Composite Structures 133 (2015) 77–84

Contents lists available at ScienceDirect

Composite Structures

journal homepage: www.elsevier.com/locate/compstruct

Low frequency acoustic characteristics of periodic honeycomb cellular cores: The effect of relative density and strain fields

Maen Alkhader [a,*], Sumantu Iyer [a], Weixiao Shi [a], T.A. Venkatesh [b]

[a] Department of Mechanical Engineering, Stony Brook University, Stony Brook, NY, United States
[b] Department of Materials Science and Engineering, Stony Brook University, Stony Brook, NY, United States

ARTICLE INFO

Article history:
Available online 23 July 2015

Keywords:
Aluminum honeycomb cores
Nondestructive testing
Bloch theory
Acoustic characteristics
Sandwich structures

ABSTRACT

Aluminum honeycomb cores, widely used in lightweight composite sandwich structures, are inherently weak and highly susceptible to buckling, permanent deformation and damage. This damage can detrimentally affect the structural integrity of sandwich structures and should be detected and repaired. Detecting damage to honeycomb cores is difficult as cores are sandwiched between composite sheets and not accessible. Typically, for such scenario a non-destructive testing method such as ultrasound is appealing. However, with the periodic and porous structure of honeycomb cores, at ultrasound frequencies they are dispersive and exhibit high transmission loss; thus they are incompatible with standard ultrasound techniques. Conversely, at sub-ultrasound frequencies honeycomb cores are less dispersive. Therefore low frequency elastic waves can potentially be used to non-destructively inspect honeycomb cores. To enable low frequency non-destructive testing of honeycombs, it is instrumental first to characterize their sub-ultrasound wave propagation and dispersion characteristics. Accordingly, this work, using finite element analysis, provides insights into the propagation characteristics of low frequency acoustic elastic waves in aluminum honeycomb cores in terms of phase velocity; dispersion and directionality characteristics; and frequency band gaps. Also, the effect of relative density and defects in the form of deformation on sub-ultrasound wave characteristics are explored.

1. Introduction

Lightweight sandwich composite structures, typically formed by adhering two stiff and thin fiber reinforced composite sheets to a thick and low density core, are widely used in composite based applications where stiffness-to-weight ratio is to be maximized and bending is the dominant loading mode, such as in naval, aerospace, and wind-energy applications. In a typical sandwich construction, the composite face sheets provide the primary load carrying capacity, while the low density core allow for achieving increased second moment of inertia, increased flexural rigidity and reduced overall weight. In a properly designed and loaded sandwich structure the composite sheets develop in-plane stresses while the core observes minor stresses, mostly in the form of transverse shear.

Today, one of the most widely used cores in the construction of lightweight sandwich structures is aluminum hexagonal honeycomb core. It is of low cost, can exhibit very low densities, and provides out-of-plane and transverse moduli values that are considered among the highest observed for common metallic and polymeric foam cores [1]. However, as is common for all cores, with the low density and porous architecture of aluminum honeycombs, they are inherently weak and have low yield and failure strengths [2–5]; in the order of few MPa [1]. Accordingly, aluminum honeycombs have high propensity to buckle, permanently deform or fail due to excessive loading or inadvertent activities such as random impacts (e.g., bird impacting a wind turbine blade, wind gusts and wave slamming). Although cores are not the primary load carrying members in a sandwich structure, significant damage to cores can detrimentally affect the structural integrity of the sandwich structure [6]. Damaged cores can negatively affect the load sharing mechanisms in sandwich structures, increase the propensity of composite sheets to buckle, wrinkle and collapse, reducing the load carrying capacity of the composite sheets. Accordingly, damage to cores of sandwich structures should be detected early on and repaired.

Detecting damage to cores in sandwich structures is difficult as cores are sandwiched between composite sheets and are not readily accessible or visible. For such scenarios, non-destructive methods such as ultrasound, which is commonly associated with

* Corresponding author.
E-mail address: maen.alkhader@stonybrook.edu (M. Alkhader).

http://dx.doi.org/10.1016/j.compstruct.2015.07.102
0263-8223/

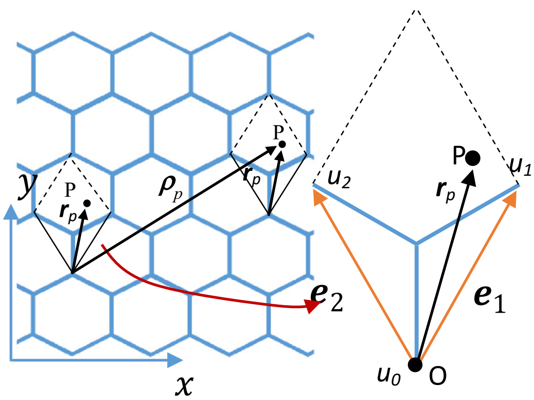

Fig. 1. Periodic hexagonal lattice, showing the corresponding unit cell and base vectors.

composite inspection, would be appealing. However, with the periodic and highly porous structure of honeycomb cores, they are very dispersive and exhibit high transmission loss, particularly at high frequencies 10^6–10^9 Hz [7] (i.e., frequencies in the ultrasound range). Hence honeycomb cores are not readily compatible with standard ultrasound inspection techniques. Conversely, at low frequencies (<10^4 Hz) common aluminum honeycombs (with cell size of few millimeters) are less dispersive [7–9]. Therefore low frequency infrasound or acoustic elastic waves can potentially be used to non-destructively inspect honeycomb cores [7], just like ultrasound is used to inspect dense materials and composite sheets for damage. The pioneering work presented in Ref. [7] demonstrated that low frequency (5–50 kHz) waves can be used to non-destructively detect defects in a honeycomb core as well as delaminations along the honeycomb-composite sheets interfaces with positional accuracy of ±2 mm.

To evolve low frequency non-destructive inspection of aluminum honeycomb cores, optimize it, increase its accuracy and enable its integration in automated health monitoring systems, it is instrumental first to characterize low frequency acoustic and low ultrasound (<10^5 Hz) wave propagation characteristics in aluminum honeycombs. For instance it is important to fully characterize the frequency dependent dispersion, phase velocities and transmissibility in honeycombs as well as their dependence on common geometrical variables pertaining to honeycomb cores. Insights into the low frequency elastic wave propagation in honeycombs would allow for the proper selection of wave frequencies, propagation direction and propagation distance (i.e., wave generator–receiver distance) as well as the proper interpretation of experimental data (i.e., relating changes in wave propagation properties to defects). So far, the low frequency elastic wave propagation in honeycombs have been investigated within the context of establishing relationships between frequency wave gaps and cellular topology [8,10,11] and developing structures with adaptive frequency band gaps [12]; mostly for low frequency selective filtering applications.

Accordingly, this work aims to characterize the frequency-dependent wave dispersion, phase velocities and wave transmissibility in aluminum honeycombs as well as provide insights into their dependence on honeycomb lattice structure (e.g., dimension), relative density and perturbation in the honeycomb geometry due to defects. To achieve its objective this work draws on recent developments in metamaterials and phononic crystals [9] and adopts a well-established theoretical tool (namely Bloch wave theory [13]) that is typically used in characterizing the complex wave behavior observed in periodic metamaterials.

This work is arranged as follows: the implementation of Bloch wave theory is first discussed in the methodology section. Results are presented after methodology and subsequently discussed in a separate section. Finally, findings and remarks are presented in the conclusions section.

2. Methodology

2.1. Material and geometry

The honeycomb considered in this work is a single sided non-welded honeycomb (i.e., its ligaments have uniform thickness). The honeycomb is made of isotropic aluminum (E = 70 GPa, ν = 0.33, and ρ = 2700 kg/m^3). The honeycomb is assumed to have 5 mm long cell walls which is common in industry. As this work is focused on the in-plane wave propagation and as honeycomb's out-of-plane height would not affect its uniform in-plane behavior, the height was set to the practical value of one unit length.

2.2. Bloch's theory and its implementation

Bloch's theory was initially introduced to solve electron and phonon wave motion in solid media with periodic atomistic structures [13]. However, it can be easily adapted to describe wave motion in any periodic or lattice-based structure such as the honeycomb considered in this study. In fact Bloch's theorem has already been used in conjunction with finite element to provide a few insights into the wave propagation in hexagonal periodic media and auxetic structures [8–11,13,14]. In this work, Bloch's wave theorem is implemented in conjunction with the finite element package ABAQUS following Refs [8–11,13,14]. However, this work extends earlier efforts to include relevant parameters such as strain fields and relative density.

As a prerequisite to the implementation of Bloch's theorem, the spatial periodicity of the honeycomb has to be mathematically described and a fundamental repeating cell (unit cell) needs to be identified. By repeating this unit cell the full structure should be reproduced. The periodic honeycomb considered in this study and its unit cell are shown in Fig. 1. This figure also shows the basis vectors along which replicating the unit cell leads to reproducing the full structure. The spatial periodicity of the honeycomb implies that any point on the honeycomb can be describe using the equation

$$\boldsymbol{\rho}_p(n_1, n_2) = \boldsymbol{r}_p + n_1\boldsymbol{e}_1 + n_2\boldsymbol{e}_2 \tag{1}$$

such that $\boldsymbol{r}_p$ is the position of point P in the unit cell (see Fig. 1), $\boldsymbol{\rho}_p$ is the position of point P in a cell located n_1 and n_2 cells away from the unit cell. The values of n_1 and n_2 are integers.

For a periodic medium such as the one presented in Fig. 1, the displacement of point P in the reference cell due to a wave propagating at a frequency ω through the reference cell can be described as

$$\boldsymbol{u}(\boldsymbol{r_p}) = \boldsymbol{u}_o e^{i\omega t - \boldsymbol{k}\cdot\boldsymbol{r}_p} \tag{2}$$

such that $\boldsymbol{u}_o$ is the magnitude of the propagating wave while $\boldsymbol{k}$ is the complex wave vector. Based on Bloch's theory and assuming that the wave vector is spatially constant (i.e., the dispersion and attenuation characteristics of the structure are spatially uniform), the displacement of a point P in cell n_1, n_2 whose location is $\boldsymbol{\rho}_p(n_1, n_2)$ can be expressed as

$$\boldsymbol{u}(\boldsymbol{\rho_p}) = \boldsymbol{u}_{r_p} e^{\boldsymbol{k}\cdot(\boldsymbol{\rho_p} - \boldsymbol{r_p})} = \boldsymbol{u}_{r_p} e^{\boldsymbol{k}\cdot(\boldsymbol{n_1 e_1} + \boldsymbol{n_2 e_2})} \tag{3}$$

To further simplify this equation, the wave vector is first expressed in the reciprocal space spanned by the vectors $\boldsymbol{b}_1$, $\boldsymbol{b}_2$ as