

Method to Design Honeycombs for a Shear Flexible Structure

2010-01-0762

Published
04/12/2010

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ABSTRACT

Conventional geometric parameters of honeycombs (cell height, h , cell length, l , and cell angle, θ) have been used to find effective properties of honeycomb structures. However, these parameters appear to be difficult to control both a target shear stiffness (4 to 4.5MPa) and a target level of shear strain ($\sim 10\%$) because the parameters are coupled to each other within a constant design space. A method to design hexagonal honeycombs is derived to design for both shear stiffness and shear flexibility independently by replacing the conventional geometric parameters with two new parameters; effective height, R , and horizontal separation, d . A parametric study with commercial software, ABAQUS, is conducted using the two new parameters to investigate their affects on in-plane effective shear stiffness, G_{12}^* , and maximum shear strain, $(\gamma_{12}^*)_{max}$ of polycarbonate honeycombs under a fixed overall honeycomb height of 12.7mm (0.5in). The suggested method is expected to be applied to design a light weight component requiring certain levels of shear stiffness and shear strain simultaneously.

2. INTRODUCTION

In ongoing research at Clemson University, materials are sought which are able mimic elastomeric properties yet are composed of low dampening materials, thereby reducing energy loss under cyclic shear loading conditions. Our previous study on a design of shear flexure with honeycombs shows that cellular solids having negative Poisson's ratio, called auxetic, have high shear flexibility [1].

Since the pioneering work on the honeycomb mechanics by Gibson and Ashby [2], many analytical and numerical models to describe in-plane effective properties of honeycombs are available in the literature. For example, researchers have developed a refined cell wall's bending model by adding a

beam's stretching and hinging motion [3], a model with the energy method [4], a refined model with round shape at cell edges [5], and a model using the homogenization method [6]. In-plane mechanical properties with different cell types, including square, hexagonal, triangle, mixed squares and triangles, diamond, were investigated by Wang and McDowell [7]. Circular and chiral shapes of honeycombs have also been studied for a functional design [8,9,10]. A multifunctional approach requiring structural stability and fast heat transfer was investigated with honeycomb structures [11].

Compared to the fundamental studies on cellular solids, their practical applications have been limited to the development of stiff and ultra-light sandwich cores for aircraft and aerospace structures, which are related to the honeycombs' out of plane properties [12,13,14,15,16], and rigidified inflatable structure for housing [17]. Recently, honeycombs' in-plane flexibility began to be designed in aerospace morphing technology [18, 19]. However, only limited practical studies on design with honeycomb configurations are available. For instance, Seepersad et al. carried out a multifunctional design of structural and thermal objectives in the application of gas turbine engines [20]. Huang and Gibson studied the design of honeycombs for beam and plate structures [21].

Hexagonal honeycomb materials are being considered here to replace conventional materials such as polyurethane to achieve lower densities and higher efficiencies under cyclic loading conditions. Specifically, to be successful, the cellular material must have effective shear properties equaling those of polyurethane while reducing the affects of hysteretic energy loss. The material must have an effective shear modulus of between 4 and 4.5 MPa and must be able to withstand shear strains up to 10% before yielding occurs. Additionally, the material must have an overall height of 12.7

mm, a length of 250 mm, and rigid membranes attached to the structure along the upper and lower surface.

One challenge for this particular design task is that the design space height permits few (1 to 2) vertical unit cells connecting the upper and lower membranes of the material. With few vertical cells, the membrane attachment points place additional constraints on the material which lead to error in the analytical solutions for effective properties developed by Gibson and Ashby [2]. For this reason, an experimental solution using finite element analysis is used in the design process.

Another challenge caused by having few vertical cells is that the overall dimensions of the structure are highly sensitive to changes in the geometric parameters. The conventional parameters are interconnected such that when a single parameter is altered, the other parameters must also change to comply with the fixed design space, making it difficult to control the geometry of the structure during the design process. For this reason, a new system for describing honeycomb structures was developed which reduces the number of geometric parameters from three to two. In this system, conventional parameters are replaced by two new parameters, R and d , where R describes the effective height of the vertical honeycomb members relative to the overall height of the structure and d is the horizontal separation between honeycomb cells. These new parameters relate the honeycomb geometry to the overall dimensions of the design space, allowing for the design space to be easily fixed. They are also independent of each other so that R or d can be freely modified without affecting the other.

The new honeycomb parameters, R and d , are investigated to determine the affects each has on the target effective shear properties. Based on these findings, a new method for honeycomb structure design is developed which takes advantage of independent honeycomb features to design for the two effective properties simultaneously.

3. PROCEDURES

Cellular materials, for the purposes of this paper, are materials constructed from an array of two dimensional, regularly patterned structures. These structures form the body of the material and are bounded by upper and lower membranes. As a whole, these cellular materials act as a single homogeneous material possessing effective mechanical properties which differ from the properties of the constituent material. The effective properties are a result of the mechanics of the structures within the material. The objective in cellular material design is to develop a material which has effective properties desired for a particular application.

3.1. HONEYCOMB CELLULAR MATERIALS

Honeycomb cellular materials are constructed from a regular pattern of hexagonal cells. The cells are oriented so that two of the hexagonal edges are parallel to the X_2 direction and the structures attach to the upper and lower membrane boundaries running parallel to the X_1 direction (Figure 1). Figure 1 shows the conventional parameters used to describe a honeycomb structure with one vertical unit cell.

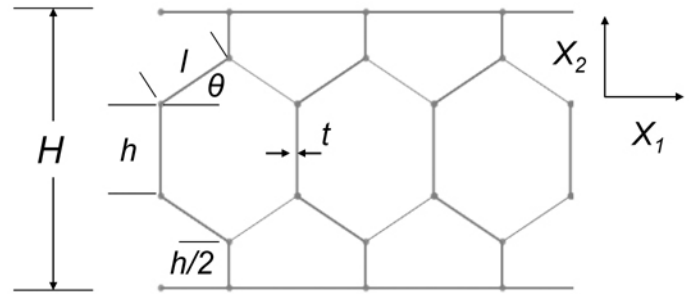


Figure 1. Conventional parameters for a two-dimensional honeycomb structure

The analysis of honeycomb materials is performed by considering the structures to be a system of interconnected beams, where the vertical beams have a length h , the angled beams have a length l and the beams have a thickness of t . The effective properties can be derived by determining the mechanical reactions of the beam system. The mechanics of the system can be altered by modifying the structural dimensions within the material, resulting in a change in effective properties.

3.2. NEW PARAMETER DEVELOPMENT

When a honeycomb structure is subjected to a shear load, the primary mode of deformation is from bending in the vertical members [2], as shown in Figure 2. The new system of parameters emphasizes the lengths and the density of the vertical members relative to the structure as a whole.

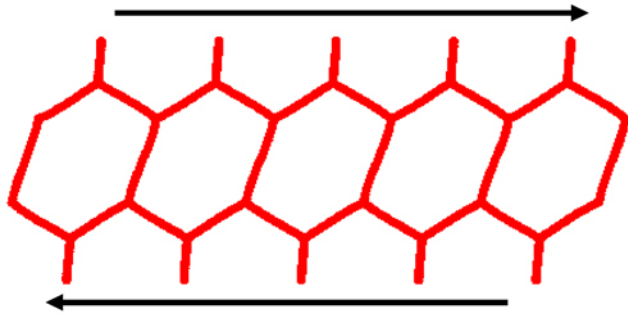


Figure 2. Honeycomb structure reaction to shear loading

In the new system, honeycomb structures are viewed as a series of vertical beams located within the shear layer which are interconnected by rigid angled beams to form the honeycomb pattern. From this perspective, two assumptions are made about the resulting effective properties, G_{12}^* and $(\gamma_{12}^*)_{max}$. First, there are two features of the structure which contribute to G_{12}^* , the stiffness of the deformed vertical members, and the horizontal density of the vertical members, and second, only one feature significantly influences $(\gamma_{12}^*)_{max}$, the compliance of the vertical members.

For a constant wall thickness, t , an increase in length of the vertical members should result in a decrease in the member stiffness, decreasing G_{12}^* , and an increase in the member compliance, increasing $(\gamma_{12}^*)_{max}$. In the new system of parameters the lengths of the vertical members are described using the effective height, R , which is a ratio of the summation of the vertical member lengths, H' , relative to the overall height, H .

$$R = \frac{H'}{H} \quad (1)$$

R is independent of the number of vertical layers, N_v , so as N_v increases, the individual heights of the vertical members will decrease, but the combined height will remain constant. Additionally, R is limited to $0 < R < 2$ to prevent zero vertical member heights at $R=0$ and cell overlap at $R=2$.

For a constant wall thickness, t , and constant vertical member heights, an increase in the horizontal density will require more horizontal cells, N_h , to be deformed over a given length of the material, resulting in an increase of G_{12}^* . The horizontal density of the vertical members is determined in the new system by the horizontal separation, d , of the horizontal cells.

$$d = \frac{L}{N_h} \quad (2)$$

Because the new parameters are independent of each other but dependent of one dimension of the design space, R and d can be modified independently without affecting each other or the overall dimensions of the material. Figure 3 shows the new parameterized system, and the conversion equations relating the new and conventional parameters are given in equations 3,4,5.

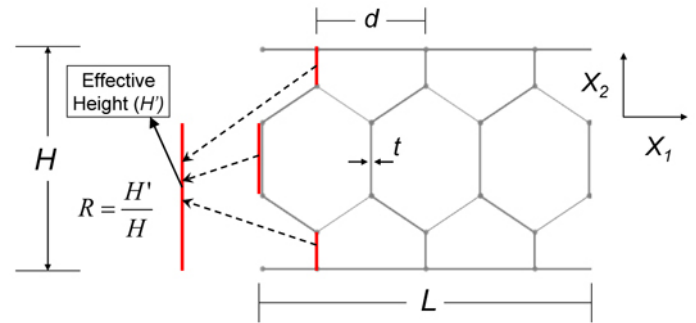


Figure 3. Honeycomb structure using the new system of parameters for $N_v=1$ and $N_h=3$.

$$R = \frac{2hN_v}{H} \quad (3)$$

$$d = 2l \cdot \cos \theta \quad (4)$$

$$\text{Where } \theta = \tan^{-1} \left(\frac{H(1-R)}{d \cdot N_v} \right) \quad (5)$$

3.3. ANALYSIS

Parametric studies are performed on the new parameters to determine their affects on G_{12}^* and $(\gamma_{12}^*)_{max}$. The studies are performed using a Matlab program which works in concert with Abaqus FEA. The honeycomb structures are generated and modified in Matlab and Abaqus is used for analysis. The material used in the analysis is polycarbonate which has a modulus of elasticity of 2.7 GPa, Poisson's ratio of 0.42, and a yield stress of 81 MPa.

For each analysis step, the structures are subjected to simple shear and the desired results are the shear stiffness, G_{12}^* , and the maximum allowable shear strain, $(\gamma_{12}^*)_{max}$. The structures are modeled using quadratic beam elements and the material is modeled as elastic. For each structure, a single static analysis step is performed.

To simulate simple shear, the bottom legs are fully constrained at the base and the bases of the top legs are