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Global bending response of composite sandwich plates with corrugated core. Part II: Effect of laminate construction

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ABSTRACT

Global bending response of simply supported composite sandwich plates with corrugated core was studied using carbon fiber reinforced epoxy laminates in both face plates and inclined webs in the corrugated core. Two different laminate constructions were considered, namely $[0/\alpha]_S$ and $[\pm\alpha]_S$ and the fiber orientation angle was varied from 0° to 90°. Sandwich plate geometric parameters, such as face thickness, pitch and face center distance were maintained constant, but the web inclination was varied from a triangular configuration to a square configuration. The web thickness was varied with web inclination angle so that the sandwich plates had the same cross-sectional area and, therefore the same mass. This allowed a direct comparison between different laminate constructions for each web inclination angle. It was shown that for the same mass, the maximum deflection under a distributed load depends on both the web inclination angle and the laminate construction. It is significantly higher with the $[\pm\alpha]_S$ construction than with the $[0/\alpha]_S$ construction. For both laminate constructions, the largest maximum deflection occurs at a web inclination angle of 48°, which can be attributed to the combined effect of the transverse shear stiffness components.

1. Introduction

Corrugated-core sandwich plates with two thin face plates and a corrugated core are found in many applications, such as fiberboards and aircraft floors, where high flexural stiffness per unit mass is desired compared to monolithic and rib-stiffened plates [1]. They can also provide vibration and noise control, shock and impact resistance, and high energy dissipation [2–6]. The core may be designed in a variety of geometries, such as triangular, trapezoidal, sinusoidal and cellular. Using fiber reinforced composites in the face plates and the core of corrugated-core sandwich plates increases their design space due to the variety of fiber architecture that can be used in making these composites. Because of this, geometric, material and fiber architecture parameters that affect the stiffness, strength and other characteristics of corrugated-core composite sandwich plates are of interest.

Most of the previous analytical and numerical work on the global bending response of corrugated-core metallic sandwich plates [7–10] are based on a homogeneous plate assumption suggested by Libove and Hubka [7]. Under this assumption, the corrugated-core sandwich plate is replaced with an orthotropic homogeneous plate with equivalent elastic constants. Fung et al. [8] extended this approach to derive the expressions for transverse shear stiffnesses of Z-core sandwich panels with unidirectional Z-shaped channels in the core and C-core sandwich panels with unidirectional C-shaped channels in the core [9]. In another study, Lok and Cheng [10] used the homogeneous equivalent thick plate approach to determine maximum plate deflection of truss-core sandwich panels made of an aluminum alloy. They used both closed-form equations and finite element method for the maximum deflection calculation and found good agreement between the two. The maximum deflection had the lowest value with a triangular truss-core and the highest value with a rectangular truss-core. They also observed that the shear stiffnesses have negligible influence on the maximum deflection if a triangular core is used. On the other hand, sandwich panels with vertical core members have low shear stiffness, which significantly influences their maximum deflection.

Chang et al. [11] analyzed the linear elastic bending behavior of a corrugated core sandwich plate in which an isotropic material, in this case steel, was used for faces and webs. They calculated the elastic constants of a three-dimensional sandwich panel using force-distortion relationship given by Libove and Hubka [7] and used them into an equivalent two-dimensional structurally orthotropic thick plate continuum model. They investigated the effects of several geometric parameters, such as corrugation angle and

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web-to-face thickness ratio, and two different boundary conditions on the deflection, bending moments and shear forces in the plate subjected to a uniform pressure load.

Wang et al. [12] treated a triangular core aluminum sandwich plate as a three-layered laminated plate in which the triangular core was replaced with an equivalent homogeneous layer. They derived the elastic constants of the equivalent homogeneous layer by applying the small-deflection beam theory to the inclined members of the triangular core.

Martinez et al. [13] developed an equivalent plate model for composite corrugated-core sandwich panels using the homogenization approach. However, unlike the previous works, the material in the faces and the webs was a laminated carbon fiber reinforced epoxy composite with a $[0/90]_S$ laminate construction. The extensional, flexural and coupling stiffness matrices as well as transverse shear stiffness terms for the equivalent plate were calculated using strain energy equivalency. The bending response, which included the maximum deflection and stresses, was determined using a higher order shear deformable plate theory.

Boorle and Mallick [14] extended the work by Martinez et al. by considering the effects of geometric parameters such as face thickness, web thickness, web inclination angle, pitch and face center distance. The laminate construction in the face plates and webs was $[0/90]_S$. The corrugated core was first transformed into an equivalent homogeneous plate and then global bending deflection, bending moment and shear force distributions were calculated using the minimum potential energy approach.

The current study considers the effects of laminate construction in the face plates and webs on the bending response of a corrugated core composite sandwich plate. Two different laminate constructions are considered, namely $[0/\alpha]_s$ and $[\pm\alpha]_s$ and the fiber orientation angle α was varied from 0° to 90°. The bending response includes the global deflection, bending moment and shear force distributions.

2. Analytical formulation

The analysis was performed using a unit cell of the type shown in Fig. 1. The unit cell is made of two thin faces (indicated as members 1 and 2 in Fig. 1) and two inclined webs (indicated as members 3 and 4 in Fig. 1) in the core. The *xyz* coordinate system is located at the centroid of the unit cell. The unit cell is aligned in the *x*-direction. It is symmetric with respect to the *xz* plane and the *y*-direction is normal to the corrugation direction. The material in the faces and the webs is a symmetric carbon fiber reinforced composite laminate with a stacking sequence of $[0/\alpha]_s$ and $[\pm\alpha]_s$, where α represents the fiber orientation angle with respect to local *x*-direction of each laminate. The angle α was varied from 0° to 90° in steps of 15°.

The analytical formulation starts with the geometric parameters of the unit cell. It then derives the bending stiffness matrix of the unit cell, the shear stiffness components and finally, the potential energy formulation to determine the global deflections, bending moment and shear force components.

2.1. Geometric parameters

The geometric parameters of the unit cell that can be independently varied are pitch of the unit cell ($2p$), face center-to-center distance (d), top face thickness (t_{TF}), bottom face thickness (t_{BF}), web thickness (t_c) and web inclination angle (θ). In this study, it is assumed that $t_{TF} = t_{BF} = t$ so that the core depth (d_c), i.e., the distance between the faces, is equal to $(d–t)$. For the unit cell considered, the maximum web inclination angle is 90°, which corresponds to a rectangular core. The minimum web inclination angle is given by $\theta_{\min} = \tan^{-1}(\frac{d}{p})$, which corresponds to a triangular core. The cross-sectional area A_θ of the unit cell with web inclination angle θ is given by the following equation.

$$A_\theta = 4pt + 2(d-t)\frac{t_c}{\sin\theta} \quad (1)$$

where, $\theta_{\min} \leqslant \theta \leqslant 90°$. A_{90} is the cross-sectional area of the unit cell with a rectangular core for which $\theta = 90°$.

2.2. Stiffness matrix for the face and web members of the unit cell

The face and core members are thin laminated composite plates. The in-plane extensional-shear and out-of-plane bending–twisting responses of each member are governed by its own [*A*], [*B*] and [*D*] matrices relative to its mid-plane [15]. Deformation $\{D^{(e)}\}$ of each member in the unit cell can be written in terms of deformation of the unit cell $\{D\}^M$ in the following way.

$$\{D\}^{(e)} = [T_D]^{(e)}\{D\}^M \quad (2)$$

In Eq. (2), $[T_D]^{(e)}$ represents the global-to-local co-ordinate transformation matrix for member *e*. Eq. (4) relates the deformations of the unit cell in the global (*x*, *y*) co-ordinate system to the deformations of each member in the unit cell in its local $(\bar{x},\bar{y})$ co-ordinate system.

The strain matrix for each member in the unit cell is given as follows:

(i) Top and bottom faces

$$\begin{Bmatrix} \varepsilon_{xo} \\ \varepsilon_{yo} \\ \gamma_{xyo} \\ \kappa_x \\ \kappa_y \\ \kappa_{xy} \end{Bmatrix}^{(1),(2)} = \begin{bmatrix} 1 & 0 & 0 & \pm\frac{d}{2} & 0 & 0 \\ 0 & 1 & 0 & 0 & \pm\frac{d}{2} & 0 \\ 0 & 0 & 1 & 0 & 0 & \pm\frac{d}{2} \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \begin{Bmatrix} \varepsilon_{xo} \\ \varepsilon_{yo} \\ \gamma_{xyo} \\ \kappa_x \\ \kappa_y \\ \kappa_{xy} \end{Bmatrix}^{(M)} \quad (3a)$$

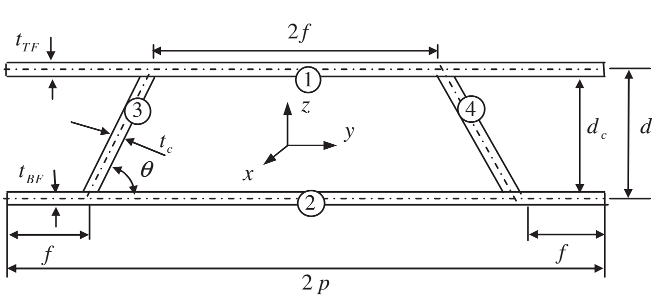

Fig. 1. Description of the unit cell.

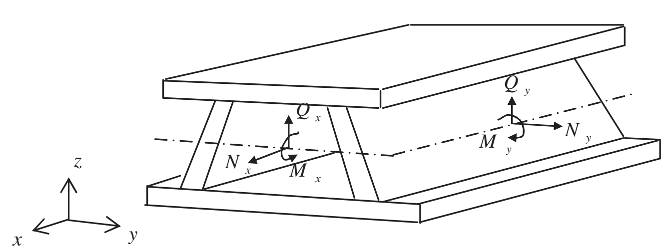

Fig. 2. Global normal forces, shear forces and bending moments on the unit cell.