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Nonlinear transient response of fibre metal laminated shallow spherical shells with interfacial damage under unsteady temperature fields ☆

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ABSTRACT

This paper is concerned with the transient response of fibre metal laminated (FML) shallow spherical shells with interfacial damage subjected to the unsteady temperature field. An exact displacement field which satisfies the boundary conditions on the outer and inner surfaces and stress continuity conditions at interfaces is presented. The nonlinear governing equations of motion for FML shallow spherical shells including the transverse shear deformation are established using the Hamilton's principle. The transient temperature is determined from the heat conduction equation by using the finite difference method. The collocation point method and Newmark method are adapted to solve the governing equations of motion numerically. The present model provides an effective method for nonlinear dynamic analysis of composites laminated structures with interfacial damage subjected to transient temperature fields. In the numerical examples, the transient temperature, thermal deformation and stresses of FML shallow spherical shells are presented. The transient temperature will increase from initial value with time to a steady state. The displacements and stresses of the shell increase with time and remain unchanged when the temperature is in a steady state. And the effects of interfacial damage on the mechanical behaviours of FML shallow spherical shells are also discussed.

1. Introduction

In the 1980s, fibre metal laminates (FMLs) were developed at Delft University of Technology in the Netherland [1]. FMLs are multi component materials, formed from the combination of the metal layers and fibre reinforced composite layers, for example, the aluminium layers and glass fibre epoxy layers with various stacking sequences. FMLs have been widely used for manufacturing aerospace and aircraft structures such as the skin of the wing, due to their better mechanical properties such as the longer fatigue, higher impact resistance, and higher strength and stiffness to weight ratios compared to the conventional composites [2–4]. However, as a result of the manufacturing processes and operating conditions, interfacial damage can often occur between the metal layer and fibre reinforced composite layer, which results in stiffness degradation and has evident influence on the mechanical properties of the structures. Another significant concern for FMLs used in aeronautics is their high probability to suffer from high temperature or temperature change rapidly, and it can also affect the properties of the structures.

Presently, a lot of research have been performed on the analysis of fibre metal laminated (FML) structures. Sexton et al. [5] investigated the room temperature formability of a fibre metal laminate system using the ARAMIS three-dimensional strain measuring system. Hashagen et al. [6] studied the behaviour of fibre metal laminates employing a geometrically and physically nonlinear solid-like shell element. Reyes and Cantwell [7] investigated the quasi-static and impact properties of fibre metal laminates by experimentation. Hagenbeek et al. [8] gave a brief overview of the static properties of fibre metal laminates. By using the Galerkin method and multiple time scales method, Shooshtari and Razavi [9] investigated the linear and nonlinear free vibrations of fibre metal laminated rectangular plates. Sun et al. [10] employed indentation tests to model the contact behaviours between the ARALL laminates (aramid aluminium laminate) and a steel ball, and then determining the impact failure modes by using a low-velocity impact test. Using an instrumented falling weight machine, the low-velocity impact tests were carried out on the fibreglass–aluminium laminates made of 2024 T3 sheets and S2-glass/epoxy prepreg layers by Caprino et al. [11]. Employing the first-order shear deformation theory, Payeganeh et al. [12] investigated the effects of parameters like the layer sequence, mass and velocity of the impactor and aspect ratio of fibre metal laminated plates on the dynamic response of the plates. The static indentation, low and high velocity impact tests were conducted on fibre metal laminates by Volt et al. [13–15], and the impact properties and dynamic

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behaviours of fibre metal laminates were presented in these articles. Fan et al. [16] developed a finite element method to simulate the impact response of fibre metal laminates. Khan et al. [17] presented the experimental and analytical investigations of the effect of variable amplitude load sequences on the delamination behaviour in fibre metal laminates. By using the extended finite element method (XFEM), Curiel Sosa and Karapurath [18] studied the delamination in fibre metal laminates. Remmers and Borst [19] studied the delamination buckling of fibre metal laminates employing the experiment and numerical models.

However, there are only a few literatures have been reported concerning the thermal problem of FML structures. Cortes and Cantwell [20] investigated the tensile properties of a titanium-based thermoplastic fibre metal laminated plate at quasi-static rates of strain. Rolfes and Hammerschmidt [21] studied the transverse thermal conductivity of the unidirectional CFRP (carbon-fibre-reinforced plastics) laminates. Using the simultaneous thermal analysis, thermogravimetry analysis (TGA) and differential scanning calorimetry (DSC), Zhu et al. [22] studied the degradation behaviour of epoxy resins in fibre metal laminates. Based on a solid-like shell element, Hagenbeek [23] developed a thermo-mechanical finite element model for fibre metal laminates.

To the author's knowledge, the transient thermoelastic problem of fibre metal laminated (FML) shallow spherical shells with interfacial damage has not been reported. In the present paper, a model for FML shallow spherical shells with interfacial damage under the unsteady temperature field is presented. The unsteady heat conduction equation is solved by the finite deference method, and the displacement functions are discrete in space and time domain by the collocation point method and Newmark method, respectively, combining the governing equations of motion and the boundary conditions, the whole problem is solved by the iterative method. Then the transient temperature, thermal deformation and stresses of FML shallow spherical shells are presented and the effects of interfacial damage on the mechanical behaviours of FML shallow spherical shells are also discussed. The present model provides an effective method for nonlinear dynamic analysis of composites laminated structures with interfacial damage subjected to transient temperature fields.

2. Basic equations

Consider a FML shallow spherical shell clamped with in-plane immovable on its edge, as shown in Fig. 1, in which R, a, h are the curvature radius of middle curved surface, radius of the base circle and the thickness of the shell, respectively. Let N denotes the number of layers, and $h^{(k)}$ is the distance between the kth interface and the outer surface. The kth interface is located between the kth and $(k+1)$ th layers. Arbitrary point in the shell can be determined by the orthogonal curvilinear coordinates (φ,θ) on the outer surface and z coordinate along the inner normal direction of the outer surface. The complementary angle of latitude φ is measured from the axisymmetric axis, and the longitude θ is measured from any radius of a parallel circle. $z = 0$ and $z = h$ denote the outer and inner surfaces of the shell, respectively. In the given orthogonal curvilinear coordinates, the principle radii of curvature are $R_1 = R_2 = R$, the Lamé coefficients of the middle curved surface are $A = R$ and $B = R\sin\varphi$ and the principle curvatures are $\kappa_1 = \kappa_2 = -1/R$.

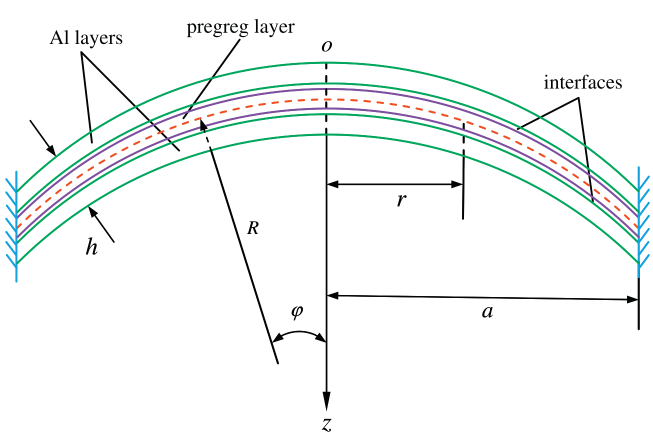

Fig. 1. Geometrical configuration of FML shallow spherical shell.

2.1. Constitutive relations

Consider the influence of a one-dimensional unsteady temperature field $T(z,t)$ on the transient behaviours of a FML shallow spherical shell, the temperature of the shell is assumed to be difference on the outer surface $(z = 0)$ and inner surface $(z = h)$, but constant in-plane. The heat conduction equation for the kth layer of the shell can be expressed as [24]

$$\kappa^{(k)} \frac{\partial}{\partial z}\left(\frac{\partial T(z,t)}{\partial z}\right) - \rho^{(k)} c^{(k)} \frac{\partial T(z,t)}{\partial t} = 0 \tag{1}$$

in which variable t denotes time, and $\kappa^{(k)}$, $\rho^{(k)}$ and $c^{(k)}$ are thermal conductivity, mass density and specific heat of the kth layer shell, respectively. The temperature on the outer and inner surfaces of the shell are T_o and T_i, respectively. And the stress free temperature is assumed to be 0.

Therefore, considering the transient temperature effect, the thermoelastic constitutive relations for the kth layer of the FML shallow spherical shell can be expressed as

$$\begin{Bmatrix} \sigma_\varphi^{(k)} \\ \sigma_\theta^{(k)} \\ \sigma_{\varphi z}^{(k)} \end{Bmatrix} = \begin{bmatrix} C_{11}^{(k)} & C_{12}^{(k)} & 0 \\ C_{21}^{(k)} & C_{22}^{(k)} & 0 \\ 0 & 0 & C_{44}^{(k)} \end{bmatrix} \left(\begin{Bmatrix} \varepsilon_\varphi^{(k)} \\ \varepsilon_\theta^{(k)} \\ \varepsilon_{\varphi z}^{(k)} \end{Bmatrix} - \begin{Bmatrix} \alpha_1^{(k)} \\ \alpha_2^{(k)} \\ 0 \end{Bmatrix} T(z,t) \right) \tag{2}$$

in which $\sigma_\varphi^{(k)}, \sigma_\theta^{(k)}$ and $\sigma_{\varphi z}^{(k)}$ are the stress components of any point in the kth layer shell. $\varepsilon_\varphi^{(k)}, \varepsilon_\theta^{(k)}$ and $\varepsilon_{\varphi z}^{(k)}$ are the strain components of arbitrary point in the kth layer shell. $\alpha_1^{(k)}$ and $\alpha_2^{(k)}$ are coefficients of thermal expansion along the r and θ directions, and $C_{ij}^{(k)}$ $(i,j = 1,2,4)$ are the elastic stiffness coefficients of the kth layer shell.

2.2. Geometric relations

Using power series expansion of displacement components along the coordinate z, the displacement components (u, v, w) of arbitrary point in the FML shallow spherical shell along the coordinate (φ,θ,z) at any time t are expressed following [25] as

$$\begin{aligned} u(\varphi,\theta,z,t) &= u_0 + z\phi_u + z^2\psi_u + z^3\eta_u + \sum_{k=1}^{N-1}\left[\delta_u^{(k)} + \Omega_u^{(k)}(z-h^{(k)})\right]H(z-h^{(k)}) \\ v(\varphi,\theta,z,t) &= v_0 + z\phi_v + z^2\psi_v + z^3\eta_v + \sum_{k=1}^{N-1}\left[\delta_v^{(k)} + \Omega_v^{(k)}(z-h^{(k)})\right]H(z-h^{(k)}) \\ w(\varphi,\theta,z,t) &= w_0 \end{aligned} \tag{3}$$

where (u_0, v_0, w_0) are the displacement components of the corresponding point of the outer surface along the (φ,θ,z) directions respectively, and $(\phi_u, \psi_u, \eta_u, \phi_v, \psi_v, \eta_v)$ are the high-order shear functions to be determined by the conditions that the transverse shear stresses vanish on the outer and inner surfaces. $\left(\delta_u^{(k)}, \delta_v^{(k)}\right)$ are the relative displacement components of the kth interface, and $\left(\Omega_u^{(k)}, \Omega_v^{(k)}\right)$ are the shape functions to be determined by the stresses continuity conditions at interfaces.