Mechanics of Materials 123 (2018) 77–87

Contents lists available at ScienceDirect

Mechanics of Materials

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

Research paper

The electromechanical behavior of a piezoelectric actuator bonded to a graded substrate including an adhesive layer

Peijian Chen[a,d], Juan Peng[b,*], Hao Liu[c], Feng Gao[a], Wang Guo[a]

[a] State Key Laboratory for Geomechanics and Deep Underground Engineering, School of Mechanics and Civil Engineering, China University of Mining and Technology, Xuzhou, Jiangsu 221116, China
[b] School of Physics, China University of Mining and Technology, Xuzhou, Jiangsu 221116, China
[c] School of Mechanical and Electrical Engineering, China University of Mining and Technology, Xuzhou, Jiangsu, China
[d] John A. Paulson School of Engineering and Applied Sciences, Harvard University, Cambridge, MA 02138, USA

ARTICLE INFO

Keywords:
Piezoelectric actuator
Graded half plane
Bonded problem
Interfacial shear stress
Debonding

ABSTRACT

A theoretical model of a thin piezoelectric actuator attached to a graded half plane with an adhesive layer under an electrical loading is analyzed in the present paper. The shear modulus of the graded half plane is assumed to vary exponentially along its depth. The governing integro-differential equation for both the perfectly bonded condition and possible imperfect one is studied and solved numerically. The interfacial shear stress and the axial stress in the actuator affected by the inhomogeneity of the graded substrate, the adhesive layer, the debonding condition, etc are comprehensively studied. It is found that the electromechanical behavior of the piezoelectric actuator/substrate system can be modified by tuning the material and geometric parameters of both the actuator and the graded substrate. The results should be helpful for the design of smart systems and structures with thin piezoelectric actuator and functionally graded materials.

1. Introduction

Piezoelectric materials, due to strong mechanical and electrical coupling characteristics, are widely serving as actuators and sensors in plenty of engineering areas, for example, in aerospace, civil engineering, ship industry, biotechnology, etc (Dagdeviren et al., 2015; Fang et al., 2013; Huang et al., 2010; Liu et al., 2015; Wang et al., 2008). Among these applications, the integrated smart systems and structures, which can self-monitor and self-control different static deformation and vibration, are commonly composed of piezoelectric actuators, the host body and the adhesive layer between them. In the study of smart systems, two fundamential issues need to be well evaluated, namely the electromechanical behavior of the smart system and the bonding condition at the actuator-host interfaces. Since the actuation is achieved by the load transferred between the interface, great attentions of the research community have been paid to the prediction of interfacial stresses, which is closely related to the eletromechanical behavior and the bonding condition.

Various works have been done to uncover the electromechacial behavior of the piezoelectric actuator bonded systems. Crawley and De Luis (1987) first analyzed the load transfer between an actuator and host structure with the Bernoulli-Euler beam theory, from which it was found that the load transfer is mainly achieved by the shear stress near the two ends of the piezoelectric actuator. Modified models also included Im and Atluri (1989), Crawley and Anderson (1990), Peng et al. (2012), etc. Besides, a series of effective models have been proposed based on classical plate theory under different loading conditions, for example, Han and Lee (1998), Reddy (1999), Tauchert (1992), Wang and Rogers (1991) and so on. Considering the disadvantage of predicting the interfacial field near the ends of the actuators by modeling the integrated smart structure as beams or plates, Wang and Meguid (2000) proposed a model of a thin piezoelectric actuator attached to an infinite host structure. Taking the fully coupled electromechanical behavior into consideration, Zhang et al. (2003) investigated the two-dimensional electromechanical field of a piezoelectric layer bonded to an elastic substrate. The interfacial analysis of a thin film of finite thickness bonded to an homogeneous substrate under different geometric and loading conditions was discussed by Lanzoni (2011), Peng and Chen (2012), Yao and Chen (2013), Franco and Royer-Carfagni (2014), Chen et al. (2014), Chen and Chen (2015), Peng et al. (2017), Yao et al. (2017), etc.

Another important concern of piezoelectric actuators bonded to host structures lies in the bonding condition at the actuator-host interface, particularly the adhesive layer and interfacial debonding. Qing et al. (2006) investigated experimently the effect of adhesive thickness on the performance of a piezoelectric actuator bonded

* Corresponding author.
E-mail addresses: chenpeijian@cumt.edu.cn (P. Chen), pengjuan@cumt.edu.cn (J. Peng).

https://doi.org/10.1016/j.mechmat.2018.05.002
Received 17 January 2018; Received in revised form 17 April 2018; Accepted 8 May 2018
Available online 09 May 2018
0167-6636/ © 2018 Elsevier Ltd. All rights reserved.

structure. It revealed that an increase of adhesive thickness alters the electromechanical impedance and the resonant frequency as well as the amplitude of the sensor signal. Lin et al. (2010) explored the durability and survivability issues associated with various environmental conditions on smart structures with adhesive layers. The significant effect of adhesive layers on the integrated smart systems and structures has also studied by Rabinovitch (2007a, b), Jin and Wang (2011), Yu and Wang (2017) . In addition to the adhesive layer, the effect of interfacial debonding at the actuator-host interface has been focused. Existing studies have shown that the existence of interfacial debonding can significantly affect the mechanical response of laminated beams (Kim and Jones, 1996; Tylikowski, 2001). The work of Sun et al. (2001) found that the efficiency of control can be siginificantly reduced by interfacial debonding. Recently, a model with a partially debonded piezoelectric actuator in smart laminates is proposed by Huang et al. (2015) using layer-wise displacement fields.

All the models mentioned above involve homogeneous materials. As a typical inhomogeneous material, functionally graded material (FGM) has been widely used in plenty of various fields, such as aerospace, biomedical industry, mechanical engineering as well as other high technology, due to its outstanding performance than its homogeneous counterpart. So far, various works such as Giannakopoulos and Pallot (2000), Chen et al. (2009a, b), Ke et al. (2010), Choi and Paulino (2010), Liu et al. (2011), Chidlow et al. (2013), Alinia et al. (2014), Liu et al. (2017), etc have been done to uncover the surface contact behaviors of graded material. Guler (2008) and Guler et al. (2012) explored the non-slipping contact problem of a thin film and a graded/FGM coated half plane. Recently, Chen et al. (2016a, b; 2017) investigated the problem of an elastic film bonded to a finite-thickness graded substrate under different mechanical loading conditions. It was found that the interfacial behavior is significantly influenced by the choice of loading condition. How about the interfacial behavior of a thin piezoelectric actuator bonded to a graded substrate through an adhesive layer? Whether a generalized model can be established to take the effect of the adhesive layer and interfacial debonding into consideration? How can we tune different material and geometric parameters to improve the electromechanical property?

In order to answer the above questions, a theoretical bonded model is established in this paper, in which a piezoelectric actuator attaches to a graded substrate with an adhesive layer under the electrical loading. The governing integro-differential equation for the perfect bonded problem is first formulated analytically in terms of interfacial shear stress, and solved numerically. Then, the model with an interfacial debonding is further studied comprehensively. The interfacial shear stress as well as the axial stress in the actuator are mainly focused in order to evaluate the interfacical behavior that is closely related to destruction and failure of the actuator-host systems.

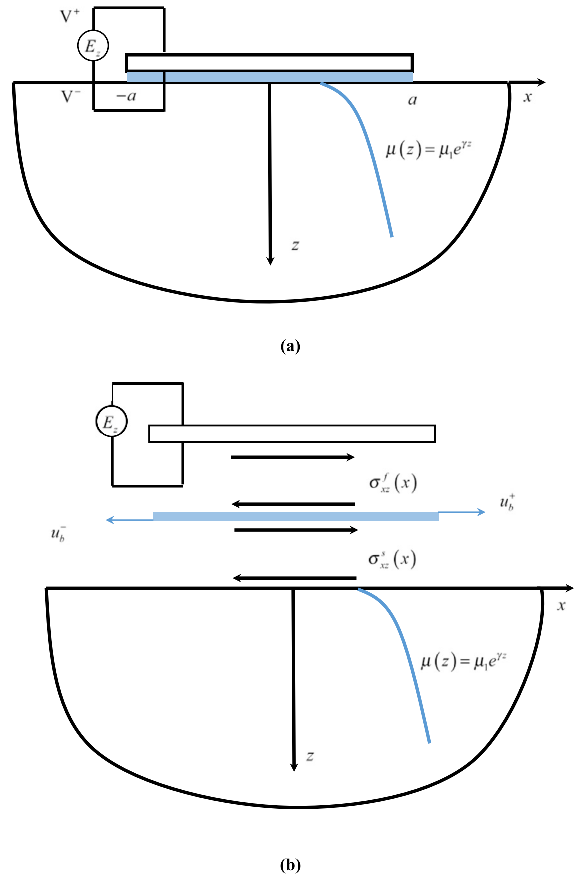

Fig. 1. (a) The two dimensional model of a thin piezoelectric actuator perfectly bonded to an elastically graded substrate through a thin bonding layer; (b) Schematic of the mechanical behavior between bonded interfaces.

2. Formulation of the perfectly bonded problem

As illustrated in Fig. 1, a thin piezoelectric actuator perfectly bonded to an elastically graded substrate through a thin bonding layer in plane strain state. Both the length of the piezoelectric actuator and that of the bonding layer are $l_f = 2a$, and the thicknesses of the piezoelectric actuator and the bonding layer are denoted as h_f and h_b, respectively. The graded substrate is modeled as a half plane to represent the case that it is much thicker than the actuator. The poling direction of the actuator is assumed to be along the z-axis. By exerting a voltage between the upper and the lower electrodes of the actuator, an electrical loading $E_z = V/h_f = (V^- - V^+)/h_f$ is generated along the poling direction of the actuator.

2.1. The piezoelectric actuator

In the present paper, the membrane assumption is employed in which the piezoelectric actuator behaves like a membrane that cannot support peel stresses, and bending in the film is assumed to be negligible. The assumption was shown to hold over distances that are large compared to the actuator thickness (Shield and Kim, 1992). Shield and Kim (1992) have shown that the results based on the membrane assumption may be viewed as a first term in an expansion of the exact solution. In order to get closer results, one should take into consideration the bending effects and the effect of peel stresses especially near the ends of the piezoelectric actuator. Clearly, the beam theory is only one more term in the expansion and the results from the membrane model can still be applicable over distances on the order of piezoelectric actuator thickness from the actuator's end (Shield and Kim, 1992).

As pointed out by Guler (2008), since the thickness of films used in the microelectronic industry is of the order of submicrons and the substrate is of much larger order, it is realistic to assume the film to act as a membrane and the substrate as a semi-infinite medium. What's more, considering the bending effects, the coupling of the shear and peel stresses between the piezoelectric actuator and the graded substrate, will make the problem too complicated to solve. The differences between membrane and beam assumptions in the bonded problem will be discussed in a future study with a more suitable technique.

In the present model, the thickness of the piezoelectric actuator h_f is assumed to be sufficiently small. The axial stress σ^f_{xx} and the horizontal displacement u^f_x in the actuator are assumed to be uniform across its thickness, and σ^f_{zz} and σ^f_{xz} are ignored. The bonding layer is the medium between the actuator and the graded substrate. As shown in Fig. 1(b), the interfacial shear stress between the piezoelectric actuator and the bonding layer is denoted as σ^f_{xz}, and that between the bonding layer and the graded half plane is σ^s_{xz}. The displacement components at the upper and lower surface of the bonding layer are termed as u_b^+ and u_b^-,

Download English Version:

https://daneshyari.com/en/article/7178500

Download Persian Version:

https://daneshyari.com/article/7178500

Daneshyari.com