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Effect of viscoelastic interface on three-dimensional static and vibration behavior of laminated composite plate

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ABSTRACT

In this study, static and free vibration analysis of laminated cross-ply rectangular plate with special emphasis on incorporating viscoelastic interface is investigated using three-dimensional theory of elasticity. The laminated plate is assumed to be simply-supported at four edges and is subjected to uniform pressure at the top surface. State space technique is used along the plate thickness to investigate the space dependent behavior where as time dependent behavior can be discussed by solving first order differential equation of sliding displacement at the viscoelastic interfaces. Numerical results depicts that the present method converges rapidly and good agreement is exist between the present results and the published results. Moreover, the effects of elastic and viscous interfaces, time, aspect ratio and length to thickness ratio on the bending and vibration behavior of laminated plate are studied.

1. Introduction

The imperfect bonding may occur due to the presence of a thin (adhesive) layer between the adjacent plies. In the limit of the thickness of interface layer, displacement jumps occur across the interface from one side to another, while the tractions must be continuous from equilibrium considerations [1]. Imperfect interface layer has low shear modulus between two neighboring layers and also natural causes and circumstances (temperature, humidity, etc.) may also weaken the interface bonding. Dynamic behavior of piezoelectric sensor and actuator layers attached to the host layer in smart structures depends on the bonding condition along the interfaces of these layers. Moreover, imperfect interface affects the static and dynamic behavior of laminated structures such as beam, plate and shell significantly. Theoretical or experimental prediction of bonding layer response exactly is more difficult in laminated structures. Diab and Wu [2]) presented a viscoelastic model which is a generalized Maxwell constitutive model to describe the long term behavior of the adhesive layer bonding FRP sheet to concrete, the FRP–concrete interface. Fotsing et al. [3] analyzed bonding behavior of carbon/epoxy composites with viscoelastic acrylic adhesive. Chowdhur and Xia [4] used experimental method integrated with finite element analysis to determine the interface strength between an elastic isotropic material and the a linear viscoelastic material. Leuscher et al. [5] used the idea of defining constitutive laws by two potential to model the cohesive interfaces appear in many materials and structures, e.g. composites or adhesive bonds. Some simplified interfacial models have been used by researchers. The first one is linear spring-like model which has been widely used by chen et al. [1] and Icardi [6] to model the load transferring at interfaces between adjacent layers which constitute the laminated structure. In this model the interface layer is modeled by a continuous linear spring in which the sliding displacement between the two adjacent layers at the interface is spring deflections which are linearly proportional to the interface tractions with the proportionality equal to the constant coefficient of spring. Cheng et al. [7] used the Hamilton's principle to investigate the bending and the free vibration behavior of laminated shell with assumption of linear spring-like model for the interface imperfection. Based on theory of elasticity, Shu [8] developed seven degree-of-freedom plate model and assumed linear spring model for imperfect interfaces to discuss the bending and the free vibration of angle-ply laminated plate. Chen et al. [9] used linear spring layer model for the interface imperfection and developed state-space technique to analyze the bending and the free vibration of a simply-supported cross-ply laminated plate. Chen et al. [10] discussed the bending and the free vibration of cross-ply laminated

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Nomenclature

a, b, h	plate dimension in x, y and z directions
C_{ij} (i,j = 1,2,…,6)	material elastic constants
σ_i (i = x,y,z)	normal stresses
$\tau_{zy},\tau_{zx},\tau_{xy}$	shear stresses
u,v,w	displacement components in the x-, y- and z-direction, respectively
ε_i (i = x,y,z)	normal strains
$\gamma_{zy},\gamma_{zx},\gamma_{xy}$	shear strains
ρ	mass density of laminated plate
q	uniform applied load
n, m	half wave numbers in the x- and y-directions
ω	natural frequency
δ	state vector
$\overline{\gamma}_i(i=x,y,z)$	relative sliding displacement components in the x, y and z direction at $z=z_k$, respectively
$\eta_{0i}^{(k)},\eta_{1i}^{(k)}$ $(i=$x,y,z$)$	elastic constants and viscous coefficients of k-th interface, respectively
t	time variable
E_1, E_2, G_{12}, G_{23}, ν_{12}, ν_{23}	engineering constant in material coordinates

cylindrical panel with weak interfaces using state-space approach coupled with the layer wise method. Chen and Lee [11] presented the bending and the free vibration analysis of simply-supported angle-ply piezoelectric laminates with perfect and imperfect interfaces by using spring-like model. Based on the three-dimensional theory of elasticity, Chen and Lee [12] investigated bending behavior of a simply-supported angle-ply laminate by assuming general spring-like model for the interfacial damage. It is noted that in the spring-like model, behaviors of laminate subjected to static loading are not time dependent. Chen et al. [13] investigated the bending and the free vibration of a laminated orthotropic piezoelectric plate using theory of elasticity and linear spring layer model for imperfect interfaces. Vibration and buckling characteristics of sandwich plates were studied by Chakrabarti et al. [14] using the refined plate theory and assumption of spring layer interfacial model. Zhou et al. [15] investigated the static and the free vibration of cross-ply laminated piezoelectric plate using differential quadrature method (DQM) and general spring layer model for imperfect interfaces. Kapurio and Nair [16] presented piezo-thermo-elasticity solution for the free vibration of hybrid laminated plate considering the contribution of linear spring model of interfacial imperfection. Li et al. [17] analyzed the free vibration of laminated composite plate using the Hamilton's principle and general spring layer model for interfacial imperfection. Based on the Hamilton's principle, Li and Liu [18] analyzed the bending of stiffened laminated plates assuming linear spring layer model for imperfect interfaces and using mesh free formulation. Another interfacial model which is used to investigate the time-dependent response of a laminate is viscous interfacial model. He and Jiang [19] discussed two-dimensional behavior of isotropic laminated strip with viscous interfaces and they depicted that the response strongly depends on time at the initial time stage. Chen and Lee [20] studied the response of angle-ply laminated strip subjected to static loading by using state space approach and power series expansions to present field variables as a function of time. They showed numerically that the influence of viscous interfaces on laminate response is more significant. The third interfacial model which considers the incorporation of interfacial imperfection is superposition of the spring-like and viscous models entitled viscoelastic model. Viscoelastic interface is more appropriate for characterizing the creep and relaxation behavior of interface bonding material subjected to elevated environment temperature and also this model is suitable for the imperfect interface under dynamic loading. Yan et al. [21] used Kelvin-Voigt constitutive relation of viscoelastic interfaces and two-dimensional theory of elasticity to investigate bending of an isotropic laminated strip. To the best author's knowledge, three-dimensional bending and free vibration analysis of laminated composite plate with considering incorporation of interfacial viscoelastic imperfection has not yet been reported. In this paper, elasticity solution of laminated cross-ply plate is carried out.

2. State space formulation

Consider a cross-ply laminated rectangular plate with length a, width b and thickness h as shown in Fig. 1. Each layer of the N-layered plate is orthotropic medium with the material axis coinciding with the geometric axis. The constitutive equations for an orthotropic layer in reference coordinate system (x, y, z) are

$$\sigma = C\varepsilon \tag{1}$$

where $\sigma = \left\{ \sigma_x \quad \sigma_y \quad \sigma_z \quad \tau_{zy} \quad \tau_{zx} \quad \tau_{xy} \right\}^T$, $\varepsilon = \left\{ \varepsilon_x \quad \varepsilon_y \quad \varepsilon_z \quad \gamma_{zy} \quad \gamma_{zx} \quad \gamma_{xy} \right\}^T$

And $C = \begin{bmatrix} C_{11} & C_{12} & C_{13} & 0 & 0 & 0 \\ C_{12} & C_{22} & C_{23} & 0 & 0 & 0 \\ C_{13} & C_{23} & C_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & C_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & C_{55} & 0 \\ 0 & 0 & 0 & 0 & 0 & C_{66} \end{bmatrix}$

In the absence of body forces, the three-dimensional governing equations of motion are

$$\begin{aligned} \sigma_{x,x} + \tau_{xy,y} + \tau_{zx,z} &= \rho \frac{\partial^2 u}{\partial t^2} \\ \tau_{xy,x} + \sigma_{y,y} + \tau_{yz,z} &= \rho \frac{\partial^2 v}{\partial t^2} \\ \tau_{zx,x} + \tau_{zy,y} + \sigma_{z,z} &= \rho \frac{\partial^2 w}{\partial t^2} \end{aligned} \tag{2}$$

Strain-displacement relations in the infinitesimal theory of elasticity are

$$\begin{aligned} &\varepsilon_x = u_{,x}, \quad \varepsilon_y = v_{,y}, \quad \varepsilon_z = w_{,z}, \quad \gamma_{zy} = w_{,y} + v_{,z}, \\ &\gamma_{zx} = w_{,x} + u_{,z}, \quad \gamma_{xy} = v_{,x} + u_{,y} \end{aligned} \tag{3}$$

Lower and upper surfaces boundary conditions for the static analysis are, respectively

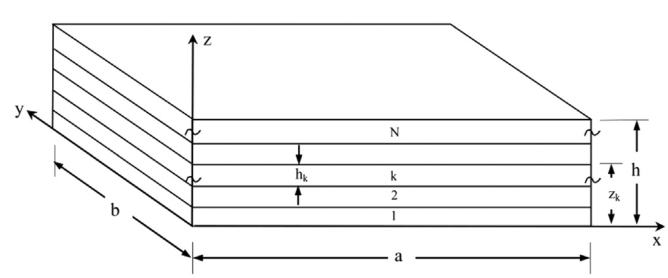

Fig. 1. Geometry and coordinates of laminated composite plate.