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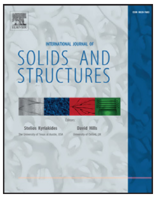

A realistic model for transverse shear stiffness prediction of composite corrugated-core sandwich elements

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ABSTRACT

Several previous studies of the transverse shear stiffness of corrugated-core sandwich elements have demonstrated that the existing analytical formulations significantly overestimate this property, especially when these lightweight elements are made of composite sub-elements. Due to the recent widespread fabrication and use of composite sandwich elements in many fields of application, a more accurate and reliable formulation is needed. This paper deals with an accurate analytical model for predicting the transverse shear stiffness of composite sandwich elements with a structural corrugated core. The effect of the directional material properties of the sub-elements, including face sheets and core, as well as the effect of a low shear modulus in composite material constituents of the sub-elements, is taken into account. It is shown that the transverse shear stiffness of corrugated web core elements is considerably lower than that predicted by the existing formulations. The present solution provides much more realistic results, especially when the corrugated-core sandwich is made of composite constituents with low shear moduli. Different combinations of the main orthotropic material orientation of the faces and core are studied comparatively for different composite material choices corresponding to an innovative timber composite floor case. It is demonstrated that the planar direction of the main orthotropic material orientation of the core has a significant influence on transverse shear stiffness, whereas that of the faces is less important. Several finite element comparisons are made to ensure the reliability of the developed formulation. The importance of the disregarded shear deformation effects on the transverse shear stiffness component versus different geometrical parameters of the sandwich element is studied and discussed.

1. Introduction

Sandwich plates offer significant advantages compared with monolithic and rib-stiffened plates, due to their high stiffness-to-weight ratio (Zenkert, 1995). They provide superior stiffness and strength properties by sandwiching a light core between stiff face sheets. The core in a sandwich element can be made of low-density materials such as foam or light core geometries such as honeycomb, trusses and corrugated configurations. Due to the superior properties of sandwich elements, they have been widely used in different modern technological applications including the aviation industry (e.g. see Sturm et al., 2014; Xie et al., 2016), the maritime industry (Kujala and Klanac, 2005;Crupi et al., 2013), bridge decks (Caccese and Yorulmaz, 2009;Nilsson and Al-Emrani, 2016) and many others. Among the many different types of core, the corrugated core offers many advantages, including ease of production and high structural performance. Sandwich structures with a corrugated core are therefore currently becoming one of the most promising concepts, playing an increasingly important role in many industrial areas (Rimoli et al., 2011; Rejab and Cantwell, 2013; He et al., 2012; Wei et al., 2014).

Recent advances in composite technologies have enabled the more rational, cost-efficient production and design of structural elements made of composite materials and this has led to an increase in the use of this material in structural applications. Corrugated-core sandwich elements fabricated from composite materials offer an extensive range of flexibility and design solutions for structural applications. In recent years, numerous studies have been conducted to characterise different aspects of the mechanical and structural behaviour of this type of sandwich structure, including bending behaviour (Xu et al., 2016; Schneider et al., 2016; Boorle and Mallick, 2016a, 2016b), axial compression and buckling (Xiong et al., 2016), failure mechanisms (Kazemahvazi and Zenkert, 2009; Kazemahvazi et al., 2009; Malcom et al., 2013; Jin et al., 2013) and foam filling effects (Zhang et al., 2013; Bin et al., 2015), as well as the dynamic and impact response of these elements (Russell et al., 2010; Schneider et al., 2015; He et al., 2016).

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A sufficient number of studies have been carried out during the past decades to formulate the equivalent stiffness properties of the corrugated-core sandwiches made of conventional isotropic materials. However, relatively little attention has been paid to applications in which the sub-elements in the sandwich are composed of composite materials. In fact, the influence of directional material properties, as well as the weak transverse shear moduli of composites, must be considered in a suitable manner in order to arrive at an accurate representation of the stiffness properties of sandwich elements made of composite materials. Among the different stiffness components of corrugated-core sandwich panels, the transverse shear stiffness perpendicular to the corrugation direction is mostly influenced by the aforementioned effects. In fact, disregarding these effects (which is often done in conventional formulations) will result in a significant overestimation of the transverse shear stiffness. This has been clearly demonstrated in some previous studies where experimental results are compared with model predictions based on the conventional formulation of the transverse shear stiffness (Nordstrand and Carlsson, 1997).

One of the first effective studies of calculating the stiffness properties of corrugated-core sandwich panels was conducted by Libove and Hubka (1951), where all the stiffness properties required to homogenise a 3-D sandwich plate with a corrugated core were derived. The transverse shear stiffness in the direction perpendicular to the core longitudinal direction, i.e. the weak direction, was derived using the Euler-Bernoulli beam theory. The derivation was based on the principle of strain energy and conservation of energy to describe the deformation of the core exterior point. Libove and Hubka (1951) used a set of equilibrium and kinematic equations to describe the interaction between applied force and deformation. Ko (1980) extended the transverse shear stiffness formulation of Libove and Hubka (1951) to account for the non-uniform thickness of the corrugation leg. Later, Nordstrand et al. (1994) derived a closed-form formula for the transverse shear stiffness of isotropic corrugated-core sandwich elements based on a classical curved-beam theory adopting non-linear through-thickness stress distribution according to Timoshenko (1930). They disregarded the transverse shear deformations of individual sub-elements in the sandwich. Nordstrand et al. (1994) compared the results from their formulation with those obtained by Libove and Hubka (1951) and reported a small difference of around 2% for some cases, which was attributed to the use of the curved-beam theory in their analysis. Nordstrand et al. (1994) also observed that the transverse shear modulus normal to the corrugation direction is much smaller and is more sensitive to the corrugation shape than the transverse shear modulus along the corrugation direction. Romanoff and Kujala (2002) presented a formulation for the transverse shear stiffness of isotropic corrugated-core sandwich panels in the weak direction, with the assumption of a continuous surface connection between the core and the face plates. In their analysis, the shear deformation of the sub-elements was also disregarded. Cheng et al. (2006) applied a numerical approach to determine the elastic constants of sandwich elements using finite element analysis (FEA). The homogenisation process for web-core sandwich panels, as sandwich panels where the core consists of a number of flat vertical plates, is described in detail in Romanoff (2007).

In an experimental study conducted by Nordstrand and Carlsson (1997), the stiffness parameters of cardboard corrugated-core sandwich panels were measured and compared with an analytical formulation. The individual elements in a cardboard sandwich plate naturally have orthotropic properties, which need to be accounted for in the analysis of these plates. Nordstrand and Carlsson (1997) observed that the measured transverse shear stiffness values were significantly lower (by a factor of more than fifteen!) than those calculated on the basis of the analyses in either Nordstrand et al. (1994) or Libove and Hubka (1951). The discrepancy between the test and analytical results was attributed to delamination damage that would have taken place during testing, as well as to changes in the core shape that may have occurred during the manufacture of the corrugated cardboard (see also Carlsson et al., 2001). Even though the aforementioned deviations between the tested plates and the idealised cases assumed in the analysis may explain part of the difference noted in that study, the authors of the present paper believe that this considerable difference is the result of disregarding two important items: the transverse shear deformations of each sub-element and the orthotropic plate action effects in these elements. The objective of the current study is therefore to present a more realistic and reliable formulation for the weak transverse shear stiffness component of composite corrugated-core sandwich elements. The current study can be regarded as an extension of the original formulation by Libove and Hubka (1951) by accounting for the weak transverse shear moduli and orthotropic material properties of plate/shell sub-elements in a three-dimensional geometry.

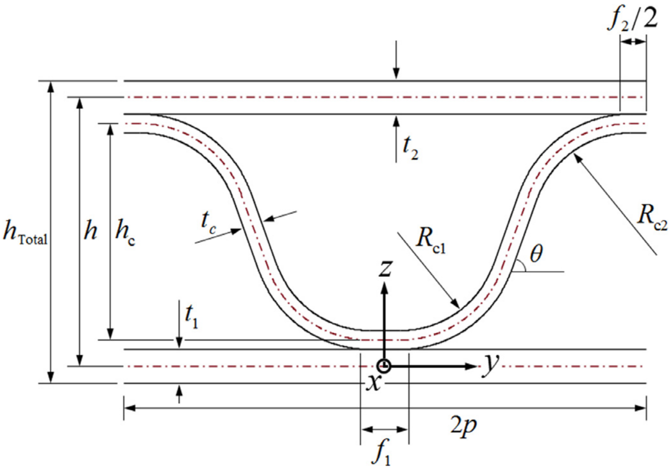

Fig. 1. Geometrical configuration of corrugated-core structural sandwich element and the co-ordinate system.

2. Mathematical analysis

2.1. Geometrical configuration

Consider the cross-section of a unit cell element of a corrugated-core sandwich plate like the one shown in Fig. 1. Even though the current study focuses on sandwich plates with a corrugated core, the derivation of the transverse shear stiffness is made general and the same procedure can be used to obtain this stiffness component for a sandwich plate with any arbitrary core, such as trapezoidal, vertical web, triangular, circular and so on. The origin of the Cartesian co-ordinate system is set in the middle of the lower faces. As shown in Fig. 1, t_1, t_c and t_2 are the thicknesses of the upper face, core and lower face respectively; R_{c1} and R_{c2} are the curvature radius of the core at the upper and lower corners respectively; f_1 and f_2 are the lengths of the horizontal straight parts of the core in contact with the faces; θ is the angle between the face sheets and the straight diagonal portion of the corrugation leg; h_c is the height of the core,h is the vertical distance between the mid-planes of the face plates and $2p$ is the corrugation pitch.

2.2. Kinematics of the model

To calculate the transverse shear stiffness of the unit cell, a shear load situation is considered, as illustrated in Fig. 2a. The unit cell element is subjected to a transverse load, Q_y, and horizontal

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