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Study on shear postbuckling failure of composite sandwich plates by a quasi-conforming finite element method

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ABSTRACT

A quasi-conforming triangular sandwich plate element with 7 degrees of freedom (DOF) per node is established based on a simplified Zig-Zag model and a transverse shear deformation theory. The accuracy of the proposed element has been validated to be equivalent to the element based on the complete Zig-Zag model (11 DOF per note). The path-following method, proposed by Huang and Atluri, is improved and applied to follow complex postbuckling paths with secondary bifurcation points and progressive failure. A finite element (FE) modeling is completed to study the shear postbuckling behavior and failure of composite sandwich plates, based on the energy criterion of stability and the strength criterion of each layer. The basic characteristics of the shear postbuckling and failure are illustrated. The complexity and computation difficulty caused by secondary bifurcations and multi-paths are discussed. Numerical examples show that the proposed method is efficient in improving the convergence of iterations.

1. Introduction

Composite sandwich plates, as a component bearing main loads, have been used extensively in various industries (such as aerospace and transportation) due to their high ratio of stiffness/strength to weight, high structural stability and damping capability. Generally, sandwich plates with high strength face sheets (FSs) and light weight cores have higher ratio of stiffness/strength to weight than plates with single materials [1].

As is well known, the buckling load does not represent the maximum load that the structure can carry. Indeed, some composite sandwich plates can still resist more loading well after the initial buckling occurs. Therefore, to exactly predict the postbuckling behavior and progressive failure of composite sandwich plates is of importance in designing and maintaining composite sandwich structures [2]. So far, the shear postbuckling failure of composite plates [3] is investigated fewer than the compression case [4,5], and the most of the studies are contributed to laminated composite panels [6,7]. In fact, the postbuckling behavior of sandwich plates is often much more complicated than that of isotropic or laminated plates. For example, the equilibrium states may be instable and with multi-paths. Moreover some secondary bifurcation points may exist besides the initial one. So nonlinear FE modeling is a widely applied approach to postbuckling analysis.

To predict the buckling and postbuckling behavior of sandwich structures, the displacement based approaches are often used. The linear zig-zag theory (Z-ZT) is more efficient and relatively simpler approach. Based on the linear Z-ZT, Hadi et al. [8] studied the buckling of sandwich plates analytically. Chen et al. [9] simulated the postbuckling behavior of face/core debonded composite sandwich plate. Recently, based on the nonlinear Z-ZT, Sahoo and Singh [10] presented a new inverse hyperbolic zig-zag element, which shows very high accuracy in analyzing the free vibration of thick sandwich plates. Generally, the postbuckling of composite sandwich plates is in connection with various damages.

Numerical approaches, represented by finite element method and path following schemes combined with arc-length method, are widely used in nonlinear postbuckling analysis of plate/shell structures. The scheme to trace the path of geometrically perturbed structures with an assumed initial imperfect is generally

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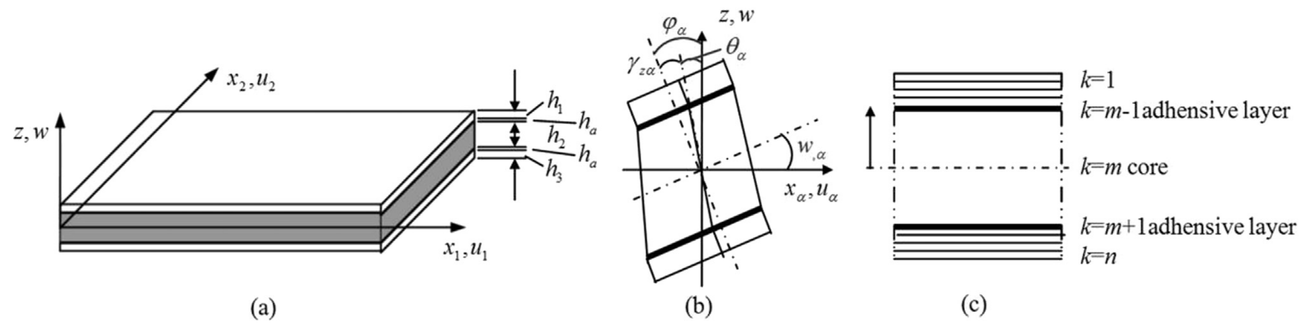

Fig. 1. (a) sandwich plate; (b) after deformation; (c) layer number.

efficient at the simple bifurcation point of linear prebuckling states, but in more complex cases, the assumed imperfects may induce to trace non-actual paths. To trace the postbuckling paths of perfect structures with bifurcation points, it is necessary to identify bifurcation points and to complete the branch-switching to secondary paths. Wagner et al. [11] and Wriggers et al. [12] proposed a branch-switching method by using the buckling mode as a prediction of the secondary path. Zhou et al. [13] improved the method and applied to the postbuckling analysis of cylindrical panels. Huang and Atluri [14] presented a simple method to identify the limit points or bifurcation points and to conduct branch-switching based on Koiter's initial postbuckling analysis. In order to trace the real path in multi-paths with complex bifurcation points, more attention should be paid to the prediction of the branch paths.

The aim of this paper is to study the shear postbuckling failure of composite sandwich plates and the approach to following multi-paths with secondary bifurcation points through FE modeling. Based on the quasi-conforming laminate plate element presented in Ref. [15] and an equivalent first order shear deformation theory, we presented a simplified Zig-Zag sandwich plate element with weak C^1 continuity (or quasi-conforming) and 7 DOF per node. Then, the path-following method proposed by Huang and Atluri [14] is improved and applied for the present purpose, and the validity of the above element is evaluated through some benchmarked examples.

2. A quasi-conforming sandwich plate element: model and formulation

2.1. Simplified zig-zag mode

A sandwich plate is considered, as shown in Fig. 1a, where h_1,h_3,h_2 and h_a are the thicknesses of two face sheets, core and adhesive layers, respectively. The upper and lower FSs are two symmetrical composite laminates, whose thickness is much less than that of core. Because the FSs have high transverse shear stiffness and are placed near the free surfaces where the shear stress equals to zero, only the transverse shear deformation of core is considered during analysis, as shown in Fig. 1b. According to this simplified Zig-Zag mode, the displacements of plates can be given by

$$\tilde{u}_\alpha(x_\alpha,z)=\begin{cases}u_\alpha-z\left(w_{,\alpha}-\gamma_{z\alpha}\right), & |z|\le h_2'/2\\ u_\alpha-zw_{,\alpha}+\gamma_{z\alpha}h_2'/2, & h_2'/2\le z\le h_1+h_2'/2\\ u_\alpha-zw_{,\alpha}-\gamma_{z\alpha}h_2'/2, & h_2'/2\le -z\le h_3+h_2'/2\end{cases}\quad(\alpha=1,2)$$
$$\tilde{w}(x_\alpha,z)=w \tag{1}$$

Where $h_2'=h_2+2h_a$; $u_\alpha(x_\alpha)$,$w(x_\alpha)$ and $\gamma_{z\alpha}(x_\alpha)$ are the displacements of the mid-plane and the transverse shear strain of core, respectively. Using the displacement assumption, the in-plane Green strain and transverse shear strain of the core are as follows

$$\tilde{\varepsilon}_{\alpha\beta}=\frac{1}{2}\left(u_{\alpha,\beta}+u_{\beta,\alpha}\right)+\frac{1}{2}\varphi_\alpha\varphi_\beta-zw_{,\alpha\beta}+\frac{1}{2}\left(zs+h_2'r\right)\left(\gamma_{z\alpha,\beta}+\gamma_{z\beta,\alpha}\right)$$
$$\gamma_{\alpha z}=w_{,\alpha}-\theta_\alpha \tag{2}$$

where $s=\begin{cases}1\\0\\0\end{cases}$, $r=\begin{cases}0 & z\in[-h_2'/2,h_2'/2]\\ 1/2 & z\in[h_2'/2,h/2]\\ -1/2 & z\in[-h/2,-h_2'/2]\end{cases}$; h is the thickness of plates; φ_α is the rotation of normal and $\theta_\alpha=\varphi_\alpha-\gamma_{\alpha z}$ is the rotation of sections.

For convenience, the above strain tensor can be decomposed as

$$\tilde{\boldsymbol{\varepsilon}}=\boldsymbol{\varepsilon}+z\boldsymbol{\kappa},\quad \boldsymbol{\varepsilon}=\bar{\boldsymbol{\varepsilon}}^{(1)}+\boldsymbol{\varepsilon}^{(2)},\quad \boldsymbol{\kappa}=\boldsymbol{\kappa}'+\boldsymbol{\kappa}''$$
$$\bar{\boldsymbol{\varepsilon}}^{(1)}_{\alpha\beta}=\left(u_{\alpha,\beta}+u_{\beta,\alpha}\right)/2+h_2'r\left(\gamma_{z\alpha,\beta}+\gamma_{z\beta,\alpha}\right)/2,\quad \varepsilon^{(2)}_{\alpha\beta}=\varphi_\alpha\varphi_\beta/2,$$
$$\kappa'_{\alpha\beta}=-w_{,\alpha\beta},\quad \kappa''_{\alpha\beta}=s\left(\gamma_{z\alpha,\beta}+\gamma_{z\beta,\alpha}\right)/2 \tag{3}$$

Where $\boldsymbol{\varepsilon}$, $\boldsymbol{\kappa}$ are the strain tensor at middle plane and total curvature deformation tensor, respectively; $\bar{\boldsymbol{\varepsilon}}^{(1)}$, $\boldsymbol{\varepsilon}^{(2)}$ are the linear and nonlinear parts of the strain $\boldsymbol{\varepsilon}$, $\boldsymbol{\kappa}'$ and $\boldsymbol{\kappa}''$ are the curvature deformation from bending and transverse shear, respectively.

2.2. Constitutive relations

The resultants $\boldsymbol{N}$ and couples $\boldsymbol{M}$ can be obtained by integrating through thickness

$$\boldsymbol{N}=\boldsymbol{N}^{(1)}+\boldsymbol{N}^{(2)},\quad \boldsymbol{N}^{(1)}=\boldsymbol{A}\boldsymbol{\varepsilon}^{(1)}+\boldsymbol{B}\boldsymbol{\kappa}'+\left(\boldsymbol{A}^*+\boldsymbol{B}''\right)\boldsymbol{\kappa}'',\quad \boldsymbol{N}^{(2)}=\boldsymbol{A}\boldsymbol{\varepsilon}^{(2)} \tag{4}$$