Composite Structures 160 (2017) 378–391

Contents lists available at ScienceDirect

Composite Structures

journal homepage: www.elsevier.com/locate/compstruct

Hygro-thermo-mechanical behavior of classical composites using a new trigonometrical shear strain shape function and a compact layerwise approach

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ARTICLE INFO

Article history:
Received 16 August 2016
Revised 5 October 2016
Accepted 6 October 2016
Available online 11 October 2016

Keywords:
Layered structures
Plates
Elasticity
Analytical modeling
Hygro-thermo-mechanical
Layerwise approach

ABSTRACT

The present paper discusses the hygro-thermo-mechanical behavior of multilayered composite and sandwich plates based on a Layerwise Displacement (LD) approach using the Carrera's Unified Formulation (CUF). Legendre polynomials and a new proposed trigonometrical shear strain shape function are evaluated within a compact shear deformation formulation. Hygro-thermo-mechanical loads are applied considering linear and calculated profiles solved by the Fick moisture diffusion law equation and the Fourier heat conduction equation. The Navier solution method was used to solve the governing equations obtained by the principle of the virtual displacement (PVD). Results are in good agreement with published results in the literature. Some bending problem benchmarks considering hygro-thermo-mechanical loads applied in a coupled manner are presented.

1. Introduction

Nowadays, the use of composite materials has been experimented a great interest in aerospace, automotive, biomechanics, civil, naval and recently in mining industries. Some composites improve the resistance of machines structures in front of relative higher changes of temperature and moisture contents. The use of composite materials in naval and aerospace has increased considerably over the years. Nowadays, mega-structures made composite material are being designed and built. Mostly, the work environments of such industries are subjected to variable changes of temperate and/or moisture (couple manner) like the conditions considered in the present paper. The authors consider that the present work is important for future studies which may take into account other mechanical problems such as free vibration, buckling, or for example, the understanding of viscoelastic materials subjected to changes of temperate and/or moisture which are not yet fully understood, etc.

The behavior of composite materials has been analyzed by different theories over the last and present century. For example, the classical plate theory (CPT) was extended to the first order-shear-deformation-theory (FSDT) in Reissner [1] and Mindlin [2] to obtain the shear deformation effect for thicker plates by a constant transverse shear strain component with a shear correction factor.

Nevertheless, the shear deformation theories mentioned above do not give accurate results for transverse stresses and strains. Thus, the higher order shear deformation theory (HSDT) was implemented to improve these drawbacks. For example, Lo et al. [3] use a HSDT to study laminated plates and compared their results with respect to elasticity solutions. HSDTs can be implemented within different approaches such as equivalent single layer (ESL), quasi-layer-wise and the layer-wise theories (LW). While the ESL approach proposes a heterogeneous laminated plate treated as a statically equivalent single layer with the characteristic that the displacement function and its derivatives are continuous, the LW theory evaluates the deformation at each layer independently along with the connectivity at the layer interfaces. Carrera [4] evaluated mixed layerwise theories to calculate the in-plane and out-of-plane responses of thick plates in two-dimensional modeling of multilayered structures. Cho et al. [5] used a higher order plate theory for each individual layer to determinate the natural frequencies and the relative stress and deflection distributions through the thickness of simply supported rectangular plates. Carrera [6] evaluated layerwise theories based upon Reissner's mixed

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http://dx.doi.org/10.1016/j.compstruct.2016.10.014

variational theorem for multilayered plates and shells. The HSDT can be applied considering polynomial shear strain shape functions such as the ones used in Levinson [7], Reddy [8], and Reddy and Liu [9]. Karama et al. [10] presented a new multi-layer laminated composite structure model to predict the mechanical behavior of multilayered laminated composite structures. Zenkour [11] analyzed the static response of a functionally graded rectangular plate subjected to a transversal uniform load. Mantari et al. [12–16] adopted the HSDT to study sandwich plates and shells with the use of trigonometrical shear strain shape functions and others. Likewise, Hebali et al. [17] presented a new quasi-three-dimensional hyperbolic shear deformation theory for the bending and free vibration analysis of functionally graded plates. Belabed et al. [18] developed a higher order shear and normal deformation theory for functionally graded material plates. In addition, Bourada et al. [19] developed a refined trigonometric higher-order beam theory for bending and vibration of functionally graded beams with only three unknown variables as in Timoshenko beam theory, but including the thickness stretching effect. Yahia et al. [20] used higher-order shear deformation plate theories to study the wave propagation in functionally graded plates with porosities. Mahi et al. [21] analyzed a new hyperbolic shear deformation theory applicable to study the bending and free vibration behavior of isotropic, functionally graded, sandwich and laminated composite plates. Furthermore, Bennoun et al. [22] presented a new five variable refined plate theory for the free vibration analysis of functionally graded sandwich plates. The effect of moisture content variations in conjunction with temperature variations produces some stresses in airplanes and vessels. Composites have the tendency to absorb humidity and because of this effect, their stiffness become more fragile. Firstly, the transverse normal strain effect on the thermo-elastic response of homogeneous and multilayered plates with the assumption of constant, linear, and higher-order forms of temperature profiles was analyzed in Carrera [23]. In addition, Carrera [24] studied the influence of the through-the-thickness temperature profile in the thermo-mechanical response of multilayered anisotropic thick and thin plates considering a large variety of theories. Reddy and Hsu [25] presented a finite-element formulation of equations governing layered anisotropic rectangular cross-ply laminated composite plates subjected to thermal and mechanical loading. Furthermore, Tungikar and Rao [26] developed a 3D exact solution for temperature distribution and thermal stresses in simply supported rectangular laminated composite plates subjected to prescribed boundary conditions under combined thermal and mechanical loading. Zenkour and Alghamdi [27] analyzed the thermo-elastic bending effect of functionally graded ceramic–metal sandwich plates where sandwich plate faces were assumed to be isotropic. Likewise, Bouderba et al. [28] studied the thermomechanical bending response of functionally graded plates resting on Winkler-Pasternak elastic foundations by the implementation of a refined trigonometric shear deformation theory. Additionally, Tounsi et al. [29] developed a refined trigonometric shear deformation theory taking into account the transverse shear deformation effects for the thermoelastic bending analysis of functionally graded sandwich plates. Hamidi et al. [30] presented a sinusoidal plate theory for the thermomechanical bending analysis of functionally graded sandwich plates. Bouderba et al. [31] used a simple first-order shear deformation theory to study the thermal buckling response of functionally graded sandwich plates with various boundary conditions; the shear deformation theory contain only four unknowns contrary to the conventional first-order shear deformation theory. Moreover, studies on the thermo-elastic bending response using a 6-unknown quasi-3D hybrid type HSDT, and new trigonometric displacement fields under CUF were developed by Mantari and Granados [32], and Ramos et al. [33], respectively.

Additionally, some researchers studied the effects of moisture absorption. For example, the moisture expansion coefficients of a woven fabric carbon-epoxy composite plate and their behavior while moisture changes were analyzed by Abot et al. [34]. To validate the results of numerical theories, Zhang et al. [35] presented a numerical and experimental analysis for stiffened composite panels subjected to hygrothermal loading effect. In addition, a new method to characterize the internal stresses induced by hygrothermal loads on laminated plates measured by the fringe projection technique were proposed by Gigliottia [36]. Sereir et al. [37] 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. [38] 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 [39,40] studied the hygrothermal bending effect for functionally graded material plates resting on elastic foundations and used a sinusoidal shear deformation plate theory to study the response of multilayered angle-ply composite plate due to a variation in temperature or moisture content, respectively. Likewise, Zidi et al. [41] analyzed the bending response of functionally graded material plate resting on Winkler-Pasternak elastic foundations and subjected to hygro-thermo-mechanical loads using a four variable refined plate theory. Additionally, the bending response of multilayered composite plates and sandwich shells in front of thermal and hygroscopic presence were analyzed by Brischetto [42,43]. Also, Zenkour et al. [44] studied the influence of temperature and moisture content on the hygrothermal behavior of cross-ply laminated plates resting on elastic foundations. Nevertheless, contrary to the previous described theories, the new shear strain shape functions (SSSFs) proposed in the present paper can be optimized by changing the arguments and/or applying a robust genetic algorithm.

Regarding compact or unified HSDTs, different displacement fields can be implemented by the use of Carrera Unified Formulation (CUF) by using polynomial, trigonometric, or miscellanies expansions depending on the applied approach. Carrera et al. [45,46] developed polynomial, trigonometric, exponential and zig-zag theories to analyze the free vibration of laminated beams.

The present paper proposes the use of a non-polynomial displacement field under the CUF mainframe maintaining the connectivity condition of the LW approach to analyze the hygro-thermo-mechanical behavior of cross-ply laminated plates. The miscellaneous shear strain shape functions composed of trigonometrical and exponential functions are used. Linear and calculated profiles of temperature and moisture loads were obtained by solving the Fourier heat conduction equation and the Fick moisture diffusion law, respectively. On the other hand, evaluations of the over-temperature and moisture content when both loads are applied at the same time, are analyzed. Furthermore, the Principle of the Virtual Work (PVD), and Navier solution method are used to obtain the highly coupled plate governing equations, and the solution, respectively.

This paper is organized as follows. In Section 2, geometrical considerations and applied formulations are briefly explained. Then, in Section 3, the analytical solution and boundary conditions are described. In Section 4, the results represented in tables and figures are discussed. Finally, conclusions, Appendix and representative reference are provided.