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Thermoelastic analysis of advanced sandwich plates based on a new quasi-3D hybrid type HSDT with 5 unknowns

J.L. Mantari [a,*], E.V. Granados [b]

[a] Faculty of Mechanical Engineering, University of Engineering and Technology, Av. Cascanueces 2281, Santa Anita, Lima, Peru
[b] Faculty of Mechanical Engineering, National University of Engineering, Av. Túpac Amaru 210, Rimac, Lima, Peru

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ABSTRACT

This paper presents a thermoelastic bending analysis of functionally graded sandwich plates by using a new quasi-3D hybrid type higher order shear deformation theory (HSDT). The mathematical model contains only 5 unknowns as the first order shear deformation theory (FSDT). The nonlinear term of the temperature field is modeled in such way that can be different from the shape functions of the displacement field. The mechanical properties of functionally graded layers of the plate are assumed to vary in the thickness direction according to a power law distribution. The governing equations for the thermoelastic bending analysis are obtained through the principle of virtual work and solved via Navier-type solution. Results reveal: (a) the good performance of the present generalized formulation; (b) the significant influence of the nonlinear temperature field on the displacements and stresses results. Consequently, discussion on nonlinear temperature field influences should be further considered in the literature.

1. Introduction

Composite materials are alternative materials utilized extensively in construction or fabrication of structures due to the high performance and reliability [1]. Mainly, there are two types of constructions with composite materials; the single skin and the sandwich construction [2,3]. The sandwich construction is noted for its exceptional stiffness-to-weight ratio compared with other structures. Classical sandwich construction is often used in ship structures because of its main features; such as high flexural resistance, high impact strength (carbon fibers), high corrosion resistance (glass fibers) and the low thermal and acoustics conductivity [4,5]. In the last decades the use of sandwich construction grew rapidly around the world. Its advantages, the development of new materials and the necessity of high performance under static, dynamic and thermal loads guarantee that the sandwich structures will be in demand for many years [6–8]. With the increased use of sandwich structures, there is a tremendous need to develop efficient manufacturing techniques, economical and effective repair techniques, and analysis methods to predict the short and long-term behavior of the multilayer composite materials under a variety of loading and environmental conditions.

Normally, a sandwich plate is composed of skins (inner and outer layers) and the core. The core of the sandwich plate is a very important component in layered structures. Several types of cores have been developed for different applications; among them are the honeycomb, foam, web, and solid type such as a functionally graded (FG) core. In recent years the behavior of sandwich structures made of functionally graded materials (FGMs) are being studied. FGMs are produced for example by mixing two or more materials in a certain volume ratio. The continuous nature of the variation of the material properties in FGMs lessens both thermal and residual stresses. Thus, the known advantages of FGMs are incorporated in the sandwich construction for several engineering applications. A sandwich construction can be composed of a FG core and two homogeneous skins or a homogeneous core and two FG skins.

A literature review reveals that many theories have been developed to study the behavior of structures composed of layers. These theories can be classified in different models, such as equivalent single layer (ESL), quasi-layerwise and layerwise models. HSDTs were developed to improve the analysis of plate responses and extensively used by many researchers. Normally, these theories comply with the free surface boundary conditions and account for approximately parabolic distribution of shear stresses through the thickness of the plate. On the other hand, layerwise theories may provide a better representation of interlaminar stresses (continuous transverse stresses at layer interfaces) and moderate

* Corresponding author. Tel.: +51 13540070, cell: +51 96224551.
E-mail address: jmantari@utec.edu.pe (J.L. Mantari).

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to severe cross-sectional warping, thus they allow to analyze the local behavior of laminated structures when needed (e.g. modeling damage, impact, non-linear effects), but they may be computationally too expensive.

In general, the structures are subjected to mechanical load and temperature changes both internally and externally. Then, it is important to analyze the behavior of structural elements subjected to mechanical or thermal loads or a combination of both. In this sense, many authors investigated the thermo-mechanical behavior of sandwich plates by using HSDTs with both layerwise and ESL approaches.

Polit and Touratier [9] presented a new six-node multilayered triangular finite element based on a HSDT to analyze the behavior of sandwich plates under mechanical load. The theory takes into account the interlaminar continuity of the transverse shear stresses. Kant and Swaminathan [10] presented an analytical solution for the static analysis of sandwich plates subjected to mechanical load based on a quasi-3D HSDT with 12 unknowns. Matsunaga [11] expanded the displacement components with power series for the analysis of sandwich plates under thermal loads by using a 2D HSDT. Ferreira et al. [12] presented the static analysis of sandwich plates under mechanical loads by using multiquadric discretization and a FSDT layerwise theory. Zenkour and Alghamdi [13] analyzed the response of FG sandwich plates subjected to thermal load based on quasi-3D HSDT. The authors considered that the function of the nonlinear term of the temperature field is equal to the shape function of the displacement field. Xiang et al. [14] studied the static behavior of sandwich plates under mechanical loads by discretizing several HSDTs by a meshless method based on inverse multiquadric radial basis functions. Cetkovic and Vuksanovic [15] used a generalized layerwise theory to study the sandwich plates under mechanical loads. This theory assumes transverse variation of the in-plane displacement components in terms of 1D linear Lagrangian finite elements. Shariyat [16,17] presented a linear and nonlinear bending analysis of sandwich plate under thermomechanical loads based on generalized 3D high-order double superposition global–local theory, respectively. Zenkour [18] analyzed the thermal buckling of FG sandwich plates subjected to uniform temperature rise or a graded temperature change across the thickness. The author utilized a sinusoidal shear deformation plate theory (SSDT) and the non-linear von Karman strain–displacement equations. Mantari et al. [19–21] analyzed the behavior of a sandwich plate subjected to mechanical loads based on news HSDTs. The ESL shear deformation theory developed in [20] was extended to layerwise shear deformation theory for the finite element analysis of sandwich plates under mechanical loads in [22]. Natarajan and Manickam [23] employed a C^0 8-noded quadrilateral plate element with 13 degrees of freedom per node based on a HSDT to study the static behavior of FG sandwich plates. Nguyen et al. [24] presented a formulation based on isogeometric finite element approach associated with a HSDT to study the static and buckling behavior of sandwich plate under mechanical loads. Thai et al. [25] also presented the static and buckling analysis of sandwich plate under mechanical loads based on isogeometric layerwise finite element approach. Grover et al. [26] developed a new inverse hyperbolic shear deformation theory for the bending and buckling analysis of sandwich plates considering a displacement field with 5 unknowns without thickness stretching effect. Neves et al. [27] presented the static and buckling analysis of FG sandwich plates under mechanical loads based on a HSDT with thickness stretching effect. The authors utilized the Carrera's Unified Formulation (CUF) to obtain the governing equations, then, the static and eigenvalue problems were solved by collocation with radial basis functions. Further extension of CUF can be seen in Refs. [28–33].

Recently, Golmakani [34] studied the large deflection analysis of FG solid and hollow rotating axisymmetric disk with uniform and variable thickness subjected to thermo-mechanical loading. Torabi et al. [35] investigated the buckling analysis of a FG conical shell integrated with piezoelectric layers that is subjected to combined action of thermal and electrical loads. Malekzadeh and Monajjemzadeh [36] studied the dynamic response of FGPs in thermal environment under a moving load and elastic foundation. The equations are derived based on the FSDT including the effects of initial thermal stresses induced by the thermal environment. Kiani and Eslami [37] presented an exact solution for thermal buckling of annular FGM plates on an elastic medium. Hamidi et al. [38] developed a refined 2D shear deformation theory with four unknowns for the bending analysis of FG sandwich plates under thermomechanical loads considering a nonlinear temperature field with a polynomial function. Houari et al. [39] analyzed the sandwich plates with functionally graded skins under thermal load by using a HSDT with thickness stretching effect. Tounsi et al. [40] presented the bending analysis of sandwich plates with functionally graded core based on refined shear deformation theory. The last two papers considered a temperature field with a sine function in the nonlinear term.

This paper presents an analytical solution of the thermoelastic bending problem of FG sandwich plates by using a new quasi-3D hybrid type HSDT. The displacement field contains two shear strain shape functions, i.e. $f(z)$ and $g(z)$. Normally non-polynomial shear strain shape functions, such as trigonometric, trigonometric hyperbolic, exponential, etc., can be used in classical HSDTs and in general $g(z) = f'(z)$. Therefore, in most of the formulation presented in the literature, it is not free to choose the shear strain shape function $g(z)$. The present generalized formulation has that freedom, and infinite hybrid type shear deformation theories (polynomial or non-polynomial or hybrid type) can be created just having five unknowns, i.e. if desired $g(z)$ can be different from $f'(z)$. This generalized quasi-3D hybrid type HSDT accounts for adequate distribution of the transverse shear stresses through the plate thickness and tangential stress-free boundary conditions on the plate boundary surface, thus a shear correction factor is not required. The nonlinear term of the temperature field can be different from the shape functions of the displacement field. The mechanical properties of functionally graded layers of the plate are assumed to vary in the thickness direction according to a power law distribution in terms of the volume fractions of the constituents. The governing equations for the thermoelastic bending analysis are obtained through the principle of virtual works. These equations are then solved via Navier solution. The solutions are obtained for simply supported sandwich plates subjected to a transverse thermal bi-sinusoidal load. The performance of the theory is verified by comparing results with other quasi-3D HSDTs and 2D HSDTs available in literature.

2. Analytical modeling

The mathematical model was built to solve two types of FG sandwich plates. The sandwich plates of uniform thickness "h", length "a", and width "b" are shown in Figs. 1 and 2. The rectangular Cartesian coordinate system x, y, z, has the plane $z = 0$, coinciding with the mid-surface of the plates. The vertical positions of bottom, the two interfaces and the top surface of the sandwich plate are denoted by $h_1 = -h/2$, h_2, h_3, $h_4 = h/2$, respectively. The ratio of the thickness of each layers from bottom to top is denoted by the combination of three numbers, for example, a symmetric sandwich plate composed of three layers of equal thickness will have a configuration or scheme "1-1-1" ($h_2 = -h/6$, $h_3 = h/6$).