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A layerwise/solid-element method of the linear static and free vibration analysis for the composite sandwich plates

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ABSTRACT

In the traditional analysis schemes of the composite sandwich structures the core is firstly simplified as an equivalent anisotropic material and then modeled by the plates and shells theories. Its main disadvantage is that the equivalent core will result in large equivalent error especially in the key area and the thick core will further reduce the analysis accuracy of the plates and shells theories. Therefore, a layerwise/solid-element method (LW/SE) is proposed in this paper, in which the layerwise theory is used to model the behavior of the composite laminated facesheets while the eight-noded solid element is employed to discretize the core. Three models, the full model, the local model and the equivalent model, are presented to model the core. Several numerical examples are investigated and the static analysis and free vibration analysis of the composite sandwich plates are tested. The results of proposed method are in good agreement with those of 3D finite element model. A detailed comparative study is conducted to investigate the performance of three modeling schemes for static analysis and free vibration analysis problems.

1. Introduction

In recent years the composite sandwich structures, which consist of two thin but stiff composite laminated facesheets bonded to a lightweight and thick core with low in-plane modulus, are widely used in transportations, marine, aeronautics and astronautics owing to the low weight and high rigidity. Similar to the flanged beam, in the sandwich structures the most of the in-plane membrane and bending forces are carried by the facesheets while the shear loads are transferred by the core. The complexity of the overall and local behavior of the sandwich structures has aroused a large number of computational methods.

The investigations of the computational models for incompressible sandwich structures started from Reissner [1] and many others [2–5]. One of the well-known conventional modeling approaches is the splitting rigidity approach [3–5]. Recently, the modeling scheme of composite sandwich structures is regarded as following the same analysis schemes of the composite laminated structures, such as the equivalent single layer theory (classical laminate theory and shear deformation laminated plate theories) [6–12], three-dimensional elastic theory (traditional 3-D elastic formulations, layerwise theory, unified formulation and generalized unified formulation) [13–17] and multiple model methods [18,19]. However, the response of composite sandwich structures is significantly affected by transverse shear deformation resulted from the large core thickness and wide variety in material properties along the thickness direction of the composite laminated facesheets. These influences cannot be considered adequately by the equivalent single layer theories. Consequently, the analysis of composite sandwich structures may require the layerwise or 3D elastic theory. Since the number of the exact 3D elasticity solutions is limited [20] and the 3D finite element analysis may need enormous computational cost, the layerwise theory would be a better choice compared to the equivalent single layer theory and 3D elasticity theory.

Hu [21] assessed the accuracy of the computational models based on various shear deformation theories and Zig–Zag theories in predicting the bending behavior of sandwich plates under static loading and the dynamic problem. It comes out from this assessment process that the Zig–Zag models are more accurate than the classical laminate theory and shear deformation theories. Ferreira [22,23] has studied the static deformations and free vibration problem with the layerwise theory and radial basis functions for laminated and sandwich plates. Roque [24] developed a trigonometric layerwise deformation theory for modeling symmetric composite plates and sandwich plates. Theofanis [25] presented a high-order discrete-layer theory for predicting the damping of composite laminated sandwich beams, in which the quadratic and cubic terms were involved when approximating the in-plane displacement in each discrete layer and the interlaminar shear stress continuity was imposed through the thickness. In addition, for the composite sandwich structures there are many other literatures studying the computational modeling by using the layerwise theories [26–29].

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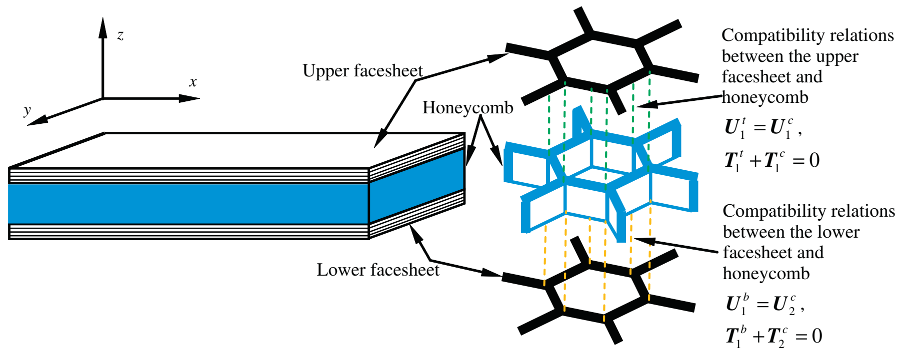

Fig. 1. Schematic diagram of the LW/SE method for the composite sandwich structures.

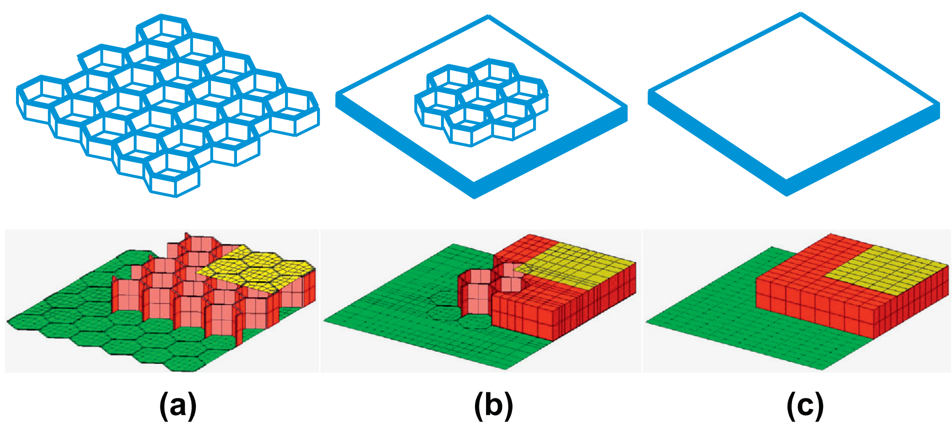

Fig. 2. Schematics diagram and meshing of three different modeling strategies for the honeycomb. (a) Full model, (b) local model, and (c) equivalent model.

The main emphasis of the above methods was to determine the overall global response. The use of a flexible core in modern sandwich structures subjected to partially distributed loads, point load and point supports yields localized deformations along the panel, in the form of indents, which are associated with inconsistent displacements of upper and lower facesheets. The detailed local damages morphology and failure process are very important for the impact dynamics analysis of the modern sandwich structures. Further, there are two more reasons which will lead to low accuracy of the above analysis schemes of the composite sandwich structures: one reason is that the material parameters calculated by the equivalent methods (such as sandwich theory [30]) cannot fully reflect the mechanical behavior of the core; another one is that the thick core reduces the analysis accuracy of the plates and shells theories which are usually employed to model the behavior of the facesheets and equivalent honeycomb. The core thickness of sandwich structures usually ranges between 3 and 26 mm [31]. Therefore, it is very necessary to develop an analysis scheme which not only can obtain the accurate local displacements and stresses of the facesheets and core but also can reduce the influence of the thickness and equivalent of core on the analysis accuracy at a reasonable computational cost.

The remarkable influence of the transverse shear deformation resulted from the high core thickness can be removed if the core is discretized independently by brick elements while the composite laminated facesheets are still simulated by the layerwise theory. Fortunately, unlike the equivalent single layer theories, the governing equations of facesheets established by the layerwise theory can be conveniently coupled with the governing equations of the core established by the brick elements based on the compatibility conditions at the interface between facesheets and core, since the degree of freedoms (DOFs) of the layerwise theory is equal to that of the brick element and the displacements variables of the upper and lower surface of facesheets appear in the governing equations. In this modeling scheme, if the overall or one part of the core is discretized by solid elements, the error introduced by the equivalent methods about the core properties [29] will disappear or decrease. In addition, the detailed local deformation of the facesheets and core can be obtained by using this scheme if the core cells belonging to the special attention area (key region) are modeled based on the real structure form completely instead of the equivalent form.

In present work, a layerwise/solid-element method is established, in which layerwise theory and the eight-noded solid elements are used to model the behaviors of the facesheets and the honeycomb, respectively. Based on the finite element formulation of the facesheets and the honeycomb, the governing equations of the composite sandwich plates are assembled by using the compatibility conditions at the interface. And the modeling method of the core is investigated in detail.

2. Layerwise laminate theory for composite laminated plates

In the layerwise laminate theory [18], the displacements at point (x, y, z) in the composite laminated plates are assumed to be

$$u(x,y,z) = \sum_{i=1}^{N+1} u_i(x,y)\phi^i(z),\ \ v(x,y,z) = \sum_{i=1}^{N+1} v_i(x,y)\phi^i(z),\ \ w(x,y,z) = \sum_{i=1}^{N+1} w_i(x,y)\phi^i(z) \tag{1}$$