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Hygrothermal analysis of laminated composite plates in terms of an improved C^0-type global–local model

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A B S T R A C T

In this paper, an efficient improved C^0-type global–local model (IGLM) considering transverse normal strain is proposed to study the hygrothermal response of thick cross-ply laminated composite plates. Based on the interlaminar continuity conditions of in-plane displacement and transverse shear stresses, layer-dependent variables could be reduced. Employing shear stress free condition at the upper and the lower surfaces, derivatives of transverse displacement are eliminated from the displacement field, so that C^0 interpolation functions are only required for the finite element implementation. As a result, the number of variables is independent of the number of layers of the laminate. To assess the proposed model, the classical quadratic eight-node isoparametric element is presented, in which the interelement C^0 continuity conditions are satisfied. Comparing the results from available three-dimensional elasticity theory and those computed from the ninth-order model, it is found that the simple C^0 finite elements could produce promising deformations and stresses for thick cross-ply laminated composite plates with different boundary conditions under hygrothermal loadings.

1. Introduction

Laminated composite structures have been increasingly used in the field of aerospace, automobile, civil and other engineering due to their advantages of high modulus, high strength, low weight and good tailoring capability. Such composite structures are often exposed to high temperature and humidity environment during the operational life, so that the variation of temperature and moisture has important impact on deformation and stresses of laminated composite structures. Hence, the study of laminated composite plates under hygrothermal environment is of great importance in engineering design and manufacture. It is necessary to carefully evaluate the effects of environmental exposure on behaviors of composite structures subjected to hygrothermal conditions.

In the early stage of the evolution of the model, the classical laminated plate theory (CLPT) and first order shear deformation theory (FSDT) [1,2] were employed to study the hygrothermal behaviors of composite plates. For example, Lee et al. [3] studied the influence of hygrothermal effects on the cylindrical bending of symmetric angle-ply laminated plates subjected to uniform transverse load for different boundary conditions via CLPT. Parhi et al. [4] developed a quadratic isoparametric element based on FSDT for the free vibration and transient response analysis of multiple-delaminated composite shells exposed to hygrothermal environment. Compared to conventional one-layer metallic structures, the laminated composites generally possess relatively soft transverse shear modulus. Nevertheless, CLPT and FSDT are unable to adequately model the relatively large transverse shear deformations, so they often produce unacceptable errors in computing displacements and stresses of thick and moderately thick laminated composite plates [5]. By adding the high-order displacement terms to the in-plane and transverse displacements, the higher order shear deformation theories [6–10] have been developed for thermomechanical analysis of composite structures. Compared to FSDT, the higher-order theory does not require the shear correction factors and can account for the warping of the cross-section. Applying the higher-order theory proposed by Reddy [11], Shen [12] studied the influence of hygrothermal effects on the postbuckling of laminated composite plates under a uniaxial compression. Based on a higher order shear deformation shell model proposed by Reddy and Liu [13] in conjunction with the micro-to-macro-mechanical analytical model, Shen [14] investigated the effects of hygrothermal environment on the buckling and postbuckling of laminated composite cylindrical shells subjected to combined loadings. Subsequently, Shen [15] employed the higher order shell model [13] to study the effects of hygrothermal condition on the buckling and postbuckling of composite cylindrical panels under axial compres-

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sion. By introducing the zig-zag function in in-plane displacement field, Patel et al. [16] proposed a higher order model to study the static and dynamic response of thick composite plates subjected to hygrothermal conditions.

Employing a sinusoidal shear deformation theory, Zenkour [17] studied the hygrothermal behaviors of multilayered angle-ply composite plates subjected to a variation of temperature and moisture concentrations. Using a refined four unknown plate theory considering transverse normal strain, Khateeb and Zenkour [18] investigated the influence of temperature and moisture on the bending behaviors of functionally graded material plates resting on elastic foundations. Zenkour et al. [19] proposed a unified shear deformation theory to assess the effect of hygrothermal conditions on the antisymmetric cross-ply laminated composite plates. Subsequently, hygrothermal effects on thick multilayered angle-ply composites were also studied by using a simplified four-unknown shear and normal deformation plate theory [20]. Based on a layerwise theory, Lee and Saravanos [21] presented a finite element formulation to explicitly model the active and sensory response of piezoelectric composite plates in thermal environments. Plagianakos and Saravanos [22] proposed a high-order layerwise theory and a finite element to investigate the damping of laminated composite sandwich beams. Applying a global/local third-order Hermitian displacement model, Di Sciuva and Gherlone [23] presented a sublaminate-FEM approach to study laminated and sandwich beams. The sub-laminates finite element approach based on a refined zig-zag plate model was also formulated for the analysis of multilayered composite plates subjected to thermal and mechanical loads [24]. Carrera [25] employed the layerwise theory and the equivalent single-layer theories to evaluate the thermal response of multilayered composite plates. The three-dimensional model also has been used to study the laminated composite and sandwich plates under thermo-mechanical loads [26]. However, layerwise model and three-dimensional model can produce very accurate displacement and stress, while the huge computing is required for multilayered plates as the number of variables generally depends on the number of layers of the laminate.

In terms of the three-dimensional (3D) thermoelastic considerations, transverse shear stresses ought to be continuous at each interface of the laminated composite plate. However, it is found that the continuity conditions of transverse shear stresses at interfaces have been violated for laminated composite plates subjected to hygrothermal loading in the literature [16,19,20]. In view of this situation, to satisfy the continuity conditions of transverse shear stresses at interfaces, a higher-order zig-zag model [27] as well as higher-order global–local model were proposed [28]. Employing a similar zig-zag plate theory, Cho and Oh [29] studied the mechanical, thermal and electric behaviors of smart laminated composite plates. It was shown that transverse normal strain should not be ignored for thermo-mechanical problems. Based on the double superposition hypothesis [28], Wu and Lo [30] developed a higher-order global–local model (HGLM) considering transverse normal strain to investigate the laminated composite plates subjected to hygrothermomechanical effects. Based on the same global–local model, a refined triangular element is constructed to analyze hygrothermal response of composite plates with general configurations [31]. By review of above literature [30,31], it is found that transverse displacement of the model HGLM is assumed to be a smooth parabolic distribution through the thickness direction. However, it is unable to eliminate the derivatives of transverse displacement completely from the displacement fields, so that C^1 continuity of transverse displacement at element interfaces will be required for the finite element formulation.

To avoid using C^1 interpolation functions during finite element implementation, an improved C^0-type global–local theory (IGLM) is to be developed in this paper. In addition to considering transverse normal strain, the merit of the proposed model is that derivatives of transverse displacement have been eliminated from the displacement field based on stress compatibility. Thus, C^0 interpolation functions are only needed for the finite element implementation. Following the proposed model, the classical eight-node isoparametric quadrilateral element is formulated for the analysis of thick laminated plates. In comparison with the other available theories (the ninth-order model and 3D models), the present model is sufficiently accurate in modeling of thick laminated composite plates under different hygrothermal loading conditions. Moreover, the proposed model is computationally economic due to a simple C^0 finite element formulation.

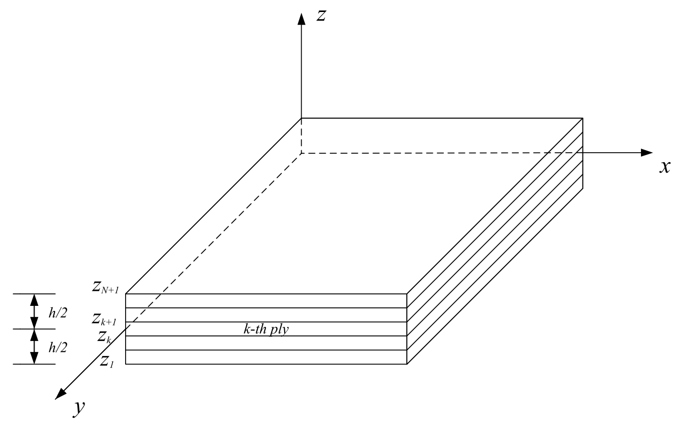

Fig. 1. Composite laminate geometry.

2. Improved C^0-type global–local model (IGLM)

In this section, an improved C^0-type global–local model (IGLM) is presented to analyze the effect on cross-ply composite plates subjected to hygrothermal loads. A N-layered laminated composite laminate geometry can be found in Fig. 1, where thickness of whole plate is h. In order to include the transverse normal effect which is significant in hygrothermal problems, the transverse displacement field is assumed to be a linear distribution through the thickness of plate. In the literature [5], it is found that higher-order shear deformations surely have an important effect on the thermal displacements and stresses of thick plates. Making a compromise between accuracy and efficiency, the global displacement field is chosen to be of fifth order polynomial in present model IGLM. In-plane displacement field is obtained by superimposing the local displacement components in the globally fifth-order displacement field. Thus, the initial displacement field of the model IGLM at the kth ply ($k = 1, 2, \cdots, N$) is given by

$$
\begin{aligned}
u^k(x, y, z) &= u_G(x, y, z) + \bar{u}_L^k(x, y, z) + \hat{u}_L^k(x, y, z) \\
v^k(x, y, z) &= v_G(x, y, z) + \bar{v}_L^k(x, y, z) + \hat{v}_L^k(x, y, z) \\
w^k(x, y, z) &= w_G(x, y, z)
\end{aligned}
\tag{1}
$$

where the superscript k represents the layer number of laminated plates.

The variables u_G, v_G and w_G are global displacement components, which can be expressed as

$$
\begin{aligned}
u_G(x, y, z) &= \sum_{i=0}^{5} z^i u_i(x, y) \\
v_G(x, y, z) &= \sum_{i=0}^{5} z^i v_i(x, y) \\
w_G(x, y, z) &= w_0(x, y) + z w_1(x, y)
\end{aligned}
\tag{2}
$$