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International Journal of Solids and Structures 44 (2007) 8457–8492

INTERNATIONAL JOURNAL OF SOLIDS AND STRUCTURES

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Numerical analysis for a crack in piezoelectric material under impact

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Received 18 July 2006; received in revised form 16 June 2007
Available online 28 July 2007

Abstract

In this paper, a numerical analysis of impact interfacial fracture for a piezoelectric bimaterial is provided. Starting from the basic equilibrium equation, a dynamic electro-mechanical FEM formulation is briefly presented. Then, the path-independent separated dynamic J integral is extended to piezoelectric bimaterials. Based on the relationship of the path-independent dynamic J integral and the stress and electric displacement intensity factors, the component separation method is used to calculate the stress and electric displacement intensity factors for piezoelectric bimaterials in this finite-element analysis. The response curves of the dynamic J integral, the stress and electric displacement intensity factors are obtained for both homogeneous material (PZT-4 and CdSe) and CdSe/PZT-4 bimaterial. The influences of the piezoelectricity and the electro-mechanical coupling factor on these responses are discussed. The effects of an applied electric field are also discussed.
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Keywords: Piezoelectric; Interfacial crack; Dynamic J integral; Finite element analysis

1. Introduction

Piezoelectric materials are of great importance in aerospace, automotive, medical and electronic technologies. Interfacial fracture for piezoelectric materials has received much attention in the last few years (McMeeking, 1999), since interfacial crack is one of the most commonly observed failure modes in piezoelectric laminates, which are used in many modern structures. Various theoretical results have been obtained to understand the interfacial fracture behavior of piezoelectric materials. Most of the analyses are quasi-static (Kuo and Barnett, 1991; Suo et al., 1992; Shen and Kuang, 1998). Applications of piezoelectric materials in the areas of electromechanical devices and electronic packaging illustrate the fact that the transient response of interfa-

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doi:10.1016/j.ijsolstr.2007.06.032

cial crack to impact loading is an important phenomenon and, hence, cannot be neglected (Khutoryansky and Sosa, 1995). Some studies have been carried out for dynamic fracture in homogeneous piezoelectric materials. Shindo and Ozawa (1990) and Parton and Kudriavtsev (1988) analyzed the interaction of piezoelectric harmonic waves with cracks. Dascalu and Maugin (1995) investigated steady-state crack propagation in piezoelectric materials. Li and Mataga (1996a,b) studied the semi-infinite propagating crack in a piezoelectric material with electrode boundary condition and vacuum condition on the crack surface. Shen et al. (1999) analyzed the interfacial crack in piezoelectric bimaterial system under impact loading on the crack surfaces by means of the integral transforms. Nishioka and Shen (2001) obtained the asymptotic transient structure of the near-tip field in a piezoelectric bimaterial containing an interfacial crack under electric/mechanical impact loading, *etc*.

In these researches the dynamic piezoelectric fracture problem is considered in the quasi-electrostatic approximation. That is, the inertial effects are taken into account while keeping the static approximation for the electric fields. This approximation is relevant for the description of the acoustic effects in piezoelectric materials, for which the electromagnetic coupling is not important (Li and Mataga, 1996a). In this paper, we also adopt this assumption.

For dynamic fracture mechanics, Nishioka and Atluri (1983) derived the path-independent dynamic J integral, which has the physical significance of energy release rate. Furthermore, for dynamic interfacial fracture mechanics, Nishioka and Yasin (1999) developed the separated dynamic J integrals, which are equivalent with the separated energy release rates from individual material sides. The separated dynamic J integrals should be very useful to identify the fracture mechanics effects of individual material in an inhomogeneous materials system.

In early works on extracting mixed-mode stress intensity factors for interfacial cracks, Yau and Wang's M integral method (1984) is commonly used. However, it is sometimes difficult to set up the auxiliary solution field that is necessary in this method. The component separation method was extended to static and dynamic interfacial crack problems in both general and piezoelectric materials by Nishioka and his colleagues (Nishioka et al., 2003; Shen and Nishioka, 2003). This method has great advantages over the M integral method, since no auxiliary solution field is needed.

Due to the practical and academic importance of impact interfacial fracture mechanics, this paper deals with loads that are applied suddenly to bimaterials containing interfacial crack. To attempt some progress on this task, a numerical analysis of impact interfacial fracture for a piezoelectric bimaterial is provided. Starting from the basic equilibrium equation, a dynamic electro-mechanical FEM formulation is briefly presented. Then, the path-independent separated dynamic J integral is extended to piezoelectric bimaterials. Based on these asymptotic fields (Nishioka and Shen, 2001) the relationship between the path-independent dynamic J integral and the stress and electric displacement intensity factors are obtained. By appealing to this relationship, the component separation method is used to calculate the stress and electric displacement intensity factors for piezoelectric bimaterials in the finite-element analysis. The response curves of the dynamic J integral and the stress and electric displacement intensity factors are obtained for homogeneous and bimaterial. Two piezoelectric materials, PZT-4 and CdSe are considered in this numerical analysis. These two materials represent two typical piezoelectric materials: PZT-4 for the materials with the stronger electromechanical coupling effect and CdSe those with the lower one, respectively. The electromechanical coupling factor has strong effect on the impact response of piezoelectric materials. The influences of the piezoelectricity and the electromechanical coupling factor on these responses are discussed. The effects of an applied electric field are also discussed.

2. Formulation of electro-mechanical coupled finite element method

Based on the virtual work principle, for the real solution of the electro-mechanical system in the domain V with the boundary ∂V, the following variational equation exists

$$\int_V [(\sigma_{ij,i} + f_j - \rho\ddot{u}_j)\delta u_j + (D_{i,i} - p^e)\delta\phi]\,\mathrm{d}V - \int_{S^\sigma}(\sigma_{ij}n_i - T_j)\delta u_j\,\mathrm{d}s - \int_{S^D}(D_i n_i - p^0)\delta\phi\,\mathrm{d}s = 0 \tag{1}$$

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