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Evaluation of homogenized effective properties for corrugated composite panels

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ABSTRACT

Corrugated panels are widely used as structural elements in engineering fields because of their high stiffness and light weight. Moreover, corrugated composite laminates have attracted much attention as a candidate for morphing aircraft wing that need to have different behaviors in different directions due to their extremely anisotropic behavior. The simple model is required to investigate the mechanical behavior of these structures in design process. On this demand, the equivalent homogenization method of corrugated panels has been used during last decades. This homogenization model is usually treated a corrugated panel as an orthotropic panel that has different material properties in two perpendicular directions. This paper presents an analytical homogenization model for corrugated composite laminates that can be applied easily to any corrugation geometry. This paper gives explicit expressions to calculate not only the effective extensional and bending stiffness but also the effective transverse shear stiffness for a composite corrugated panel. The effective stiffness of the trapezoidal corrugation shape which is the most common corrugation geometry is evaluated and compared with those of the flat composites. To validate the proposed approach, the obtained results are compared with the previously published results.

1. Introduction

A corrugated panel is usually corrugated in one direction. This panel is flexible along the corrugation direction and stiff transverse to the corrugation direction. This is assumed to have periodic corrugations in the longitudinal direction only. Adapting corrugated panels to structures, we can achieve a higher strength than flat panels, and can thus improve the strength/weight ratio of structures. Because of these advantages, corrugated panels have been widely used over many decades in various engineering fields where low weight is important, such as aviation, aerospace, automotive and civil engineering. Because it is very difficult to determine its mechanical behavior of 3-dimensional corrugated structures analytically, 3-D finite element method is commonly employed to analyze these structures. 3D FE model can be represented the actual geometry. But 3D FE modeling will be extremely tedious and time-consuming. It is inadequate when one is interested in the overall response of the structure. For these reasons, 2D equivalent orthotropic models can be used to represent the behaviors of corrugated structures. The resulting orthotropic panels could be analyzed by closed-form solutions or numerical methods. It should be estimated the effective stiffness of the equivalent models correctly to obtain the satisfactory approximated solution.

Numerous studies have been carried out on the homogenization method and the mechanical behavior of corrugated structures for general applications. Samanta and Mukhopadhyay [1] carried out static and dynamic analysis of trapezoidal corrugated sheet by considering extensional and bending rigidities. Lok and Cheng [2] presented equivalent bending, twisting, and transverse shear stiffness of a sandwich panel and discussed the influence of the relatively weak transverse shear stiffness on the behavior. Machimdamrong et al. [3] considered the transverse shear stiffness to estimate the elastic shear buckling capacity of corrugated plates with edges elastically restrained against rotation. Liew et al. [4,5] studied the equivalent elastic properties by means of a mesh-free Galerkin method for the nonlinear bending and vibration analysis of corrugated plates. Isaksson et al. [6] investigated the shear correction factor for the sinusoidally corrugated core panels. For the triangular corrugation, Wang and Chung [7] described the equivalent elastic constants analytically and compared the accuracy with FE simulation. Bartolozzi et al. [8] determined the properties of the equivalent material of a metal sandwich panel with sinusoidal corrugated core based on energy approach. They [9] extended these methods to obtain the equivalent properties of the sandwich structures with a general shape corrugated core. And they [10]

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performed the experiment, which involved both the static and dynamic behavior of the sandwich structure, to validate their analytical modeling method. Cheng et al. [11] employed the finite element analysis method to derive equivalent stiffness properties of sandwich structures with various types of cores. Hernández-Pérez et al. [12] determined effective elastic constants based on finite element analysis and analyzed the twist stiffness of single and double-wall corrugated boards theoretically, numerically and experimentally. Mohammadi et al. [13] presented equivalent mechanical properties of the trapezoidal corrugated core using the similar method that Bartolozzi et al. [8] presented. Ye et al. [14] derived an equivalent plate of corrugated structures using the variational asymptotic method based on a thin shell theory.

Because the corrugated panels offer both load carrying capacity and large shape change efficiency, they can be applicable to morphing aircraft wings and flexible blades. Besides, the composite materials, which have become common engineering materials and are designed for various applications, are applicable in morphing structures because of their highly anisotropic behavior. Yokozeki et al. [15] evaluated mechanical properties of the corrugated composites both by analytical method and experiment. Martinez et al. [16] developed an equivalent plate model for composite corrugated-core sandwich panels using a micromechanics approach. They were calculated the extensional, flexural and coupling stiffness matrices as well as transverse shear stiffness terms for the equivalent plate using the strain energy approach. Talbi et al. [17] determined the effective homogenized properties for an equivalent orthotropic plate for corrugated orthotropic cardboard structures and proposed a new shell torsion model to derive the twist stiffness. Thill et al. [18] investigated the local failure mechanisms of trapezoidal corrugated aramid/epoxy laminates experimentally. Abbés and Guo [19] presented an analytic homogenization model for the torsion of orthotropic sandwich plates and its application to the torsion modelling of corrugated cardboards. Kress and Winkler [20] derived the expressions of effective stiffness of composite laminates with circular corrugations using a thin shell theory. They [21] investigated the influence of the cross-section geometry of corrugated laminates using finite element method. Xia et al. [22] gave explicit expressions to calculate the equivalent material properties of corrugated laminates, which could be used for any corrugation shape. Rejab and Cantwell [23] investigated the compressive properties of triangular corrugated-core composite sandwich panels both experimentally and numerically. Dayyani et al. [24] provided equivalent models of composite corrugated cores with elastomeric coatings to calculate the equivalent tensile and bending flexural properties and compared numerical and experimental results. Ghabezi and Golzar [25] evaluated effective mechanical properties of the trapezoidal corrugated composites analytically and experimentally. Golzar and Ghabezi [26] presented the effective stiffness in the longitudinal and transverse directions of various composite corrugated structures. Schmitz and Horst [27] investigated deformation limits and stiffness of circular corrugated unidirectional reinforced composites experimentally as well as theoretically. Shaw et al. [28] examined the optimization of a corrugated skin in order to minimize weight whilst resisting a compressive buckling load. Recently, Boorle and Mallick [29] extended the work by Martinez et al. [16] by considering effects of various geometric parameters on the global bending response of composite sandwich plates with corrugated core.

The equivalent orthotropic model is adequate when one is interested in the overall response of the structure. Therefore, a corrugated panel may be homogenized as an equivalent thick panel. And the shear stiffness in the transverse direction is relatively weak. Hence, it is to be considered the effect of transverse shear deformation to predict correctly the behavior of corrugated or sandwich structures. Generally, most of the researchers presented the effective extensional, bending, twisting and in-plane shear stiffnesses for an equivalent model. Some studies presented the effective transverse shear stiffness for isotropic materials [2–3,6–13]. However, it is very limited for the composite laminates [16,29].

In this paper, an analytical homogenization model based on the energy approach for laminated composite corrugated panels is presented. This homogenization model is treated as an orthotropic panel with uniform thickness that has different material properties in two perpendicular directions. This homogenization method can be applied easily to any corrugation geometry. To evaluate the effective stiffness of corrugated panels the trapezoidal corrugation which is the most common corrugation geometry is considered. The effective extensional, bending, twisting, in-plane shear and transverse shear stiffnesses of the equivalent panel are derived for the analysis. To demonstrate the validity of the proposed approach, the comparisons are made with the previously published results. To compare the equivalent transverse shear stiffness, results for the isotropic material are presented because there is no available data for equivalent transverse shear stiffness of composite corrugate panels. The comparison shows the efficiency and accuracy of our homogenization model. Some numerical results are presented to check the influence of material configurations and geometric properties.

2. Formulation

Fig. 1(a) shows a typical corrugated panel with length a and thickness t. The width of the panel is unitary. The corrugated panel is treated as an equivalent orthotropic panel of uniform thickness. A corrugated panel homogenizes as an equivalent thick panel with uniform thickness t_e.

From classical plate theory, the constitutive equation of a corrugated composite panel of a symmetrical lay-up can be written in the local curvilinear coordinate (s, y, n) as

$$\begin{Bmatrix} \mathbf{N} \\ \mathbf{M} \end{Bmatrix} = \begin{bmatrix} \mathbf{A} & 0 \\ 0 & \mathbf{D} \end{bmatrix} \begin{Bmatrix} \boldsymbol{\varepsilon} \\ \boldsymbol{\kappa} \end{Bmatrix}, \quad \mathbf{Q} = \mathbf{A}_s \boldsymbol{\varepsilon}_s \tag{1}$$

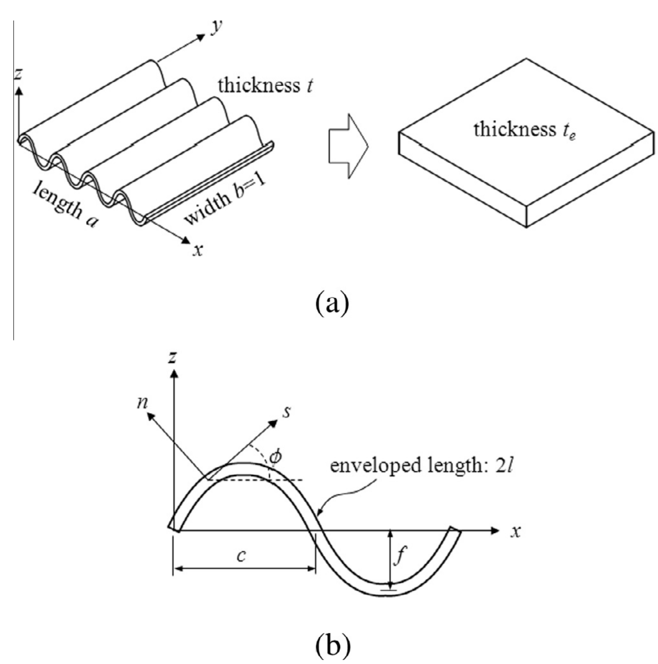

Fig. 1. Illustration of (a) homogenization of corrugated panel, (b) cross-section of its unit corrugated cell.