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Optimal design of sandwich panels made of wood veneer hollow cores

S. Banerjee [a,*], D. Bhattacharyya [b]

[a] Centre of Excellence in Engineered Fibre Composites, Faculty of Engineering & Surveying, University of Southern Queensland, Toowoomba, Old 4350, Australia
[b] Centre for Advanced Composite Materials, Department of Mechanical Engineering, The University of Auckland, Private Bag 92019, Auckland, New Zealand

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ABSTRACT

In response to the growing interest in replenishable, lightweight, stiff and strong materials, a novel sandwich panel with a hollow core has been manufactured using commercially produced 3-ply veneer. In this paper, the out-of-plane shear behaviour of the novel hollow core is analysed and the expressions for the failure loads are developed. A strength-based optimisation problem is formulated for predicting the optimum values of the panel dimensions that would produce minimum panel weight when subjected to bending. It has been found that the minimum weight, as predicted by the full four-parameter optimisation, is slightly lower than that obtained by using the closed form expressions derived on the basis of simplified three-parameter optimisation. Relationships between the active failure modes are explored. Design maps are shown for a wide range of loading that can be used to calculate the minimum panel weight and the corresponding values of the geometric parameters. The approach developed is general and is equally applicable for sandwich panels with similar hollow cores made of other materials.

1. Introduction

Sandwich structures, originally developed and used in aerospace industries, have found applications in marine, automotive and sports goods industries. Typical sandwich structures are made of a low density core material bonded with thin, strong skins at top and bottom. While the skins are solid materials, cellular materials including balsa wood, manmade metallic, paper, ceramic and thermoplastic honeycombs, polymeric and metallic foams are popular as core materials. Apart from the excellent stiffness and strength to weight ratios, cellular cores are attractive due to their good thermal and/or acoustic insulation, and energy absorbing capabilities.

In conjunction with the experimental investigation of the development of new materials and topologies for cellular materials, theoretical/computational research has been concentrated on how to calculate their effective mechanical properties in terms of the topology, cell geometry and elastic properties of the cell wall material. The problem becomes more complicated for honeycomb cores as the skin affects the core deformation at the skin–core interface.

Kelsey et al. [1] used strain energy method for predicting the upper and the lower bounds on the effective transverse shear moduli of honeycombs. Gibson and Ashby [2] applied the mechanics of materials and the energy method for determining the transverse shear stiffness of hexagonal core. Penzien and Didriksson [3] used a displacement field for incorporating warping of the cell walls produced by the skin. The homogenisation approach for periodic media was used by Shi and Tong [4] to evaluate the expressions for out-of-plane shear moduli of honeycombs. Using a similar approach, Xu et al. [5] presented formulae of equivalent stiffnesses for common cellular cores. Hohe and Becker [6,7] used a homogenisation approach based on the equivalence of strain energy and developed expressions for the effective elastic constants of several core topologies. Chen and Davalos [8] incorporated the effect of skin, and presented an explicit analytical model for calculating the stiffness and stress distributions in the honeycomb cell walls. Among the numerical approaches, Grediac [9] determined the transverse shear moduli of honeycombs, by analysing a representative unit cell using the finite element method. Though a number of articles on the estimation of the out-of-plane stiffness parameters of cellular cores are available, few address the out-of-plane strength properties. Zhang and Ashby [10] developed expressions for the failure loads of honeycombs under transverse compression and shear loading and compared with the experimental results for Nomex honeycombs.

Performance optimisation of metallic sandwich panels and plates with various cores has been widely explored. For example, optimisation of metallic sandwich plates with truss cores by Wicks and Hutchinson [11,12], design of metallic sandwich panels with textile cores [13], pyramidal truss cores [14] by Zok et al. and corrugated cores by Valdevit et al. [15]. Rathbun et al. [16] developed a general methodology for the weight optimisation of metallic sandwich panels subjected to bending loads. Wei et al. [17] showed that the optimised performances of the prismatic cores are comparable to that of a honeycomb core. Furthermore, Cote et al. [18] analysed the compressive and shear behaviour of corrugated and diamond lattice materials. Extensive study of

* Corresponding author. Tel.: +61 7 4631 1325; fax: +61 7 4631 2526.
E-mail address: Sourish.Banerjee@usq.edu.au (S. Banerjee).

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mechanical behaviour of sandwich structures can be found in the classic book by Allen [19], monographs of Zenkert [20] and Vinson [21], review article on various computational models for sandwich panels and shells by Noor et al. [22] and the references thereof.

With the worldwide interest in replenishable and biodegradable materials, a corrugated profile has been successfully manufactured by roll forming and matched-die forming of commercially available 3-ply veneer sheets [23]. Wood veneers are obtained from Radiata Pine trees of New Zealand and are generally considered to be replenishable, with the advantage of being lightweight as well. For the present work, these profiles were adhesively bonded in the out-of-plane mode to produce a novel multiple corrugated core (referred to as 'hollow core') which was glued to veneer sheets at the top and bottom, Fig. 1a. The average density of the core is 118 kg/m^3, a 77% reduction from the veneer density of 520 kg/m^3. The flexibility of the manufacturing process of the core allows a wide range of cell geometry to be produced, giving the possibility of tailoring the cell structure and the panel geometry to achieve optimal performance for specific materials and end usages. This study focuses on developing a methodology for predicting the optimum values of the geometrical parameters of the panel that would lead to minimum panel weight. The panel subjected to bending load is considered as the loading case. Because the core is subjected to out-of-plane shear forces due to the bending of the sandwich panel, the out-of-plane shear behaviour of the new core material is analysed first. For this purpose, the microstructure is modelled at the mesoscale, i.e. at the cell level. Failure criteria of the whole panel are then developed for optimisation. Strength-based design is chosen as it is more important from the design point of view and is suitable for higher loads. Based on the optimisation results, design maps are generated that can be used to calculate the optimal geometrical parameters and weight of the sandwich panel for a wide range of loading.

2. Out-of-plane shear behaviour of the hollow core

The plan view of the hollow profile is shown in Figs. 1b and 2. Geometry of the core can be characterised in terms of the radius R_c, depth of the half cell h_c, half angle θ_c and thickness of the cell wall t_c; subscript 'c' denotes core. As $R_c(1 - \cos\theta_c) = h_c/2$, the effective mechanical properties of the core become functions of two independent geometric parameters, t_c/R_c and θ_c. For a quarter of a cell, the unit cell (the triangle in Fig. 2) has an area of $2h_cR_c\sin\theta_c$. Therefore, for thin cell walls, $4R_c^2(1-\cos\theta_c)\sin\theta_c\rho^* = 2R_c\theta_ct_c\rho_c$, where, ρ_c and ρ^* are the densities of the cell wall material and the hollow core, respectively. Simplification of the above relationship, leads to an approximate expression of the relative density ϕ of the hollow core as (for $\phi \ll 1$)

$$\phi = \frac{\rho^*}{\rho_c} = \frac{1}{2}\frac{t_c}{R_c}\frac{\theta_c}{(1-\cos\theta_c)\sin\theta_c}. \quad (1)$$

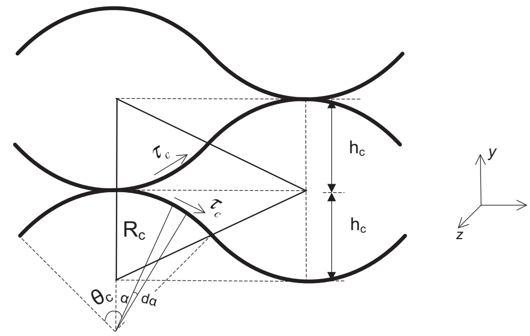

Fig. 2. A unit cell, along with the shear stresses acting in the cell walls, is shown. The triangle is the effective area of the unit cell.

The main assumption for the analysis of sandwich structures under bending loads is that the faces carry all the flexural stresses and the core carries all the out-of-plane shear stresses. When subjected to out-of-plane shear forces, the deformation and hence, the stress distribution in a cell wall is affected not only by its interconnecting neighbours, but also by the strain compatibility condition at the interface of the face and core. This results in a very complicated stress distribution in the cell walls. In this work, neglecting skin effect, the core stresses are determined based on the force equilibrium condition, in the middle of the core (away from the faces).

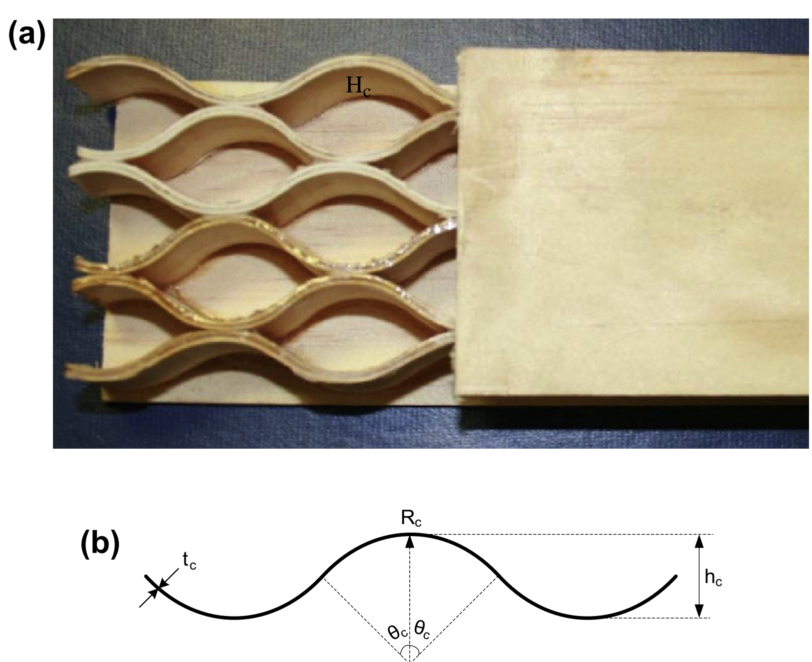

Fig. 1. (a) A typical sandwich panel made with hollow core and face sheets made of 3-ply veneer. (b) The geometric parameters characterising the hollow core in the plane of paper.