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Analysis of stress intensity factors for edge interfacial cracks in bonded dissimilar media with a functionally graded interlayer under antiplane deformation

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ABSTRACT

In this paper, the problem of bonded dissimilar, homogeneous media with a functionally graded interlayer weakened by two parallel, edge interfacial cracks is investigated under the state of antiplane deformation. The Fourier integral transform method is employed to reduce the crack problem to a system of singular integral equations with generalized Cauchy kernels, which is solved based on the expansion–collocation technique. In the numerical results, parametric studies are conducted such that the mode III stress intensity factors are evaluated, addressing the interaction between the two neighboring edge cracks strongly affected by geometric and material parameters of the bonded system.

1. Introduction

One of the major concerns in the use of conventional bonded materials is the existence of interfaces between piecewise dissimilar phases across which the apparent property mismatch prevails. As a result, the interfaces are regarded as areas that should endure high stress concentrations, relatively poor bonding strength and ensuing increased probability of failure. The analysis of such composite bodies further weakened by interfacial flaws has thus been a topic of vital interest and significance to the fracture mechanics community, accompanied by a great deal of research being carried out to date to better understand how the interfacial imperfections degrade the material and structural integrity [1].

With the evolution of functionally graded materials in recent years that feature smoothly varying thermophysical properties, the utilization of this new generation of nonhomogeneous media in the form of a transitional interlayer to join dissimilar materials was proved to be one of the highly effective applications of such engineered material systems [2]. Nevertheless, the improvement gained via the insert of graded interphase in-between can be frustrated by cracking initiating in the vicinity of the interfacial zone under harsh loading environments, as can be exemplified in a series of some relevant crack problems resolved by Erdogan and his colleagues [3–9]. In these studies, a crack was assumed to be aligned parallel to, perpendicular to or along the kink line of distributions of elastic moduli in bonded materials, with the effects of material gradations being manifested through the values of corresponding stress intensity factors.

Further contributions have subsequently been reported, clarifying additional issues and needs pertaining to the fracture behavior of bonded media in the presence of a graded interlayer. Among others, Jin and Batra [10] investigated the effect of coating architectures on the interfacial cracking in a graded coating/substrate system subjected to antiplane shear. Shbeeb and Binienda [11] considered the plane problem of an interface crack for a graded strip between homogeneous layers of finite thickness. Zhou et al. [12] obtained the solution to the thermoelastic problem of a partially insulated interface crack between a graded coating and a homogeneous substrate, while Ding and Li [13] solved the antiplane problem of periodic interface cracks in a graded coating. Besides, Choi and Paulino [14] considered a coupled crack/contact problem of a graded coating/substrate system, where the interaction between the frictional flat punch and the interfacial crack was elaborated and Clements [15] tackled the antiplane crack along the interface of two dissimilar functionally graded half-spaces. The interactions of two offset interfacial cracks embedded in the bonded system with a graded interlayer were also studied by Choi [16–19], under the conditions of antiplane static and impact loading and those of mixed-mode mechanical and thermal loading, respectively. Most recently, Choi [20] examined the antiplane problem of an embedded or edge interfacial crack in bonded dissimilar semi-infinite strips with a graded interlayer, subjected to either traction-free or clamped boundary conditions.

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For the cases of a crack at an arbitrary angle to the graded interfacial zone in bonded materials, the variations of stress intensity factors were evaluated by Choi [21–24], involving various modes of deformation, whereas the antiplane shear behavior of an inclined crack in a functionally graded strip bonded to two dissimilar half-planes was studied by Torshizian and Kargarnovin [25]. Meanwhile, the mixed-mode response of an arbitrarily oriented crack crossing the interface in a functionally graded layered structure was discussed by Guo et al. [26] and that of an inclined crack in a graded plane due to the impact loading was dealt with by Ding and Li [27]. To be further mentioned is the multilayered approach based on the piecewise-exponential model, by which the intractable crack problems of functionally graded materials with arbitrary properties can be made amenable to analytical treatment, in conjunction with the use of integral transform techniques [28–30]. Various computational models (e.g., finite and boundary element methods) also appeared in the literature for the numerical simulations of some crack problems in the graded materials and structures under different loading and geometric configurations: the graded finite elements [31]; the generalized interaction integral method [32]; the equivalent domain integral method [33]; the meshless method [34]; the extended finite element method [35,36]; and the extended isogeometric analysis [37], etc.

As described in the foregoing, in resolving a variety of interfacial crack problems that entail graded properties, most of related preceding analytical efforts appear to have been limited to such cases as containing a single interfacial or oblique crack and the interfacial cracks that are embedded deep inside the bonded media. In consideration of the fact that the interfacial region may intersect a free surface and the possible surface damage is likely to trigger the multiple interfacial failures starting from the free edge of the bonded system, the objective of this paper is to provide the solution to the problem of two parallel, edge interfacial cracks in bonded dissimilar media with a functionally graded interlayer. The homogeneous constituents take three different geometric configurations: two semi-infinite strips; a semi-infinite strip and a quarter-plane; two quarter-planes. The state of antiplane deformation is assumed, not only because it has its own practical applications when the third fracture mode is separable, but also because it often forms the informative basis for understanding more involved inplane or three dimensional counterpart. Based on the use of Fourier integral transform, the formulation of the crack problem is reduced to a system of integral equations with generalized Cauchy singular kernels to be solved employing the properties of Chebyshev polynomials. The variations of mode III stress intensity factors are presented, elaborating the effects of geometric and material parameters of the bonded system on the interaction of singular stress fields between the two edge cracks spaced apart by the graded interlayer.

2. Problem statement and formulation

The crack problem to be considered is depicted in Fig. 1, where two dissimilar, homogeneous strips of semi-infinite length are bonded through a functionally graded interlayer and two edge cracks of length a and b are located along the upper and lower interfaces, respectively. The constituents of the bonded system are distinguished in order from the top, with the thicknesses and shear moduli denoted by h_j and μ_j, $j = 1, 2, 3$, respectively.

For the graded, nonhomogeneous interlayer, based largely on analytical tractability, its shear modulus is assumed to obey the particular variation expressed in terms of an exponential function [8]

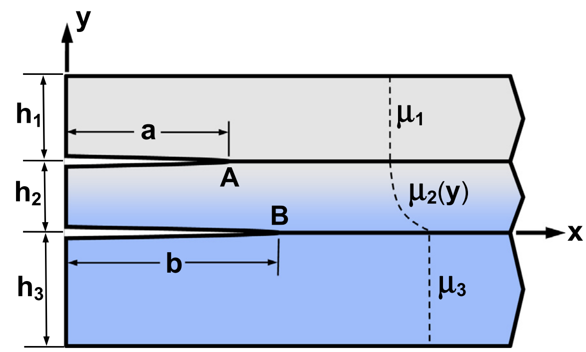

Fig. 1. Schematic of the crack problem for bonded dissimilar media with a functionally graded interlayer.

$$\mu_2(y) = \mu_3 e^{\beta y}, \quad \beta = \frac{1}{h_2} \ln\left(\frac{\mu_1}{\mu_3}\right); \quad 0 < y < h_2 \tag{1}$$

which ensures the continuous transition of the elastic moduli across the nominal interfaces.

Under the antiplane deformation, there exists only a z-component of the displacement vector as $w_j(x, y)$, $j = 1, 2, 3$, with the stress components and governing equations given by

$$\tau_{jxz} = \mu_j \frac{\partial w_j}{\partial x}, \quad \tau_{jyz} = \mu_j \frac{\partial w_j}{\partial y}; \quad j = 1, 2, 3 \tag{2}$$

$$\nabla^2 w_j + \beta \frac{\partial w_j}{\partial y} = 0; \quad j = 1, 2, 3 \tag{3}$$

where $\beta = 0$ for the homogeneous constituents ($j = 1, 3$) and $\beta \neq 0$ for the graded interlayer ($j = 2$).

Let the bonded media be loaded by tractions applied on the crack surfaces and the left-hand side flank edges at $x = 0$ be traction-free. As a result, a set of boundary and interface conditions is prescribed as

$$\tau_{1xz}(0, y) = 0; \quad h_2 < y < h_1 + h_2 \tag{4}$$

$$\tau_{2xz}(0, y) = 0; \quad 0 < y < h_2 \tag{5}$$

$$\tau_{3xz}(0, y) = 0; \quad -h_3 < y < 0 \tag{6}$$

$$\tau_{1yz}(x, h_1 + h_2) = 0, \quad \tau_{3yz}(x, -h_3) = 0; \quad x > 0 \tag{7}$$

$$\tau_{1yz}(x, h_2) = \tau_{2yz}(x, h_2), \quad \tau_{2yz}(x, 0) = \tau_{3yz}(x, 0); \quad x > 0 \tag{8}$$

$$w_1(x, h_2) = w_2(x, h_2); \quad x > a \tag{9}$$

$$w_2(x, 0) = w_3(x, 0); \quad x > b \tag{10}$$

$$\tau_{1yz}(x, h_2) = f_1(x); \quad 0 < x < a \tag{11}$$

$$\tau_{3yz}(x, 0) = f_2(x); \quad 0 < x < b \tag{12}$$

where the functions, $f_k(x)$, $k = 1, 2$, refer to the crack surface tractions.

The Fourier integral transform is employed to yield the general solutions for the displacements that satisfy the traction-free conditions at the flank edges in Eqs. (4)–(6) as

$$w_j(x, y) = \frac{2}{\pi} \int_0^\infty (A_{j1} e^{sy} + A_{j2} e^{-sy}) \cos sx ds; \quad j = 1, 3 \tag{13}$$

$$w_2(x, y) = \frac{2}{\pi} \int_0^\infty \sum_{k=1}^{2} A_{2k} e^{\lambda_k y} \cos sx ds \tag{14}$$