Composite Structures 94 (2012) 2017–2024

Contents lists available at SciVerse ScienceDirect

Composite Structures

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

Experimental studies on mechanical properties of cellular structures using Nomex® honeycomb cores

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ARTICLE INFO

Article history:
Available online 2 February 2012

Keywords:
Experiment
Compliance
Nomex®
Honeycomb core
Stress
Strain

ABSTRACT

An experimental method is presented to obtain the effective in-plane compliance matrices of cellular structures using Nomex® honeycomb cores without a priori assumptions such as orthotropy. In this method, firstly, uni-axial tension tests are carried out for different material orientations. The independent variables in these experiments are the material orientation and displacement of the actuator, while the main dependent variables are positions of the marker points and the force acting on the specimens. Marker tracking technique is used to determine the marker positions which are processed to get strain of the measuring domain, while the stress is estimated through external loading and core geometry. The analysis is confined to the measuring domain under near homogeneous stress and strain fields. The experiment results are processed with transformation and least squares functions to obtain all effective in-plane elastic parameters, which are compared with analytical solution based on deformation of idealized cell structure. Through this comparison, the effects of geometrical parameters of cell structure are discussed in detail. By means of the introduced method, the problem of lack of experimental studies on the effective in-plane compliances of cellular structures in the literature is expected to be solved.

1. Introduction

Honeycomb cores are extensively used in different structural applications such as aviation and automotive industries due to their high stiffness-to-weight ratios. Various analytical techniques and numerical analysis methods have been developed in order to predict in- and out-of-plane mechanical properties of these structures. In many analytical studies, predictions of in-plane core properties have been limited to the assumptions of regular geometry and constant mechanical properties. The approaches are mainly based on bending deformation of inclined walls of a hexagonal unit cell modeled as fixed end-guided end beam [1,2], while the axial deformation of the vertical walls is neglected due to its minor effect on slender honeycomb cell walls [3,4]. The studies related to in- and out-of-plane geometrical variations such as core thickness are also available in the literature [5,6]. In contrast to abundance of analytical approaches, there have been very few experimental studies observing the deformation and predicting the material behavior. Schwingschakl et al. [7] made a broad investigation on fifteen analytical approaches and proposed an alternative dynamic experimental method based on resonance response frequencies. Balawi and Abot [8] conducted series of uni-axial tension tests in order to understand the effect of relative densities on in-plane elastic moduli of core structures. Despite these efforts, almost no experimental investigations have been performed to calculate all effective in-plane elastic parameters. The main reason is that the experimental calculations, especially for in-plane shear modulus, require either more complicated setup than uni-axial tension test setup or a very clever approach. However, in order to understand the deformation of cellular solids, the experiments on in-plane properties have great importance.

In order to complete this missing link in the literature, an experimental method for the effective in-plane compliances of cellular structures is introduced by testing Nomex® honeycomb cores without a priori assumptions such as orthotropy, periodicity, etc. In order to understand the mechanical behavior, uni-axial tension tests are carried out for different material orientations and positions of the marker points on the material are precisely measured through the presented marker tracking technique. These data are processed to get strain of the measuring domain as function of stress and thereby the compliance matrix describing the elastic properties of material. Analysis is confined to a measuring domain under near homogeneous stress and strain fields. Experimental results are further compared to analytical results based on an idealized cell structure. This comparison gives opportunity to investigate the effects of the geometrical parameters such as cell wall length, thickness, and corner angle on the effective in-plane elastic parameters.

The present study is expected to advance the current state of the art through simplicity and low cost of the experiment setup,

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doi:10.1016/j.compstruct.2012.01.024

the measurement and analysis techniques, and the applicability of the introduced method to wide range of cellular structures such as honeycomb cores and wood species.

2. Material and methodology

2.1. Material

Experiments are carried out for Nomex® honeycomb cores with thin cell walls, which are produced from aramid fiber based Nomex® paper dipped in phenolic resin. Its mechanical behavior arises from both the nature of cell wall material and manufacturing process of the core structure. It is known that the cell wall material, Nomex® paper, is produced from fibers aligned in the direction of travel of the paper machine. Thus, it has anisotropy defined with machine and cross (-machine) directions [9]. Besides this characteristic, as shown in Fig. 1, manufacturing of the core structure using corrugation and expansion processes results in directional dependence of mechanical properties [10].

2.2. Theoretical background for in-plane compliance analysis

In order to calculate the effective in-plane mechanical properties of honeycomb cores, various analytical studies have been conducted in which the main strategy comprises core modeling and homogenization [2,8]. Cell geometry is usually described in terms of cell wall thickness t, wall height h, wall length l and corner angle θ as shown in Fig. 2, whereas cell deformation is based on single cell wall deformation as a consequence of bending, shear and/or axial loading. This mechanism is well described with the beam models and suitable boundary conditions. Thereafter, the effective properties are determined through the behavior of regular cell collection [12].

According to [5], the analytical compliance matrix $[\underline{\mathbf{C}}]$ of honeycomb cores with double thickness vertical walls based on bending deformation can be expressed as

$$[\underline{\mathbf{C}}] = \frac{l^3}{E_s t^3}\begin{bmatrix} \dfrac{\sin^2\theta(h/l+\sin\theta)}{\cos\theta} & -\cos\theta\sin\theta & 0 \\ -\cos\theta\sin\theta & \dfrac{\cos^3\theta}{(h/l+\sin\theta)} & 0 \\ 0 & 0 & \dfrac{\cos\theta(h^3+4h^2l)}{4(hl^2+l^3\sin\theta)} \end{bmatrix} \tag{1}$$

in which E_s is the cell wall elastic modulus. Comparison between Eq. (1) and the compliance matrix for orthotropic materials in planar case

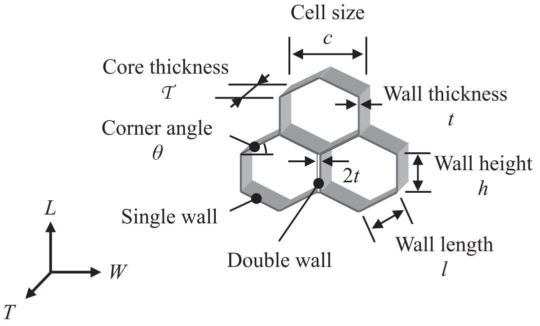

Fig. 2. Geometrical parameters for honeycomb cores and cell walls. Here, W, L, T refer to transverse, longitudinal and thickness directions, respectively [2,11].

$$[\underline{\mathbf{C}}] = \begin{bmatrix} 1/E_W & -\nu_{LW}/E_L & 0 \\ -\nu_{WL}/E_W & 1/E_L & 0 \\ 0 & 0 & 1/G_{WL} \end{bmatrix} \tag{2}$$

gives the effective in-plane elastic parameters in terms of cell geometry and cell wall elastic modulus. In Eq. (2), E_W, E_L, ν_{WL}, ν_{LW}, and G_{WL} are the effective elastic moduli, shear modulus and Poisson's ratios, respectively, for which $\nu_{LW}/E_L = \nu_{WL}/E_W$ [13].

Eq. (1) describes an orthotropic material having two axes of reflection symmetry and, strictly speaking, applies only to idealized material with a regular cellular structure and constant mechanical properties. However, in the authors' opinion, a priori restrictive assumptions like orthotropy, incompressibility etc. should not be used in any material experiments. Instead, the common approach should include the generalized engineering terms and general anisotropic linear elastic materials because the alignment of principal material directions may not initially be known. In this case, the in-plane compliance matrix is

$$[\underline{\mathbf{C}}] = \begin{bmatrix} 1/E_W & -\nu_{LW}/E_L & \eta_{WL,W}/E_W \\ -\nu_{WL}/E_W & 1/E_L & \eta_{WL,L}/E_L \\ \eta_{WL,W}/E_W & \eta_{WL,L}/E_L & 1/G_{WL} \end{bmatrix} \tag{3}$$

in which $\eta_{WL,W}$ and $\eta_{WL,L}$ are called coefficients of mutual influence by Lekhnitski and are characterizing the coupling between shearing and normal stresses [14]. After obtaining the parameters of Eq. (3), one should analyze $[\underline{\mathbf{C}}]$ posterior to classify the material. For this purpose, different approaches such as eigendecomposition of $[\underline{\mathbf{C}}]$ can be employed [15].

2.3. Theoretical background for experiments

As illustrated in Fig. 3, laboratory XY and material WL Cartesian coordinate systems (hereafter, abbreviated as cs) are used. The first

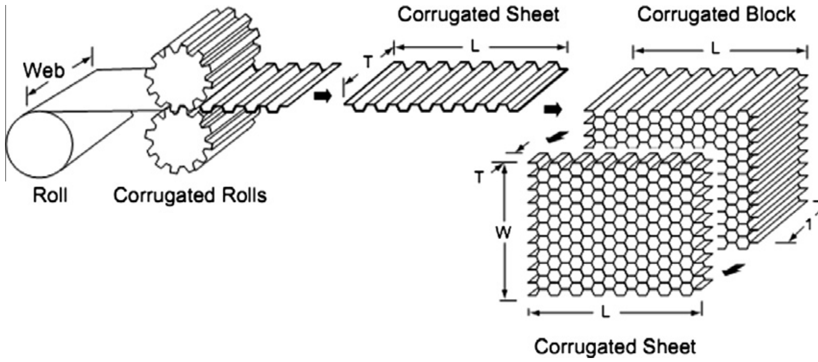

Fig. 1. Production process of honeycomb core [11].