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A refined five-unknown higher-order model including transverse normal hygrothermal deformation

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ABSTRACT

Hygrothermoelastic stress has strong impact on composite structures due to their intrinsic heterogeneity, so five-unknown higher-order models have been usually employed for hygrothermal bending analysis of composite plates. If these models are used to analyze hygrothermal expansion problem, inaccurate conclusion will be drawn as transverse normal strain is neglected. Thus, a refined five unknown higher-order model including transverse normal hygrothermal deformation will be developed. In order to include the transverse normal deformation, the hygrothermal deformation through the thickness due to the thermal and moisture loads is introduced in the transverse displacement field. Applying the bounding surface free traction condition, effects of transverse normal hygrothermal deformation can be incorporated in the in-plane displacement field which can actively influence the accuracy of in-plane stresses. By analyzing hygro-thermo-mechanical behaviors of multilayered composite plates, effects of different temperature, number of layers and transverse normal strain on the displacements and stresses of composite plates have all been studied. Through the numerical examples of hygrothermal analysis, the accuracy and efficiency of the proposed model are demonstrated.

1. Introduction

The structural components made of composite materials used in aerospace structures are often subjected to severely hygrothermal environment during their service life. Thus, hygrothermal effects including thermal expansion, moisture swelling and shrinkage contraction are common to these structures [1]. Composite structures are very sensitive to hygrothermoelastic stress due to their intrinsic heterogeneity [2]. In order to overcome difficulties in the design and manufacture, the analysis and the modeling of composite structures exposed to hygrothermal conditions have drawn considerable attention of investigators [3–5].

In the early stage of the development of models, classical laminated plate theory has been employed to analyze the hygrothermal effects on the cylindrical bending of angle-ply composite plates with different boundary conditions [6]. Subsequently, Sai and Sinha [7] employed the first-order shear deformation theory to study the bending and the free vibration behaviors of composite plates under hygrothermal conditions. However, for the accurate analysis of thermomechanical behaviors for general layup configurations of thick composite structures, the classical laminated plate theory and the first order shear deformation theory are not adequate [8]. Consequently, the higher-order models with smeared displacements have been developed for hygrothermal analysis of laminated composite plates. Shen [9] studied the influence of hygrothermal effects on postbuckling of shear deformable composite plates subjected to a uniaxial compression using Reddy's higher-order model [10] which satisfies the zero shear stress boundary conditions at the top the bottom surfaces of the plate. In addition, Reddy's higher-order model was extended to investigated the effect of hygrothermal environment on the buckling and postbuckling of shear deformable composite cylindrical panels under axial compression [11].

Based on Reddy's higher-order model [10] and the sinusoidal shear deformation plate model [12,13], Zenkour [14] studied the static thermo-elastic response of symmetric and antisymmetric cross-ply composite plates. Hygrothermal response of multilayered composite plates with general lamination configurations has been also studied using Reddy's higher-order model and the sinusoidal shear deformation plate model [15]. In addition, effect of elastic foundations on bending response of cross-ply composite plates subjected to thermo-mechanical loading was studied employing the higher-order models [16]. The effects of temperature and moisture on hygrothermal response of composite plates resting on elastic foundations has been also studied employing Reddy's

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higher-order model and the sinusoidal shear deformation plate model [17]. Moreover, the static response of antisymmetric cross-ply composite plates subjected to sinusoidally distributions of temperature and moisture concentrations were studied using the refined higher-order models [18]. In addition, Reddy's higher-order model and the sinusoidal shear deformation plate model were extended to analyze the hygrothermal behaviors of the functionally graded material plates [19–24].

Constitutive equations of most plate models [9–24] are based on the plane stress assumption, in which transverse shear deformation effect is only taken into account while transverse normal deformation effects has been neglected. However, for thermo-mechanical problem of moderate thick composite plates, transverse normal deformation effect is unable to be neglected as the influence of transverse normal thermal deformation is equally important in comparison with the in-plane thermal deformation [25–27]. Therefore, for the complete analysis of composite plates under hygrothermal environments, transverse normal deformation effect should be considered for the reliable analysis. In order to consider transverse normal effect, the higher-order terms of transverse coordinate z have to be added in transverse displacement field which will increase computational cost [28–30]. Thus, it is still required to propose the accurate and efficient model which can predict the hygrothermal response without increase of additional displacement parameters.

In the present study, an efficient and accurate higher-order model for composite plates is developed, in which transverse normal as well as transverse shear deformation are completely considered for reliable prediction. For the efficient evaluation of the hygrothermal behaviors, the hygrothermal deformation across the thickness due to the thermal and the moisture loads is introduced in the transverse displacement field. Applying the bounding surface free traction condition, effects of transverse normal hygrothermal deformation can be incorporated in the in-plane displacement field which will actively influence accuracy of in-plane stresses. Additionally, only five displacement variables are incorporated in the proposed model as transverse normal deformations due to hygrothermal conditions are absorbed in the generalized force vector.

2. Theoretical formulation

2.1. A refined higher-order model with five displacement parameters

A rectangular composite plate with length a, width b and thickness h is taken into account in Fig. 1. The composite plate is subjected to the distributed transverse loadings on the top and bottom surfaces $q(x,y)$, a temperature $T(x,y,z)$, and a moisture concentration $C(x,y,z)$. Rectangular Cartesian coordinates (x,y,z) are used to describe deformations of a composite plate, in which $x \in [x_0,x_a]$ represents the plate longitudinal axis, $y \in [y_0,y_b]$ represents the plate width axis, and $z \in [-h/2,h/2]$ is the thickness coordinate. The composite plate is composed of n orthotropic layers oriented at angles $\theta_1, \theta_2, \ldots, \theta_n$.

To efficiently describe hygrothermal behaviors of the composite plates without losing accuracy, an efficient higher order shear deformation plate theory considering transverse normal strain is developed in present work. To consider the transverse normal effect, transverse normal deformation induced by hygrothermal loading is introduced in the out-of-plane displacement field, so that initial displacement field of the proposed model can be expressed as

$$
\begin{aligned}
u(x,y,z) &= u_0(x,y) + zu_1(x,y) + z^2u_2(x,y) + z^3u_3(x,y) \\
v(x,y,z) &= v_0(x,y) + zv_1(x,y) + z^2v_2(x,y) + z^3v_3(x,y) \\
w^k(x,y,z) &= w_0(x,y) + w_T^k(x,y,z) + w_C^k(x,y,z)
\end{aligned}
\tag{1}
$$

where the parameters u_0, v_0 are the in-plane displacements and w_0 is the transverse displacement of a point (x,y) on the middle plane of composite plate; the displacement variables u_1, v_1 are respectively rotations of the normal to the middle plane about y and x axes; the variables u_2, v_2, u_3 and v_3 are the higher-order terms in Taylor's series expansion which denote the higher-order transverse cross-sectional deformation modes [29]; w_T^k is the transverse normal deformation caused by thermal loading at kth ply, and w_C^k is the transverse normal deformation caused by moisture concentration loading at kth ply of composite plate.

Transverse normal deformation at kth ply induced by hygrothermal loadings can be respectively written as follows

$$
\begin{aligned}
w_T^k(x,y,z) &= \alpha_z^k \int T(x,y,z)dz \\
w_C^k(x,y,z) &= \beta_z^k \int C(x,y,z)dz
\end{aligned}
\tag{2}
$$

in which α_z^k and β_z^k are respectively the transverse normal thermal expansion coefficient and transverse normal moisture expansion coefficient at kth ply of composite plate.

The temperature field $T(x,y,z)$ and the moisture concentration $C(x,y,z)$ can be written as

$$
\begin{aligned}
T(x,y,z) &= f_T(z)\bar{T}(x,y) \\
C(x,y,z) &= f_C(z)\bar{C}(x,y)
\end{aligned}
\tag{3}
$$

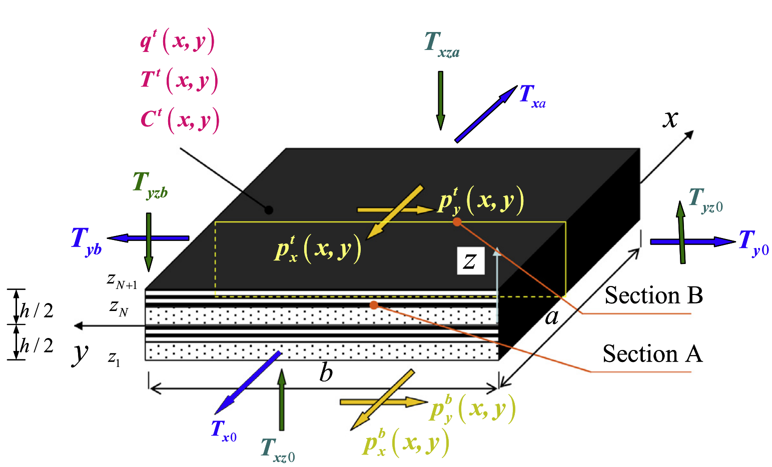

Fig. 1. A composite plate subjected to hygro-thermo-mechanical loading.