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Hygro-thermo-mechanical behavior of classical composites

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ABSTRACT

This paper presents the hygro-thermo-mechanical analysis of sandwich plates using an Equivalent Single Layer (ESL) approach under Carrera's Unified Formulation (CUF) with the introduction of five different non-polynomial shear strain shape functions (SSSFs). The laminated plates are subjected to hygro-thermo-mechanical loads with constant, linear and calculated profiles by the solution of Fick moisture diffusion law equation and Fourier heat conduction equation, each one individually, and in a coupled manner. Bending benchmark results are presented. The plate highly coupled governing equations are obtained by using Principal of the Virtual Displacement (PVD) and they are solved via Navier solution method. Finally, benchmark results are presented.

1. Introduction

During recent years, some hygro-thermo-mechanical studies on classical composites were performed. Aerospace, automotive, biomechanics, civil, naval and mining industries were beneficed with the outcomes of such studies. Laminated composite materials have been substantially used to improve the resistance of machines in front of relative higher changes of temperature and moisture contents in structures such as aircrafts or boats.

Abot et al. (2005) determined experimentally the moisture expansion coefficients of a woven fabric carbon-epoxy composite plate and determined its behavior while the moisture concentration changes. Zhang et al. (2016) detailed a numerical and experimental analysis for stiffened composite panels subjected to hygrothermal loading effect.

Many studies on the variation of temperature within a structure were analyzed using different temperature profiles, see for example the paper by Carrera (2005). The author analyzed the transverse normal strain effect on the thermos-elastic response of homogeneous and multilayered plates with the assumption of constant, linear, and higher-order forms of temperature profiles. Moreover, Carrera (2002) studied the influence of through-thickness temperature profile in the thermo-mechanical response of multilayered anisotropic thick and thin plates considering a large variety of classical and advanced theories. Reddy and Hsu (1980) studied the effect of shear deformation and anisotropy on the thermal bending of layered composite plates. Tungikar and Rao (1994) developed a 3D exact solution for temperature distribution and thermal stresses in simply supported rectangular laminated composite plates. Zenkour and Alghamdi (2008) analyzed the thermo-elastic bending effect on functionally graded ceramic-metal sandwich plates. In addition, studies on the thermo-elastic bending response using a 6-unknown quasi-3D hybrid type HSDT, and a new trigonometric displacement fields under CUF were developed by Mantari and Granados (2015), and Ramos et al. (2016), respectively.

On the other hand, the variation of moisture content in conjunction with the variation of temperature was studied, because of the tendency of composites to absorb humidity and change their temperature at the same time. Gigliottia et al. (2006) presented a new method to characterize internal stresses induced by hygrothermal loads on laminated composite plates measured by the fringe projection technique. Sereir et al. (2006) studied the stresses due to the effect of the temperature and moisture variation in unidirectional laminated plates considering the variation of material properties due to these effects. Benkhedda et al. (2008) assessed an approximate model to evaluate the hygro-thermo-elastic stress in composite laminated plates during moisture absorption taking into account the change of mechanical characteristics induced by the variation of temperature and moisture. Zenkour (2010) studied the hygrothermal bending effect for functionally graded material plates resting on elastic foundations. Zenkour (2012) used a sinusoidal shear deformation plate theory to study the response of multilayered angle-ply composite plates due to a variation in temperature or moisture content. Brischetto (2013, 2012) analyzed the bending response of multilayered composite plates and sandwich shells in front of thermal and hygroscopic presence. Zenkour et al. (2014) studied the influence of temperature and moisture content on the hygrothermal behavior of cross-ply laminated plates resting on elastic foundations.

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Nomenclature

h	Plate thickness
a	Plate length
b	Plate width
u	Displacement vector
u_s, u_τ	Generalized displacement vector
u^k	Displacement vector for each layer
u_x^k, u_y^k, u_z^k	Displacement components for each layer
F_s, F_τ, F_t, F_m	Expansion functions
N	Expansion order of F_s, F_τ
N_t	Expansion order of F_t
N_m	Expansion order of F_m
θ	Over-temperature
θ_t	Generalized over-temperature
θ^k	Over-temperature for each layer
α^k	Thermal expansion coefficient vector for each layer respect to the material coordinates
α_1^k, α_2^k, α_3^k	Thermal expansion coefficient components for each layer respect to the material coordinates
$\widetilde{\alpha}^k$	Thermal expansion coefficient rotated vector for each layer
M	Moisture content
M_m	Generalized moisture content
M^k	Moisture content for each layer
β^k	Moisture expansion coefficient vector for each layer respect to the material coordinates
β_1^k, β_2^k, β_3^k	Moisture expansion coefficient components for each layer respect to the material coordinates
$\widetilde{\beta}^k$	Moisture expansion coefficient rotated vector for each layer
ε^k	Strain vector for each layer respect to the plane coordinates
ε_u^k	Elastic strain vector for each layer respect to the plane coordinates
ε_{xu}^k, ε_{yu}^k, ε_{zu}^k	Elastic axial strain components for each layer respect to the plane coordinates
γ_{yzu}^k, γ_{xzu}^k, γ_{xyu}^k	Elastic shear strain components for each layer respect to the plane coordinates
ε_{mu}^k	Elastic strain for each layer respect to the material coordinates
ε_{1u}^k, ε_{2u}^k, ε_{3u}^k	Elastic axial strain components for each layer respect to the material coordinates
γ_{23u}^k, γ_{13u}^k, γ_{12u}^k	Elastic shear strain components for each layer respect to the material coordinates
ε_{pu}^k	In-plane elastic strain vector for each layer
ε_{nu}^k	Out-of-plane elastic strain vector for each layer
ε_θ^k	Thermal strain vector for each layer respect to the plane coordinates
$\varepsilon_{1\theta}^k$, $\varepsilon_{2\theta}^k$, $\varepsilon_{3\theta}^k$	Thermal strain components for each layer respect to the material coordinates
ε_M^k	Hygroscopic strain vector for each layer respect to the plane coordinates
ε_{1M}^k, ε_{2M}^k, ε_{3M}^k	Hygroscopic strain components for each layer respect to the material coordinates
L^k	Rotation matrix for each layer
$\varnothing$	Rotation
$\widetilde{C}^k$	Hooke's law stiffness rotated matrix for each layer
C_{11}^k, C_{12}^k, C_{13}^k, C_{22}^k,	Hooke's law stiffness coefficients for each layer
C_{23}^k, C_{33}^k, C_{44}^k, C_{55}^k, C_{66}^k, $\widetilde{C}^k$	Hooke's law stiffness matrix for each layer
$\widetilde{C}_{pp}^k$, $\widetilde{C}_{pn}^k$, $\widetilde{C}_{np}^k$, $\widetilde{C}_{nn}^k$	In-plane and out-of plane Hooke´s law stiffness rotated matrix components
$\widetilde{\lambda}^k$	Thermal stiffness rotated vector for each layer
$\widetilde{\lambda}_p^k$	In-plane thermal stiffness rotated vector for each layer
$\widetilde{\lambda}_n^k$	Out-of-plane thermal stiffness rotated vector for each layer
$\widetilde{\mu}^k$	Hygroscopic stiffness rotated vector for each layer
$\widetilde{\mu}_p^k$	In-plane hygroscopic stiffness rotated vector for each layer
$\widetilde{\mu}_n^k$	Out-of-plane hygroscopic stiffness rotated vector for each layer
σ_m^k	Stress vector for each layer respect to the material coordinates
σ_{m1}^k, σ_{m2}^k, σ_{m3}^k	Axial stress components for each layer respect to the material coordinates
σ_{m23}^k, σ_{m13}^k, σ_{m12}^k	Shear stress components for each layer respect to the material coordinates
σ^k	Stress vector for each layer respect to the plane coordinates
σ_p^k	In-plane stress vector for each layer
σ_n^k	Out-of-plane vector for each layer
E_1, E_2, E_3	Young's modulus for each direction respect to the material coordinates
ν_{12}, ν_{31}, ν_{23}	Poison's ratios for each plane
$\triangle$	Hooke's law delta
G_{12}, G_{13}, G_{23}	Shear modulus respect to the material coordinates
K_1, K_2, K_3	Heat transfer coefficients respect to the material coordinates
D_1, D_2, D_3	Diffusion coefficients respect to the material coordinates
K_x^k K_y^k K_z^k	Heat transfer coefficients for each layer respect to the plane coordinates
D_x^k D_y^k D_z^k	Diffusion coefficients for each layer respect to the plane coordinates
L_e^k	Work of the external forces
N_l	Number of layers
$K_{uu}^{k\tau s}$, $K_{ut}^{k\tau s}$, $K_{uM}^{k\tau s}$	Fundamental nucleus for stiffness matrix, thermal load and hygroscopic load

In order to analyze the behavior of composite materials, some theories have been developed to obtain more accurate results while the material and geometry considerations change. For example, the classical plate theory (CPT) was extended to the first order-shear-deformation-theory (FSDT) in Reissner (1945) and Mindlin (1951) to obtain the shear deformation effect for thicker plates by a constant transverse shear strain component with a shear correction factor. The higher order shear deformation theory (HSDT) was implemented to improve bending results and correctly model the transverse shear stresses. HSDTs can be implemented within different approaches such as Equivalent single layer (ESL), quasi-layer-wise and the layer-wise theories (LW), and their displacement field can be expanded with at least four unknown variables using polynomial and non-polynomial functions. Levinson (1980), Reddy (1984), and Reddy and Liu (1985) developed a HSDT for laminated composite plates and shells with orthotropic layers. Karama et al. (2003) presented a new multi-layer laminated composite structure model to predict the mechanical behavior of multilayered laminated composite structures. Zenkour (2006) analyzed the static response of a functionally graded rectangular plate subjected to a transversal uniform load. Mantari et al. (2011, 2012, 2014a, 2014b) Mantari and Soares (2014) adopted the HSDT to study sandwich plates and shells with the use of trigonometrical theories and others.

The use of Carrera Unified Formulation (CUF) permits to implement a displacement field using Taylor's expansion of N-order (Carrera, 1998). Carrera, (1998, 2001, 2003) developed a layerwise