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Equivalent mechanical properties for cylindrical cell honeycomb core structure

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ABSTRACT

Structural members made up of two stiff, strong skins separated by a lightweight core are known as sandwich panels. The separation of the skins by the core increases the moment of inertia of the panel with little increase in weight, producing an efficient structure against in-plane and out-of-plane loadings. In general, the mechanical behavior of cellular structures is given by the effective elastic modules, which are also dependent on the structure topology and different geometric parameters. This paper presents analytical equations for equivalent stiffness properties of a cylindrical cell honeycomb core. The cylindrical cells are obtained by connecting bended plate strips using adhesion or laser-welding. The stiffness properties and effective elastic modules for in-plane and out-of-plane compression and shear loadings are derived using an energy based approach. The analytical models are validated by 3D finite element method based on solid elements. The obtained mechanical properties are used to assess the stress and strain state of a sandwich beam in three-point bending. The present investigation shows that the analytical equations can predict the stiffness coefficients and respectively the effective elastic modules with very good accuracy.

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1. Introduction

Sandwich structures have excellent mechanical properties, such as ratio between weight, stiffness and weight and strength. Therefore, the topic has been studied extensively in scientific research. This paper presents a sandwich structure with cylindrical cell honeycomb core. Typically, the sandwich panels are loaded by spatially varying transverse loads, and consequently the core of the panel must possess adequate compressive and shear stiffness and strength. The properties of the core are sensitive to both material choice and topology. There has been a significant activity in creation, manufacturing and testing of new topologies, starting with foam and honeycomb cores and continuing with structures as: metallic truss cores and all-metal sandwich panels.

Cellular materials offer low densities and are efficient in absorbing energy from external loading. In the past decade, major advances were made in the design of cellular materials with periodic topologies by exploiting minimum weight design, novel material fabrication processes, quasi-static and dynamic experiments, and large-scale simulations.

Honeycombs usually comprise hexagonal or square cells, with the prismatic direction normal to the plane of face plates of the sandwich panel. Hexagonal honeycombs are routinely employed as the cores for lightweight sandwich panels and as energy absorbers; they are typically manufactured from aluminum alloys and have a relative density $\bar{\rho}$ (ratio of the density of the honeycomb treated as a homogeneous continuum to the density of the solid) of less than 3%. Experiments and simple analyzes have shown that their out-of-plane elastic properties scale linearly with their relative density $\bar{\rho}$, [1]. In out-of-plane crushing, these honeycombs exhibit a stress peak followed by large stress oscillations associated with the formation of a succession of plastic folds within each cell. The out-of-plane shear strength is governed by cell wall buckling as discussed by Zhang and Ashby, [2]. Once the wrinkles have formed, the shear stress drops and subsequently remains approximately constant until failure occurs by the fracture of the cell walls. Square honeycomb cores having a high relative density ($\bar{\rho} > 0.05$) are preferable over hexagonal honeycombs for high loadings such as blast and shock loads because of their high out-of-plane crushing resistance; shear resistance and in-plane stretching strength, [3]. Circular cell honeycombs have also been studied analytically and experimentally by J. Chung and Waas, [4–7], for uniaxial and biaxial compressive in-plane loads. They observed an orthotropic behavior of these structures and also presented analytical solutions for determining the in-plane elastic properties. It

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was found that the elastic properties are dependent on their cell size and thickness and ellipticity of the cell walls. In Ref. [8] it was shown that cell ellipticity and cell-wall-thickness variation are highly influential in affecting the macroscopic in-plane elastic properties of honeycomb. Perfectly circular cell honeycombs are transversally isotropic. The studies on these structures have been continued in Refs. [9,10], by presenting analytical models for in-plane elastic moduli, Poisson's ratios, brittle crushing strengths and plastic yielding strengths. In all these studies superior mechanical properties of circular cell honeycomb structures compared to the hexagonal cell have been reported.

Metallic truss cores with tetragonal topology were theoretically studied by Wicks and Hutchinson [13,14]. This work demonstrated that such cores possess an excellent combination of compressive strength and low weight. Experimental measurements and numerical simulations were also performed on the tetragonal and triangular truss cores as well as truss-cored sandwich panels in [11, 12, 15–21]. Whereas these truss cores were studied thoroughly by theoretical and numerical means, the performed experiments were limited due to the manufacturing process.

Another category of structures that are in continuous development is represented by all-metallic sandwich structures, which are widespread in various industrial fields, such as marine, mechanical and civil engineering industry. Analytical, numerical and empirical methods have been used to determine the stiffness properties of various metallic sandwich structures. Using the stiffness expressions from [22,23] in Ref. [24], small deflection theory was used to obtain prediction for the deflection, stress and strain fields in all-steel sandwich panels with a spot-welded corrugated core. Concentrating their efforts on other core configurations, in Refs. [25,26] the unit-load method was applied to derive closed-form expressions for the transverse shear stiffness of sandwich panels with C and Z-type stiffeners. Based on this works, later studies have focused on the analysis and optimization of the web-core sandwich panel [28,29].

In addition to the previous studies, this paper presents a cylindrical cell honeycomb core structure that can be considered as an alternative to the existing ones. In the first part of the paper the core structure is analyzed in terms of manufacturing and the mechanical properties are analytically derived for in- and out-of-plane. The analytical derivations are validated with finite element analyzes. In the second part of the paper the bending response of a sandwich beam is analyzed using finite element method.

2. The cylindrical cell honeycomb structure

2.1. Design and manufacture procedure

The cylindrical cell honeycomb core structure is defined by four parameters: the mean radius of the cell, R; the mean connection radius between cells, r; the thickness of the wall cell, t, and the modulus of elasticity, E_m. In Fig. 1a and b the structure with two different stacking sequences is presented.

Both variants can be achieved by the same manufacturing procedure, where a half-cell is obtained by plastic deformation process of a strip of the base material. Joining the two halves of the cells with laser welding or adhesives make the core material, Fig. 1c. The core can be connected then to the faceplates by laser-welding or adhesion.

The relative density of such a structure is given by:

$$\frac{\rho^*}{\rho_S} = \frac{2\cdot R\cdot t\cdot\left(\frac{\pi}{2}-\arcsin\left(\frac{r}{R}\right)\right)+2\cdot r\cdot t\cdot\pi}{\left(R^2+R\cdot t+0.25\cdot t^2\right)\cdot\left(\frac{\pi}{2}-\arcsin\left(\frac{r}{R}\right)\right)+\left(r^2+r\cdot t+0.25\cdot t^2\right)\cdot\pi} \quad (1)$$

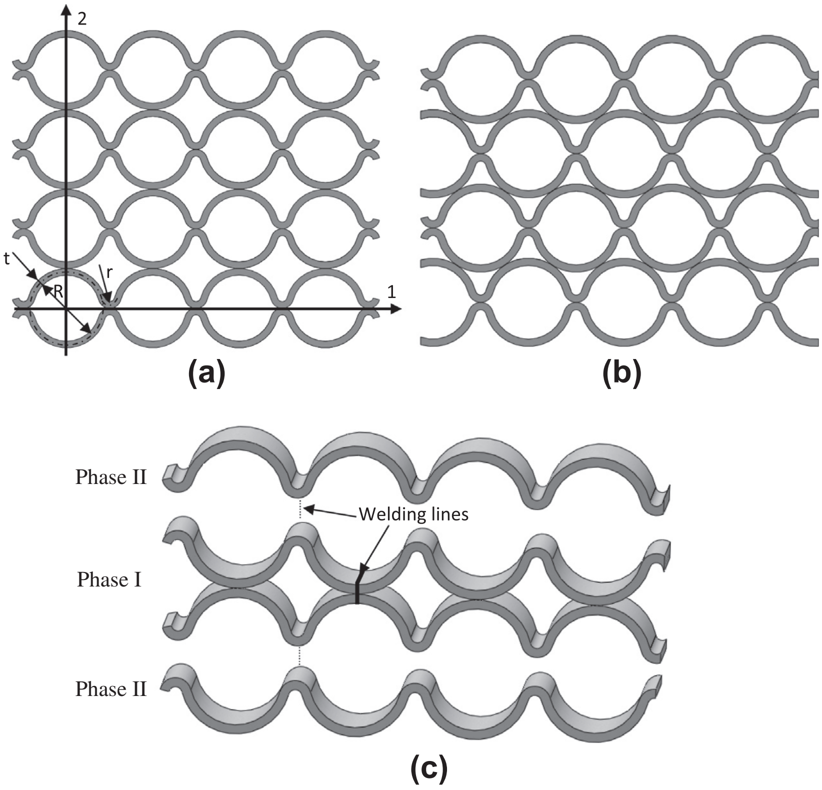

Fig. 1. Cylindrical cell honeycomb structure: (a) the cells are ordered arranged in two rows; (b) the cells are interspersed among others (1 – longitudinal direction; 2 – in-plane transverse direction); (c) the structure assembly procedure.

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