longitudinal force N of a composite beam are:

$$M = B\varepsilon_x + D\frac{d^2w}{dx^2}, \quad N = A\varepsilon_x + B\frac{d^2w}{dx^2} \tag{2}$$

where w represents the beam deflection as a function of x and ε_x is the mid-plane strain along the longitudinal direction. A, B and D are extensional stiffness, coupling stiffness and bending stiffness respectively, which are determined by the cell wall's ply arrangement:

$$A = \sum_{i=1}^{n} E_{si}(z_i - z_{i-1}), \quad B = \frac{1}{2}\sum_{i=1}^{n} E_{si}(z_i^2 - z_{i-1}^2), \quad D = \frac{1}{3}\sum_{i=1}^{n} E_{si}(z_i^3 - z_{i-1}^3) \tag{3}$$

where E_{si} is the elastic modulus of the ith ply. Fig. 3 illustrates the cross section of an n-layer composite cell wall, where t_i is the thickness of ith

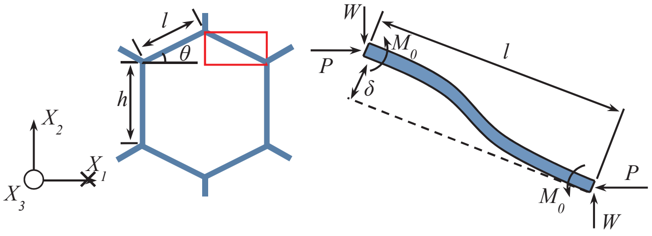

Fig. 2. The bending mode of the inclined cell walls when the honeycomb is subjected to uniform in-plane compression.

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