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Thermal buckling of cross-ply laminated composite and sandwich plates according to a global higher-order deformation theory

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Abstract

A two-dimensional global higher-order deformation theory is presented for thermal buckling of cross-ply laminated composite and sandwich plates. By using the method of power series expansion of continuous displacement components, a set of fundamental governing equations which can take into account the effects of both transverse shear and normal stresses is derived through the principle of virtual work. Several sets of truncated Mth-order approximate theories are applied to solve the eigenvalue problems of a simply supported multilayered plate. Modal transverse shear and normal stresses can be calculated by integrating the three-dimensional equations of equilibrium in the thickness direction, and satisfying the continuity conditions at the interface between layers and stress boundary conditions at the external surfaces. Numerical results are compared with those of the published three-dimensional layerwise theory in which both in-plane and normal displacements are assumed to be C^0 continuous in the continuity conditions at the interface between layers. Effects of the difference of displacement continuity conditions between the three-dimensional layerwise theory and the global higher-order theory are clarified in thermal buckling problems of multilayered composite plates.

Keywords: Thermal buckling; Cross-ply laminated composite plates; Sandwich plates; Orthotropic materials; Global higher-order deformation theory

1. Introduction

The increased applications of advanced composite materials in structural members have stimulated interest in the accurate prediction of the response characteristics of laminated composite plates. Because of their light weight, high stiffness and durability, these materials have been rapidly and widely used in laminated composite structures especially in aerospace, building and other industrial facilities. Mechanical buckling of laminated composite plates subjected to in-plane compressive stresses has been investigated and reviews of the contributions on this subject are given in a number of literatures (for example, [1–3]).

Laminated composite and sandwich plates may also experience thermal buckling due to severe change in temperature. In certain cases, the thermal load turns out to be the primary loading for designing such plates of important structures. The three-dimensional layerwise analysis has made a contribution to obtain accurate prediction of the thermal buckling response of angle-ply laminated composite and sandwich plates (for example, [4–6]). The effects of including or neglecting the initial thermal displacement on the critical temperature have been investigated by Noor and Burton [7]. It has been pointed out that if the prebuckling deformation is neglected, the critical temperature is underestimated. The three-dimensional layerwise theory assumes both in-plane and normal displacements to be C^0 continuous in the continuity conditions at the interface between layers. The number of unknowns which is dependent on the number of layers in a laminate will increase dramatically as the number of layers increases. Accurate prediction of critical temperatures based on the three-dimensional layerwise theory are often computationally intractable, especially for laminated plates with a large number of

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layers. On the other hand, equivalent single-layer approaches based on higher-order shear deformation theories have been used for buckling analysis of laminated composite plates. In equivalent single-layer theories, the continuity conditions of displacement components are usually higher than C^1. Although various models of higher-order displacement fields have been considered, most of these theories are the third-order theories in which the in-plane displacements are assumed to be a cubic expression of the thickness coordinate and the out-of-plane displacement to be a quadratic expression at most. A number of single-layer higher-order plate theories that include the effects of transverse shear and normal stresses have been published in the literature (for example, [8–10]. General higher-order theories of laminates which take into account the complete effects of transverse shear and normal deformations and rotatory inertia have been investigated recently for the vibration and stability problems of cross-ply and angle-ply laminated composite plates by Matsunaga [11–13]. The modal transverse stresses have been obtained accurately at the ply level by integrating the three-dimensional equations of motion or equilibrium in the thickness direction, and satisfying the continuity conditions at the interface between layers and stress boundary conditions at the external surfaces. Interlaminar stresses and displacements in cross-ply laminated composite and sandwich plates subjected to mechanical/thermal loading are analyzed by Matsunaga [14,15]. For multilayered composite plates, it is very advantageous for a global higher-order theory that the total number of unknowns does not increase as the number of layers increases. The global responses of multilayered composite plates such as natural frequencies and buckling stresses have been obtained accurately by two-dimensional higher-order theories. For thermal buckling problems, however, general two-dimensional higher-order theories have not been applied to the analysis of critical temperatures of multilayered composite and sandwich plates.

This paper presents a global higher-order theory for analyzing thermal buckling problems of cross-ply laminated composite and sandwich plates which consist of a number of perfectly-bonded layers. Based on the quasi-static theory of linear thermoelasticity, the coupling between the heat conduction problem and the elasticity problem is neglected. Complete effects of shear and normal stresses can be taken into account within the approximate two-dimensional theory. The effects of prebuckling deformations of the plates subjected to a temperature change that is independent of the in-plane coordinates are taken into account in the present analysis. Based on the power series expansions of continuous displacement components, a fundamental set of equations of a two-dimensional higher-order plate theory is derived through the principle of virtual work. Several sets of the governing equations of truncated approximate theories are applied to the analysis of thermal buckling problems of a simply supported laminated composite and sandwich plates. Critical temperatures of a simply supported laminated composite and sandwich plates are obtained by solving eigenvalue problems. For laminated composite and sandwich plates, the distribution of modal displacements in the thickness direction has been obtained accurately at the ply level. The present results obtained by various sets of approximate theories are verified to be accurate enough for general cross-ply laminated composite and sandwich plates through the energy balance computations. In order to assess the importance of transverse shear and normal stresses associated with thermal buckling of laminated composite plates, the strain energy ratios are shown. The two-dimensional global higher-order theory can predict critical temperatures and modal displacement distributions of simply supported laminated composite and sandwich plates accurately.

2. Fundamental equations of cross-ply laminated composite plates

Introducing a Cartesian coordinate system x_α $(\alpha = 1, 2)$, x_3 on the middle plane of a plate of uniform thickness h, having a rectangular plan $a \times b$ as shown in Fig. 1. The individual layers are assumed to be homogeneous and orthotropic. Perfect bonding is assumed between the layers of laminated composite and sandwich plates.

The displacement components in a plate are expressed as

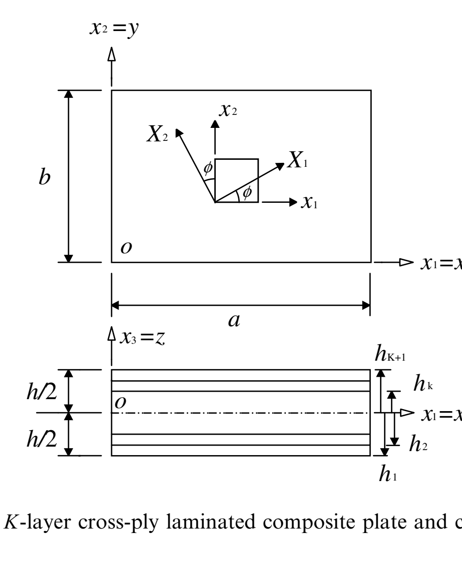

Fig. 1. K-layer cross-ply laminated composite plate and coordinate.