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Effective spring stiffness for a planar periodic array of collinear cracks at an interface between two dissimilar isotropic materials

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ABSTRACT

Explicit analytical expressions are obtained for the longitudinal and transverse effective spring stiffnesses of a planar periodic array of collinear cracks at the interface between two dissimilar isotropic materials; they are shown to be identical in a general case of elastic dissimilarity (the well-known open interface crack model is employed for the solution). Since the interfacial spring stiffness can be experimentally determined from ultrasound reflection and transmission analysis, the proposed expressions can be useful in estimating the percentage of disbond area between two dissimilar materials, which is directly related to the residual strength of the interface. The effects of elastic dissimilarity, crack density and crack interaction on the effective spring stiffness are clearly represented in the solution. It is shown that in general the crack interaction weakly depends on material dissimilarity and, for most practical cases, the crack interaction is nearly the same as that for crack arrays between identical solids. This allows approximate factorization of the effective spring stiffness for an array of cracks between dissimilar materials in terms of an elastic dissimilarity factor and two factors obtained for cracks in a homogeneous material: the effective spring stiffness for non-interacting (independent) cracks and the crack interaction factor. In order to avoid the effect of the crack surface interpenetration zones on the effective spring stiffness, the range of the tensile to transverse load ratios is obtained under the assumption of small-scale contact conditions. Since real cracks are often slightly open (due to prior loading history and plastic deformation), it is demonstrated that for ultrasound applications the results obtained are valid for most practical cases of small interfacial cracks as long as the mid-crack opening normalized by the crack length is at least in the order of 10^{-5}.

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1. Introduction

Layered materials are extensively used in various products and devices to improve structural performance such as strength and durability. Thermal barrier coatings, for example, are used in turbine blades to protect the core material from thermal fatigue (Miller, 1987). In the field of dentistry, resin-retained ceramic restorations are performed to protect remaining teeth and restore mechanical function without loss of aesthetics (Wang et al., 2007). Wide applications of adhesive bonds in aerospace industry for both aluminum and composite structures are well documented. Failures of these layered structures are often attributed to interfacial damage in the form of micro-cracks or debonded zones, which are either preexisting or developed during service due to mechanical/thermal fatigue and environmental degradations.

Ultrasonic methods have been widely used to detect and characterize interfacial imperfections such as distributed

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micro-cracks or micro-disbonds (Thompson and Thompson, 1991; Rokhlin et al., 2004). For modeling of ultrasonic wave interactions at imperfect interfaces, a quasi-static approximation (Baik and Thompson, 1984; Margetan et al., 1988) has been widely used. In this model the reduction in static stiffness of the overall structure due to compromised interfaces (micro-cracks or micro-disbonds) is represented by continuous, uniform distributions of interfacial springs. It has been demonstrated by Angel and Achenbach (1985) that the quasi-static approximation is applicable at low frequencies, when the size of the imperfections is much smaller than the wavelength.

Significant experimental and theoretical advances have been made towards inversion of the interfacial stiffness distributions from ultrasonic measurements (Wang and Rokhlin, 1991; Rokhlin et al., 2004; Baltazar et al., 2003; Wang et al., 2006; Leiderman et al., 2007) and relating the spring stiffness constants to the micromechanical and geometric properties of the micro-cracks (Baik and Thompson, 1984; Lavrentyev and Rokhlin, 1994; Pecorari and Kelly, 2000). Explicit expressions of effective spring stiffness in terms of the crack geometry and density are important since they can be used to estimate the percentage of disbond area (Palmer et al., 1988), which is critical in assessing the bond integrity and the remaining life.

Using an available fracture mechanical model, Baik and Thompson (1984) have obtained the expression for effective normal spring stiffness for a planar array of periodically spaced strip cracks in a homogeneous material. For this geometry, Angel and Achenbach (1985) have obtained an exact solution of the elastodynamic reflection/refraction boundary-value problem and have numerically compared the exact solution with the quasi-static (spring) approximation. They have demonstrated for this problem that for $a/b < 0.8$ (a/b: crack density, see Fig. 1(a)) the approximation is suitable at $2b/\lambda_T < 0.25$ (λ_T is a transverse wavelength). The applicability range of the $2b/\lambda_T$ ratio decreases with increase of crack density a/b (increase of crack interaction). Excellent agreement between the spring approximation and experiment has been obtained by Palmer et al. (1988) who have reported measurements of the ultrasonic reflectivity on imperfectly diffusion-bonded samples.

For non-interacting cracks at the interface between two dissimilar materials, Pecorari and Kelly (2000) have obtained an explicit expression of the effective normal spring stiffness and have shown that their expression reduces to that of Baik and Thompson (1984) when elastic moduli difference and crack area fraction approach zero. While crack interactions have been investigated in regard to overall effective material properties (Nemat-Nasser et al., 1993), the analysis of effective spring stiffness for interacting cracks between dissimilar materials is not available.

In this work, for a planar periodic array of collinear cracks between two dissimilar isotropic materials (Fig. 1(a)), explicit expressions for effective transverse and normal spring stiffnesses have been obtained; they are shown to be identical in a general case of elastic dissimilarity. We have examined the effect of an elastic dissimilarity and crack interaction on the effective

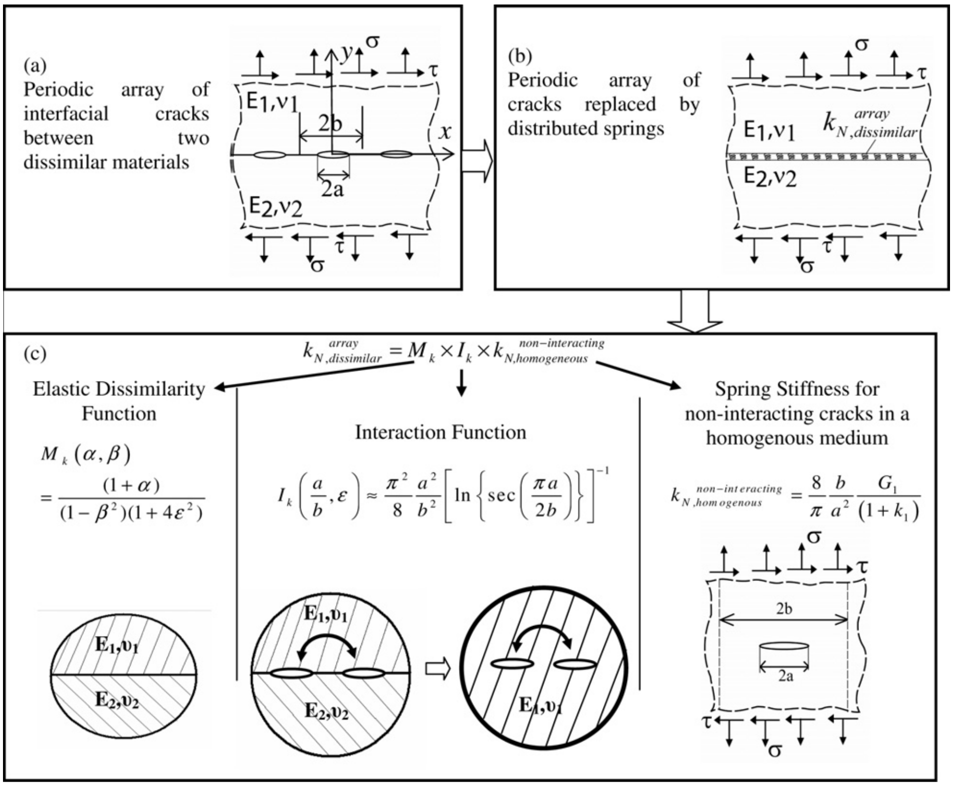

Fig. 1. Effective spring stiffness for a planar periodic array of collinear cracks between two dissimilar isotropic materials.

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