International Journal of Solids and Structures 77 (2015) 15–27

Contents lists available at ScienceDirect

International Journal of Solids and Structures

journal homepage: www.elsevier.com/locate/ijsolstr

Interfacial sliding in a bi-layered multiferroic ceramics: Localized sliding-prevention/promotion based mechanism of intra-layer fracture

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ARTICLE INFO

Article history:
Received 12 April 2015
Received in revised form 14 July 2015
Available online 28 August 2015

Keywords:
Imperfect interface
Spring model
Interfacial sliding
Localized sliding-prevention/promotion
Fracture
Piezomagnetic/piezoelectric ceramics

ABSTRACT

Sliding is a typical failure mode of composite interfaces. According to traditional theory, interfacial sliding can be represented by the linear shear-spring model (LSSM). Although the required driving interfacial shear stress has been characterized by LSSM, the relation between interfacial normal stress and sliding is not yet reflected by it. The present paper proposes an interfacial sliding-prevention/promotion model to consider the effect of interfacial normal stress on interfacial sliding. As an example of application, the intra-layer fracture problem is analyzed on a bi-layered multiferroic ceramics. Green's functions are derived to construct the Cauchy singular integral equations, which are further numerically solved to get mechanical strain energy release rate (MSERR) and interfacial normal stress. Parametric studies yield a new finding that non-zero normal stress may be produced in local interfacial regions by intra-layer cracks under pure in-plane shear. Local positive normal stress gives rise to local sliding-promotion effect, while local negative normal stress leads to local sliding-prevention effect. The interfacial shear imperfection and local sliding-prevention/promotion constitute the mechanisms for the variation of MSERRs of the two intra-layer cracks.

1. Introduction

Interfacial imperfection widely exists in composites due to manufacturing process, fatigue damage and/or chemical action (Lavrentyev and Rockhlin, 1998). Its modeling is significant for the mechanical analyses and safety assessment of composite structures. In traditional theory, imperfect interfaces are generally formulated by the linear spring model, which regards that stresses are continuous, but displacements are discontinuous across the interface. The interfacial imperfection is represented by the jumps of displacements, and the interfacial stresses are assumed to be proportional to the corresponding displacement jumps (Hashin, 1990, 1991, 2002; Benveniste and Miloh, 2001).

Interfacial imperfection will reduce the structural stiffness and thus deteriorate the mechanical performances of composites. Based on this consideration, researchers has done various investigations on composites with imperfect interfaces in recent years. Cheng et al. (1996) discussed the effect of interfacial imperfection on the buckling and bending behaviors of composite laminates. Icardi (1999) studied the effect of inter-laminar sliding imperfection on the free vibration response of composite beams exposed to thermo-mechanical loading. Sudak et al. (1999) considered the circumferentially inhomogeneous distribution of interfacial imperfections, and derived the rigorous solution of a circular inclusion embedded in an infinite matrix in plane elasto-statics. Chen and Lee (2004a) investigated a simply supported angle-ply laminate with interfacial damage in cylindrical bending and free vibration based on the state-space method in three-dimensional theory of elasticity. Kovacs (2007) performed dynamic analysis on a laminated band with imperfect interfaces, and got its free vibration response under bending, shear and normal deformation. Nairn (2007) implemented the spring-type model of imperfect interfaces into both finite element analysis and the material point method and validated the two numerical methods by comparison to existing results. Zhong et al. (2009a) performed fracture analysis on a mode-I crack perpendicular to an imperfect interface, and revealed the effect of interfacial imperfection on the fracture behavior. Guessasma et al. (2010) derived the effective Young's modulus of biopolymer composites with imperfect interface. Kam and Kueh (2013) proposed a finite element formulation to study the bending of composite laminate plates, in presence of diagonally perturbed interfacial degeneration. Massabo and Campi (2014) presented a new mechanical model for multilayered beams/wide plates with an arbitrary number of imperfect interfaces/delaminations in the theoretical framework of the discrete-layer approach and affine traction laws. Mishuris et al. (2006, 2014) presented the boundary integral formulation for cracks at imperfect interfaces.

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http://dx.doi.org/10.1016/j.ijsolstr.2015.08.007
0020-7683/

Due to the wide applications of piezoelectric/piezomagnetic devices in recent years, the imperfect interfaces in smart composites have also drawn the attention of researchers. Because piezoelectric/piezomagnetic composites have magneto-electro-mechanical couplings, magnetic, electric and mechanical imperfections may simultaneously occur on their interfaces. In this case, the traditional linear spring model is generalized to formulate the constitutive behaviors of these three kinds of interfacial imperfections, i.e., the magnitudes of stress, electric displacement and magnetic induction are assumed to linearly depend on the jumps of mechanical displacement, electric potential and magnetic potential, respectively. Up till now, much effort has been devoted to the investigation on piezoelectric/piezomagnetic composites with imperfect interfaces. Chen and Lee (2004b) employed the state-space approach to investigate the bending and free vibration of simply supported angle-ply piezoelectric laminates in cylindrical bending, and obtained the benchmark numerical results. Kim and Lee (2008) also used the state-space formulation to survey the buckling of an orthotropic piezoelectric rectangular laminate with imperfect interfaces in the frame of three-dimensional theory of elasticity. Fang et al. (2009) considered circular cross-section inclusions embedded in piezoelectric solids with imperfect interfaces, and analyzed the electro-elastic coupling interaction between a piezoelectric screw dislocation and the inclusions. Zhou et al. (2010) derived a semi-analytical solution for orthotropic piezoelectric laminates in cylindrical bending with interfacial imperfections. Fu and Li (2011) presented a non-linear model for laminated piezoelectric plates with inter-laminar mechanical and electrical damage based on the general six-degrees-of-freedom plate theory, and discussed the effects of interfacial imperfections on the inter-laminar stress and electric potential profiles. Gu and He (2011) derived a general imperfect interface model for a 3D curved thin interphase under the coupled multi-field condition by the method of Taylor's series expansion. Otero et al. carried out continuous researches on the effects of interfacial imperfections on interfacial waves between two piezoelectric half-spaces (Otero et al., 2012), piezoelectric and piezomagnetic half-spaces (Otero et al., 2013) and two magneto-electro-elastic half-spaces (Otero et al., 2014), respectively. Kuo (2013) studied a piezoelectric and piezomagnetic circular fibrous composite with imperfect interfaces under longitudinal shear with in-plane electromagnetic fields, and discussed the effects of interfacial imperfections on the effective property. Wang et al. (2014) predicted the effective elastic, dielectric, and piezoelectric properties of piezoelectric composites with ellipsoidal particles embedded imperfectly in the matrix by combining the dilute approximation method, the Mori–Tanaka method and the self-consistent method. Shi et al. (2014) considered the coupling between interfacial electric and mechanical imperfections, and determined the variation bounds for the effective electro-elastic moduli of piezoelectric particulate composites with imperfect interfaces. McArthur and Sudak (2015) rigorously analyzed an arbitrarily shaped piezoelectric inclusion in an infinite piezoelectric matrix under anti-plane shear deformation, and demonstrated the effects of the inclusion shape and imperfect interface condition on the stress distribution. Li et al. (2015a,b,c) proposed a new interfacial imperfection coupling model, and applied it to fracture analyses on layered multiferroic plates and cylinders consisting of alternate piezoelectric and piezomagnetic layers.

For layered composites, interfacial sliding is a failure mode frequently encountered in engineering. According to the linear spring model, the required driving shear traction of a sliding interface is linearly related to the sliding dislocation (Icardi, 1999). This relation is applicable to the cases that there is no normal stress across the interface. However, interfacial normal stress may be non-vanishing in many cases. The effect of interfacial normal stress on the required driving shear traction of a sliding interface is still an unsolved problem in this field. In this paper, an interfacial sliding-prevention/promotion model is proposed to consider the influence of interfacial normal stress on interfacial sliding. Then, for the purpose of demonstration, the intra-layer crack problem of a multiferroic composite is analyzed. The local non-vanishing normal stress across the interface induced by the intra-layer cracks are revealed, and the resulted phenomena of local sliding-prevention and sliding-promotion are in return used to explain the mechanism of intra-layer fracture.

2. Problem formulation

2.1. Geometrical model

Shown in Fig. 1 is the fracture model of a multiferroic composite consisting of an upper ferromagnetic layer, a lower ferroelectric one and an intermediate sliding interface. The thickness of the interface is zero, and those of the two layers are h_1 and h_2. The composite contains two cracks, each locating in a layer and parallel to the interface. The half-lengths of the two cracks are a_{01} and a_{02}, and their distances from the interface are d_1 and d_2. Hereafter, the quantities of the ferromagnetic layer are marked by subscript/superscript 1, and those of the ferroelectric one are labeled by subscript/superscript 2. For the convenience of description, a Cartesian coordinate system is set up in such a way that the rightward x-axis is along the interface, the upward z-axis follows the direction of thickness, and the y -axis is determined by the right-hand rule.

2.2. Basic equations

Assume that the composite is polarized along the z-axis. Then, the magnetic/electric field in the xoz plane is coupled with the deformation field therein, and the corresponding constitutive relations of the ferromagnetic and ferroelectric layers take the form

$$\left.\begin{aligned}
\sigma_x^{(i)} &= c_{11}^{(i)}u_{,x}^{(i)} + c_{13}^{(i)}w_{,z}^{(i)} + \delta_{1i}h_{31}\varphi_{,z}^{(i)} + \delta_{2i}e_{31}\phi_{,z}^{(i)}\\
\sigma_z^{(i)} &= c_{13}^{(i)}u_{,x}^{(i)} + c_{33}^{(i)}w_{,z}^{(i)} + \delta_{1i}h_{33}\varphi_{,z}^{(i)} + \delta_{2i}e_{33}\phi_{,z}^{(i)}\\
\tau_{zx}^{(i)} &= c_{44}^{(i)}(u_{,z}^{(i)} + w_{,x}^{(i)}) + \delta_{1i}h_{15}\varphi_{,x}^{(i)} + \delta_{2i}e_{15}\phi_{,x}^{(i)}\\
B_x^{(i)} &= \delta_{1i}h_{15}(u_{,z}^{(i)} + w_{,x}^{(i)}) - \mu_{11}^{(i)}\varphi_{,x}^{(i)}\\
B_z^{(i)} &= \delta_{1i}(h_{31}u_{,x}^{(i)} + h_{33}w_{,z}^{(i)}) - \mu_{33}^{(i)}\varphi_{,z}^{(i)}\\
D_x^{(i)} &= \delta_{2i}e_{15}(u_{,z}^{(i)} + w_{,x}^{(i)}) - \in_{11}^{(i)}\phi_{,x}^{(i)}\\
D_z^{(i)} &= \delta_{2i}(e_{31}u_{,x}^{(i)} + e_{33}w_{,z}^{(i)}) - \in_{33}^{(i)}\phi_{,z}^{(i)}
\end{aligned}\right\}, \quad (i = 1, 2) \tag{1}$$

where σ, τ, B and D are the normal stress, shear stress, magnetic induction and electric displacement; u and w the corresponding mechanical displacements in the directions of x and z axes; φ and

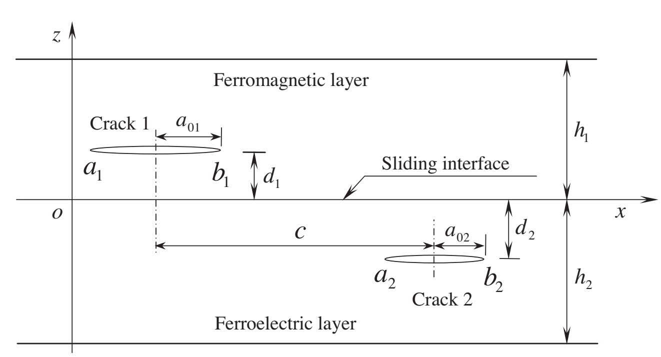

Fig. 1. Fracture model of a multiferroic composite containing a sliding interface.