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An approach for bending and transient dynamic analysis of integrated thermal protection system with temperature-dependent material properties

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ABSTRACT

A C^0 higher-order layerwise finite element model combined with homogenization techniques for bending and transient dynamic analysis of integrated thermal protection system (ITPS) panel is presented. The ITPS panel is homogenized as an equivalent sandwich plate, and a reduced temperature field for the entire panel is derived. An advanced analytical equivalent model based on energy approach and Castigliano's theorem for the mechanical properties of the trapezoidal corrugated core is presented, which considers the effects of temperature-dependent material properties. The proposed layerwise theory which is developed for a sandwich plate, assumes linear, quadratic and cubic polynomial distributions of displacements for middle layer and linear polynomial distributions of displacements for top and bottom layers. And the effect of transverse normal strains is taken into account in the layerwise theory. A four-noded isoparametric element with 16 degrees of freedom per node is employed to model the equivalent sandwich plate. The accuracy of the proposed method is verified by comparison with the results by three-dimensional (3D) finite element analysis. It has been shown that the proposed method requires significantly less computational effort and agrees well with the finite element results.

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1. Introduction

The technology development conducts the future launch vehicle to be durable, operable and cost effective [1]. The vehicle's thermal protection system (TPS) is one of the most expensive and critical systems of the space vehicle. Future space vehicles require more advanced TPS than the one currently used. This means that the TPS not only withstands serious temperature induced by aero-heating during launch and re-entry process, but also should be required to be lightweight, easily maintained and fully reusable [2]. Because the traditional TPS is unable to satisfy the requirements, a new TPS concept has been developed to meet these goals. The ITPS design using metallic materials and trapezoidal corrugated cores is presented in this article. The concept provides an integrated structural component for thermo-mechanical load bearing and thermal protection function [3]. A precise and rapidly static and transient dynamic analysis of the ITPS under thermal and mechanical loads is important in the preliminary design.

The efficient structural analysis of these periodic structural plates requires homogenization techniques [4]. Many authors have studied the homogenization method for corrugated plate. The key of homogenization techniques is the correct estimation of equivalent rigidities. The earliest estimation of equivalent elastic properties of corrugated plate was found in the work of Seydel [5]. Since then, several authors have analyzed these corrugated core sandwich plates, see Refs. [6,7]. Until Briassoulis's study [8], the Castigliano's second theorem was developed, and the precise of extensional and flexural rigidities of the corrugated plates was improved greatly. Following the approach introduced by Briassoulis et al. [9], the transverse stiffness is not negligible for modeling thick plate. Samanta and Mukhopadhyay [10] derived new formulas for the equivalent extensional rigidity of trapezoidal corrugated plates based on energy methods, and carried out static and dynamic analysis on the corrugated plates. Liew et al. [11] proposed a mesh-free Galerkin method for the free vibration analysis of corrugated plates using the homogenization method based on the first shear deformation theory. Bartolozzi et al. [12] presented a new analytical technique for deriving the in-plane and out-of-plane equivalent rigidities of sinusoidal corrugated plates. Mohammadi et al. [13] following Bartolozzi' s method had formulated the equivalent rigidities of trapezoidal corrugated plates.

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By using the homogenization techniques, the entire panel can be analyzed as an equivalent sandwich plate, and the corrugated core is homogenized as an orthotropic layer [14]. Many researchers derived different solutions to predict the static and dynamic behavior of sandwich plates. Two approaches mainly considered based on displacement field are equivalent single layer (ESL) theories and layerwise (LW) theories [15]. Classical laminate theory (CLT) and first-order shear deformation theories (FSDT) were the earliest ESL theories adopted for analysis of sandwich plate [16]. Martinez [14] presented an analytical solution based on the FSDT to deal with the bending analysis of corrugated core ITPS, but the solution did not include the effects of transverse normal strains and temperature-dependent material properties. To represent the transverse shear stresses along the thickness of thick plate, higher-order shear deformation theories (HSDT) were developed, which must include cubic distributions of displacement fields [17]. However, the ESL theories fail to capture precise bending and dynamic behavior for sandwich structure, because the transverse strain considered to be continuous functions across the laminate thickness leads to discontinuous interlaminar stresses at layer interface. Thus, the LW theories is employed by many researchers in order to accurately predict the through thickness displacement, strain and stress fields [18,19]. The ITPS is homogenized as a thick sandwich structure, therefore, higher-order distributions of the displacement fields through the thickness of the middle layer should be assumed. There are a few layerwise theories published about the higher-order displacement fields. Plagianakos and Saravanos [20] developed a higher-order layerwise theoretical framework, which enables prediction of the static response of thick sandwich composite plates. The method assumed linear, parabolic and cubic distributions of the in-plane displacements through the thickness of each layer, and globally smeared through the laminate thickness. Pandey [21] presented a new layerwise plate formulation based on a C^0 higher-order finite element model for static and free vibration analysis of sandwich plates. The new layerwise theory assumed higher-order displacement field for the middle thick layer and first-order displacement field for top and bottom thin layers.

The objective of this paper is to propose a simplified approach for calculating bending and transient dynamic responses of trapezoidal corrugated core ITPS under thermal and mechanical loads. The ITPS panel is homogenized into a thick sandwich plate. The temperature field for the entire panel is reduced according to the geometry of the ITPS structure. An advanced analytical equivalent model based on energy approach and Castigliano's theorem considering the effects of temperature-dependent material properties is presented for the problem of equivalent rigidities. In addition, the equivalent mass density and coefficient of thermal expansion for the corrugated core are also derived. By using the homogenization techniques above, a C^0 higher-order layerwise theory based on kinematic assumptions is presented. The theory employs higher-order displacement field for the core and first-order displacement field for both top and bottom layers, and satisfies a priori the displacement field continuity through the thickness of sandwich plate. The effect of transverse normal strain is also included in the core layer. A four-noded isoparametric plate element with 16 degrees of freedom per node is employed for the finite element method (FEM) model. The accuracy of the proposed method is verified by comparing with the available results from literature and FEM.

2. Homogenization method

As Figs. 1 and 2 shown, the ITPS panel is homogenized as an equivalent sandwich plate. Therefore, the homogenization technique of corrugated core ITPS panel is necessary to study. In this section, the equivalent properties with temperature-dependent material properties needed to model a trapezoidal corrugated core are derived. Fig. 1 shows a typical corrugated core panel with the key dimensions including the sheet thickness h_1 and h_3, the corrugated sheet thickness t_w, the core height h_2, the inclined angle of the corrugation θ, the corrugated sheet spacing p, and the panel length and width a and b. In addition, Fig. 2 shows an equivalent sandwich plate with the key dimensions including the location of lower and upper surfaces of each layer $z_l^{(1)}, z_u^{(1)}, z_l^{(2)}, z_u^{(2)}, z_l^{(3)}, z_u^{(3)}$. E_w, μ_w and α_w are the Young's modulus, Poisson's ratio and coefficient of thermal expansion of the isotropic material used to build the trapezoidal corrugated core.

2.1. Reduced temperature fields

Before the equivalent properties are derived, the temperature field of ITPS panel is simplified in this subsection. $\Delta T^{(1)}(x,y,z)$, $\Delta T^{(2)}(x,y,z)$ and $\Delta T^{(3)}(x,y,z)$ are defined as the temperature fields for the bottom face sheets, the entire corrugated core and the top face sheets, respectively. As shown in Fig. 1, the ITPS panel is composed of two outer face sheets and a trapezoidal corrugated core. The height of the corrugated core needs to be thick enough to maintain the temperature of underlying structures within acceptable limits, and the outer face sheets are thin in comparison with the core height. Therefore, the temperature fields through the thickness of the outer face sheets are treated as uniform. As a result, the variable z in $\Delta T^{(1)}(x,y,z)$ and $\Delta T^{(3)}(x,y,z)$ are vanished, and the temperature fields for the bottom and top face sheets are reduced to:

$$\Delta T^{(1)} = \Delta T^{(1)}(x,y), \qquad \Delta T^{(3)} = \Delta T^{(3)}(x,y) \tag{1}$$

The temperature field $\Delta T^{(2)}(x,y,z)$ for a unit cell that build the corrugated core can be divided into two parts Block 1 and Block 2 as shown in Fig. 3. For the Block 1, the temperature fields of part AB and CD are assumed to be uniform in y direction in the half unit cell, because the length of the two parts in y direction is significant short with respect to the length in x direction, and the gradient of temperature distributions of the two parts in y direction is small. The temperature fields for the horizontal corrugated sheets as parts AB and CD are reduced to $\Delta T^{(2)}\left(x, y = y_B, z = z_l^{(2)}\right)$ and $\Delta T^{(2)}\left(x, y = y_C, z = z_u^{(2)}\right)$, respectively, where y_B and y_C are the location of point B and point C in y direction. For the inclined corrugated sheets as part BC, the variable y in the temperature field $\Delta T^{(2)}(x,y,z)$ is replaced by $y_B + \frac{z - z_l^{(2)}}{\tan\theta}$.

For the Block 2, the temperature fields for part $A'B'$ and $C'D$ are reduced to $\Delta T^{(2)}\left(x, y = y_{B'}, z = z_l^{(2)}\right)$ and $\Delta T^{(2)}\left(x, y = y_{C'}, z = z_u^{(2)}\right)$, respectively, where $y_{B'}$ and $y_{C'}$ are the location of point B' and point C' in y direction. For part BC, the variable y in the temperature field $\Delta T^{(2)}(x,y,z)$ is replaced by $y_{B'} - \frac{z - z_l^{(2)}}{\tan\theta}$. By using the treatment described above, the variable y in the temperature field for the entire core can be vanished, thus $\Delta T^{(2)}(x,y,z)$ will be reduced to a function with respect to x and z, which is given by:

$$\Delta T^{(2)}(x,y,z) = \Delta T_r^{(2)}(x,z) \tag{2}$$

2.2. Equivalent elastic properties

According to Bartolozzi's study [12], a unit cell of the corrugated core can be divided into four sections by its center line as shown in Fig. 4. The width of the corrugated core db in x direction is assumed to be significant small, hence the temperature distribution can be considered as uniform along x direction. From the study by

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