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Transient fracture of a layered magnetoelectroelastic medium

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ABSTRACT

Most magnetoelectroelastic composites were developed in the form of a composite laminate by alternating the ferromagnetic layers and ferroelectric layers during stacking. Presence of interfacial crack may influence the magneto-electro-mechanical coupling behavior of magnetoelectroelastic materials considerably. This paper describes a method to analyze the transient response of a layered magnetoelectroelastic medium of finite size with an interface crack. Based on Fourier and Laplace transforms, the boundary value problem is reduced to a system of generalized singularity integral equations in the Laplace transform domain. By utilized numerical Laplace inversion, the time-dependent full field solutions are obtained in the time domain. Effects of medium size, crack-face electric and magnetic boundary conditions on the dynamic crack tip fields are studied. By investigating an interface notch of finite gap thickness, the electric and magnetic properties of the medium inside the notch are included in the analytical model so that the applicability of crack-face electric and magnetic boundary conditions on the transient response of the magnetoelectroelastic medium can be investigated.

1. Introduction

Materials possessing electro-magneto-mechanical coupling effects are a class of important functional materials in the application of smart materials/intelligent structures. Since a broadband magnetoelectric transducer with a flat frequency response was reported in 1981 (Bracke and Van Vliet, 1981), many investigations of magnetoelectric coupling have been conducted both theoretically and experimentally (Benveniste, 1995; Harshe et al., 1993; Javelined and Harshe, 1994; Nan, 1994). The effects of electro-magneto-mechanical coupling have been observed in single-phase materials and in composites made of ferroelectric and ferromagnetic phases (Alshits et al., 1992; Van Run et al., 1974). In particular, composites made of ferroelectric/ferromagnetic phases can exhibit a much high magnetoelectric (ME) coupling coefficient than single-phase ferroelectric or ferromagnetic materials (Pan and Heyliger, 2002).

Magnetoelectroelastic composites can be developed in the form of secondary-phase piezoelectric (or magnetostrictive) inclusions embedded in a magnetostrictive (or piezoelectric) matrix, or in the form of a composite laminate by alternating the ferromagnetic layers and ferroelectric layers during stacking. Naturally, the effective properties and responses of the magnetoelectroelastic composites must be evaluated. Using the micromechanics method, Srinivas et al. (2006) recently estimated the properties of multiferroic composites by taking into account the effects of the shape and orientation distribution of the second phase. Huang and Kuo (1997) studied the magnetoelectroelastic media based on three-dimensional Green function method. Pan (2001) obtained the exact solutions for three-dimensional, anisotropic magnetoelectroelastic, simply supported and layered rectangular plates under surface and internal loads. Wang and Shen (2002) presented a general solution to the three-dimensional problems of the magnetoelectroelastic materials. Chen et al. (2002), Wang et al. (2005) and Bichurin and Petrov (2003) gave the static or low-frequency magnetoelectric coupling for layered composites. Lee et al. (2005) used

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finite element method to study the effective properties of an elastic medium with a piezoelectric phase and a piezomagnetic phase embedded. Micromechanics method was also used to study the effective properties of magnetoelectric composites with inclusions of piezoelectric and magnetostrictive phases (Huang and Zhou, 2004; Wang and Shen, 2003; Zhong and Sun, 2002). Li and Dunn (1998a,b) analyzed the inclusion problems and solved the average fields and effective moduli of nonhomogeneous media with elastic, electric, and magnetic coupling effects. Wang and Shen (1996) obtained the conservation laws and the path-independent integrals based on the concept of the energy-momentum.

Both piezoelectric and magnetostrictive materials are brittle. Thus magnetoelectric composites made of piezoelectric and magnetostrictive materials prone to cracking. Further, the ME coupling coefficient measured in magnetoelectroelastic composites is much lower than that predicted from theoretical calculations. One critical factor that can deteriorate the mechanical coupling between the piezoelectric and magnetostrictive layers is the presence of cracks at the interface, which will alter the integrity of the structure, and hence weaken the mechanical coupling effect. Thus, it is essential to study the inclusion and crack problems of these advanced materials. Many researchers have been aiming to find the solutions of various crack problems. For example, interface crack problem with various boundary conditions (Gao et al., 2003; Soh and Liu, 2005; Li and Kardomateas, 2007; Feng et al., 2005; Zhong and Li, 2006), three-dimensional crack problem based on general displacement discontinuity method by Zhao et al. (2008). It should also be noted that the dynamic behavior of magnetostrictive materials has become one of the current topics for research. For example, the scattered fields of SH waves and the crack opening displacement by a partially debonded magnetoelectroelastic cylindrical inhomogeneity (Du et al., 2004), and interface cracks between dissimilar magnetoelectroelastic strips (of infinite length) under out-of-plane mechanical and in-plane magneto-electrical impacts (Su et al., 2007).

The above-mentioned fracture mechanics studies were conducted mainly to obtain the crack tip fields in the magnetoelectroelastic composites under static loading or of infinite size. This paper focuses on the transient response of an interface crack (notch) in a magnetoelectroelastic laminate subjected to mode III mechanical and mode I magneto-electrical impacts. The mode III problem is important because the actual structures could subject to out-of-plane shearing and in-plane electromagnetic fields. In this paper, the medium is assumed to be finite in width and thickness. Unlike the existing work which considered only the ideal crack-face electric and magnetic boundary conditions, this paper investigates the effect of the electric permeability and magnetic permeability of the medium inside the crack (notch). The dynamic crack tip field intensity factors are obtained. Dependency of the crack tip behaviors on the material properties and medium size, which are particular important in the analysis and design of smart sensors/actuators constructed from magnetoelectroelastic composite laminates, are displayed graphically. The model includes simultaneously the previous dynamic crack problems of piezoelectric, piezomagnetic, and purely elastic materials, and the previous dynamic interface crack problems of different material combinations of piezoelectric, piezomagnetic, and elastic materials. Therefore, the present results are general enough and can serve as benchmarks to impact theories of layered magnetoelectroelastic composite structures.

2. Description of the problem

Fig. 1 shows a layered magnetoelectroelastic medium occupying $-h \leqslant x \leqslant h$, $-c < y < c$, $-\infty < z < \infty$. There is a through Griffith mode-III crack (or a notch) of length $2a$ located at the geometric center of the medium, $y = 0$, $-a \leqslant x \leqslant a$, $-\infty < z < \infty$. Here Cartesian coordinates x, y, z are the principal axes of the material symmetry. The poling direction of the magnetoelectroelastic layers is oriented in the z-axis, which is perpendicular to the (x, y) plane. In this situation, the mechanical and electric/magnetic fields are coupling through the following constitutive equations are (Wang and Mai, 2004):

$$\sigma_{xz} = c_{44}\frac{\partial w}{\partial x} + e_{15}\frac{\partial \phi}{\partial x} + h_{15}\frac{\partial \varphi}{\partial x},$$
$$\sigma_{yz} = c_{44}\frac{\partial w}{\partial y} + e_{15}\frac{\partial \phi}{\partial y} + h_{15}\frac{\partial \varphi}{\partial y}, \tag{1a}$$

$$D_x = e_{15}\frac{\partial w}{\partial x} - \in_{11}\frac{\partial \phi}{\partial x} - \beta_{11}\frac{\partial \varphi}{\partial x},$$
$$D_y = e_{15}\frac{\partial w}{\partial y} - \in_{11}\frac{\partial \phi}{\partial y} - \beta_{11}\frac{\partial \varphi}{\partial y}, \tag{1b}$$

$$B_x = h_{15}\frac{\partial w}{\partial x} - \beta_{11}\frac{\partial \phi}{\partial x} - \gamma_{11}\frac{\partial \varphi}{\partial x},$$
$$B_y = h_{15}\frac{\partial w}{\partial y} - \beta_{11}\frac{\partial \phi}{\partial y} - \gamma_{11}\frac{\partial \varphi}{\partial y}. \tag{1c}$$

Accordingly, in the absence of body forces, concentrated electric charges, and concentrated magnetic source, the system equilibrium equations are:

$$c_{44}\nabla^2 w + e_{15}\nabla^2\phi + h_{15}\nabla^2\varphi = \rho\partial^2 w/\partial t^2, \tag{2a}$$

$$e_{15}\nabla^2 w - \in_{11}\nabla^2\phi - \beta_{11}\nabla^2\varphi = 0, \tag{2b}$$

$$h_{15}\nabla^2 w - \beta_{11}\nabla^2\phi - \gamma_{11}\nabla^2\varphi = 0. \tag{2c}$$

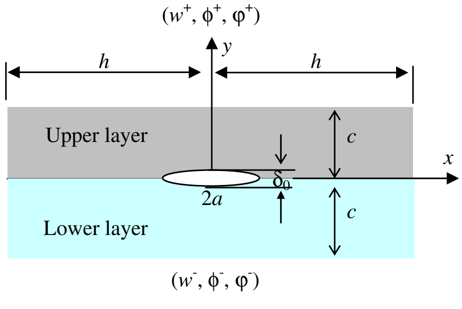

Fig. 1. An interface crack (notch) at the center of a layered magnetoelectroelastic medium of finite dimension (c: plate height; a: half crack (notch) length; h: half plate length; δ_0: maximum gap thickness of the notch).