DEBOND FRACTURE AND KINKING IN MULTILAYER SYSTEMS: THEORETICAL SOLUTIONS AND PRACTICAL APPLICATIONS

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Abstract

Debond fracture is a dominant failure mechanism in multilayer systems used for various current applications, from laminated and sandwich structural components to protective coatings and thermal barrier coatings; from microelectronic devices, in the electronics and flexible electronics fields, to biomedical devices. Debond cracks originate and propagate at the interfaces between the layers, which often have disparate mechanical and thermal properties; they may kink out of the interfaces and lead to unexpected collapses, such as those observed in marine sandwich composites where these mechanisms may yield to the detachment of entire portions of the core from the outer facesheets. The presentation reviews elasticity techniques and closed form solutions recently derived by the authors for the fracture parameters of interface cracks in edge cracked orthotropic layers, bimaterial layers and sandwich beams and for the crack tip compliance coefficients (root rotations and displacements) in bimaterial isotropic and orthotropic layers. Practical applications of the solutions will be discussed: operative formulae for the characterization of the interfacial toughness in classical and novel fracture mechanics specimens; calibration of the parameters of one-dimensional model; and analytical criteria for kinking in multilayer systems.

1. Introduction

Fundamental two-dimensional elasticity solutions for debond cracks in multilayered systems subjected to end loadings acting far from the crack tip have been derived some years ago [1-4]. The energy release rate and mode mixity phase angle are defined in terms of two (for problems in the absence of shear) or four elementaty loading modes, which are related to the applied end loadings through simple formulas. The solutions require the numerical derivation of a few coefficients, which are uniquely defined for each specific combination of elastic constants and thicknesses of the layers, and presented in tabular form. The solutions are limited to specific ranges of the elastic constants and cannot be extrapolated to different material systems. An elasticity technique has been recently formulated which uses Laplace transforms of stresses and relative displacements to define an homogeneous matrix Riemann-Hilbert problem which can be solved in closed form for some specific cases, namely bimaterial isotropic equal thickness layers and thin films on half planes with special elastic constants (zero second Dundurs' parameter) [5,6]. The technique, applied in combination with accurate numerical solutions, allows the derivation of the fracture parameters in multilayer systems with a very large mismatch of the elastic constants, such as the systems used in current applications, for instance in flexible electronics or in foam core sandwich structures.

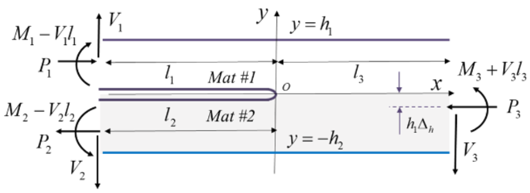
2. Results

Starting from the original formulations in [5,6], the problem of an edge-cracked homogeneous and orthotropic layer subjected to axial and shear forces and bending moments acting far away from the crack tip, has been solved for the entire admissible range of orthotropy ratios [7]. The closed form solutions for the fracture parameters are applicable to unidirectionally reinforced laminates to support laboratory tests.

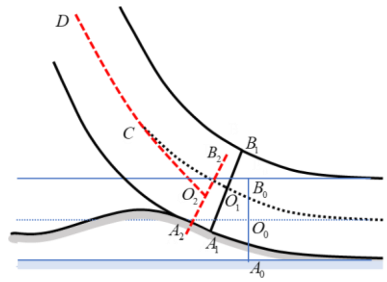
The fracture parameters for the problems of the decohesion of a thin isotropic film from an isotropic substrate, a bimaterial layer and a sandwich layer, have been solved in [8,9,10] for a large range of Dundurs' parameters using the analytical results in [6] and accurate numerical calculations.

An elasticity technique has been formulated in [11] for the derivation of the crack tip compliance coefficients, which define relative rotations and displacements of the neutral axes of the detached layers at the crack tip (root rotations and displacements) and are necessary as boundary conditions for beam/plate theories used to analyze the detaching layers. The compliance coefficients are defined as functions of the energy release rate contributions associated to the elementary loading modes and are derived in closed form for some relevant problems. They can be applied to all problems for which the energy release rate contributions are known, either analytically or numerically. The coefficients are essential for the solution of statically indeterminate problems where the calculation of the forces in the layers require the imposition of kinematic conditions.

Practical applications of the results will be presented: the operative formulas derived in [10,12] for classical and novel bimaterial fracture specimens; the technique proposed in [13] for the calibration of the parameters of approximate one-dimensional models for the analysis of the Single Cantilever Beam sandwich specimen; novel analytical kinking criteria for multilayer systems.



(a)



(b)

Fig.1 – (a) Schematics of bimaterial layer subjected to arbitrary end loadings; (b) crack tip root rotations and displacements in a thin film on a soft substrate.

3. Conclusions

Novel elasticity techniques and closed form solutions have been presented for the problem of debond fracture in multilayer systems subjected to arbitrary end loadings. The solutions have been applied to derive effective operative formulas and kinking criteria for classical and novel fracture specimens.

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