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Nonlinear delamination buckling and expansion of functionally graded laminated piezoelectric composite shells

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ABSTRACT

In this paper, an analytical method is presented to investigate the nonlinear buckling and expansion behaviors of local delaminations near the surface of functionally graded laminated piezoelectric composite shells subjected to the thermal, electrical and mechanical loads, where the mid-plane nonlinear geometrical relation of delaminations is considered. In examples, the effects of thermal loading, electric field strength, the stacking patterns of functionally graded laminated piezoelectric composite shells and the patterns of delaminations on the critical axial loading of locally delaminated buckling are described and discussed. Finally, the possible growth directions of local buckling for delaminated sub-shells are described by calculating the expanding forces along the length and short axis of the delaminated sub-shells.

1. Introduction

Functionally graded material (FGM) is microscopically inhomogeneous composites composed of some different materials along a determined direction (Reddy, 2000; Shen, 2005; Shariyat, 2009a). By gradually changing the volume fraction of constituent materials, the properties of FGM appear in a smooth and continuous variation from one surface to another, so that the interface stress concentration usually taking place in laminated composite structures can be eliminated. Therefore, FGM have been potential for the engineering application for tailoring the desired thermo-mechanical properties. Piezoelectric materials are widely utilized in modern engineering due to its direct and inverse electro-mechanical effects (Shariyat, 2008, 2009b). Investigations on the usage of piezoelectric layer in active structure control as noise attenuation, deformation control and vibration suppression have been presented. As the usage of these materials increases, the composite structures consist of the fiber reinforced layer, piezoelectric material layer and FGM layer have been the focus in the engineering application of smart structure. Thus, it is important to understand the deformation and failure characteristics of FGM laminated piezoelectric composite structures under various loads (Sheng and Wang, 2011, 2009a,b; Sarangi and Ray, 2013).

Numerous studies on the FGM and piezoelectric material structures subjected to mechanical, thermal and electrical loads have been performed. Assuming that the material property of the FGM beam was graded in the thickness direction according to a simple exponent-law distribution, a thermo-elastic solution of FGM hybrid beam with simply-supported edges under pressure and thermal loads was presented (Alibeigloo, 2010; Alibeigloo and Chen, 2010). Shen (2009) investigated the compressive postbuckling of shear deformable functionally graded piezoelectric plate under thermal loading. Malekzadeh et al. (2012) presented the dynamical analysis of pressurized rotating multi-layered FGM cylindrical shells in thermal environment, in which the variations of the field variables across the shell thickness were described by dividing the shell into a set of layers along the radial direction. Wu (2007) investigated the deformation characteristics of functionally graded laminated piezoelectric cylindrical shells subjected to coupling bend and electromechanical loads utilizing the perturbation method. Based on Fourier differential quadrature and polynomial differential quadrature methods, Alashti and Khorasnd (2011) described three-dimensional thermo-elastic analytical method of a FGM cylindrical shell with piezoelectric layers under the asymmetric thermo-electro-mechanical loads. Sheng and Wang (2010) investigated the coupling thermopiezoelectric elastic problem of FGM laminated composite shells subjected to moving mechanical loads and sudden temperature change, where active vibration was controlled by using piezoelectric layers embedded on the surface of functionally graded shell.

Because of the manufacturing defects and the surface damages induced by impact with lower energy, the local delamination near the surface of laminated structures is one of main failure modes, so that the delamination failure along the interface of laminated structures has been concerned in the optical

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design of composite laminated structure. Ghasemnejad et al. (2010) investigated the effect of hybrid laminate lay-up with different delamination positions in composite laminated beam. Predicting the damage and expanding extents of delaminations is essential to the continued employment of laminated composite structures in various engineering applications. Naghipour et al. (2011) studied the delamination mode in multidirectional laminate structures subjected to fatigue loading by simulating and experimental methods.

Because laminated composite structures are often subjected to loading in-plane, delaminated sub-structures easily appear in local buckling. Therefore, the delaminated buckling of laminated composite structures under various loads is one of the most critical problems in composites engineering application and is much attended. Delaminations (sub-laminations) near the surface of laminated structures are much smaller than the layer number of laminated structures (base-laminations), so that the deformation of delaminations is free and the boundary of the local delamination is fixed at the interface between sub-lamination and base-lamination. In previous literature, many investigations on the delaminated buckling of laminated composite structures have mainly focused on the delaminated buckling of fiber reinforced laminated structures. Tsouvalis and Garganidis (2011) described the effect of some delamination parameters on the delaminated buckling characteristics of laminated composite structures. Based on the modified variational principle and a nonlinear spring-layer model, Li (2012) presented a three-dimensional analytical model to study delaminated buckling for laminated composite cylindrical shells. Chirica and Beznea (2012) described the effect of delaminations on the buckling and postbuckling characteristics of the laminated composite plates subjected to shear and compression loadings. Obdržáleka and Vrbkab (2011) investigated the buckling and postbuckling behavior of delaminations in laminated composite plates with irregularly delaminated shapes. Based on laminated plate theories, Kharazi et al. (2010) presented an analytical method to study the delaminated buckling behavior of the composite laminates with through-the-width delaminations. Craven et al.(2010) investigated delaminated buckling for a carbon fibre composite laminate with multiple delaminations of realistic shape subjected to compression loading by utilizing a finite element model. Tay (2003) gave an overview on characterization and analysis of delamination fracture in laminated composite structures. Ren (2008) presented an investigation into the buckling of orthotropic piezoelectric rectangular laminates with weak interfaces based on the state-space formulation established directly from the three-dimensional theory of elasticity. Bruno and Greco (2000) gave a continuous analysis method to calculate one-dimensional modeling of failure in laminated beams and plates. Meng et al. (2010) reported the result of an investigation into the buckling characteristics for the local delamination near the surface of piezoelectric laminated shells, where local delaminated sub-shells may be monolayer and multiplayer. However, investigations on buckling behaviors of local delaminated sub-shells near the surface of FGM-laminated piezoelectric composite shells under thermal, electrical and axial compressed loads have not presented in literatures because of its complexity.

In this paper, an analytical method is presented to investigate the nonlinear buckling characteristics for local delamination near the surface of FGM laminated piezoelectric composite shells subjected to coupling electric, thermal and mechanical loads, where FGM laminated piezoelectric composite shells consist of FGM layers, piezoelectric layers and carbon fiber reinforced layers and the stack sequence of delaminated patterns near the surface of FGM laminated piezoelectric composite shells is arbitrary. The nonlinear temperature distribution along the thickness of FGM is given by solving the thermal conductive equation of FGM shell. The piezoelectric layers bonding the internal and external surface of FGM laminated piezoelectric composite shells are taken as active control layer by radial polarizing. The carbon fiber layer in FGM laminated piezoelectric composite shells is used to enhance the strength and stiffness of the FGM laminated piezoelectric composite shells. The material properties of carbon fiber layer and piezoelectric layer are taken as a function of temperature change. In examples, the stacking patterns of FGM laminated piezoelectric composite shells are, respectively, taken as $[P_0/30°/60/90/\text{FGM}/90°/60/30/P_0]$ and $[P_0/0°/45°/-45°/\text{FGM}/-45°/45°/0°/P_0]$, in which P_0 represents piezoelectric layer, and the other layers present fiber reinforced layers. The stacking patterns of locally delaminated sub-shells are $[P_0]$, $[P_0/30°]$ and $[P_0/0°]$. The results show the effects of thermal loading, electric field, stacking pattern and delaminated pattern on the critical loading of locally nonlinear delaminated buckling. Finally, by calculating the expanding forces along the length and short axis of elliptical delaminations, the possibly expanding directions of locally nonlinear buckling for the elliptical delaminations are described and discussed.

2. Calculating model and basic equations

Fig. 1 shows that a FGM (Functionally Graded Material) laminated piezoelectric composite shells is composed of FGM layer, fiber reinforced layers and piezoelectric layers, where the fiber layer and piezoelectric layer embedded on inner and outer surfaces of the FGM laminated piezoelectric composite shells is acted as reinforced and actuator effects. When the surface of FGM laminated piezoelectric composite shells is impacted by objects, a local delamination with arbitrary sequence may occur near the surface of the FGM-laminated piezoelectric shells. Because FGM layer is a single layer and the piezoelectric fiber reinforced layers is symmetrical to the FGM layer, only the tension and bending coupling effect of locally delaminated sub-shells is considered in the present model. Here, R, h_b and h_s, respectively represent the mid-plane radius, the thickness of FGM laminated piezoelectric shells and the thickness of delaminations, where $h_b/R \ll 1$ and $h_s/h_b \ll 1$. The axial, circumferential and radial directions of FGM-laminated piezoelectric shells are denoted by global coordinate system (x, y, z) fixed at the mid-plane of FGM-laminated piezoelectric shells. The geometric axes of delaminations are denoted by the local coordinate system (x', y', z') fixed at the mid-plane of delaminated sub-shells. The angle between the axes x and x' in two coordinate systems is defined as φ. The material's main axes of the fiber reinforce and piezoelectric active layers are defined by $(1, 2, 3)$, and the angle between the material's main axes 1–2 and the global coordinate axis x–y is defined by θ.

The material property of FGM layer is described using a simple rule of mixtures composed of metal and ceramic (Fig. 1), and varies along the thickness of FGM layer according to a power low, as follows:

$$F_{eff}(z) = F_o V(z) + F_i(1 - V(z)), \quad V(z) = \left(\frac{z + h_f/2}{h_f}\right)^{\Phi}, \quad -0.5h_f \leqslant z \leqslant 0.5h_f \tag{1}$$

where F_{eff} is used to effectively describe the variation of elastic modulus, mass density, Poisson's ratio, thermal expansion coefficient and the thermal conductivity of functionally graded materials along the thickness h_f of FGM layer, F_o and F_i denote the material property of the outer surface $(z = 0.5h_f)$ and inner surface $(z = -0.5h_f)$ of the FGM layer, respectively, and Φ denotes the volume fraction exponent $(\Phi \geqslant 0)$.

Expanding Eq. (1), the effective elastic modulus, thermal expansion coefficient and thermal conductivity of FGM layer are written as