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RAPID PROPAGATION OF INTERFACE-FLAWS IN COMPOSITE BODIES.(U)
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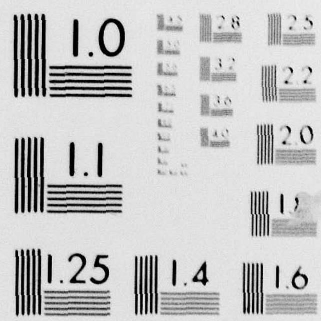
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RAPID PROPAGATION OF INTERFACE-FLAWS IN COMPOSITE BODIES

FINAL REPORT, 1975-1979

by

J. D. Achenbach

November 1979

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1. Introduction, Statement of Research Objectives, and Summary of Results

Bodies consisting of components of different materials glued, fused or otherwise continuously joined are employed in many structural applications. An example is a laminated medium consisting of alternating layers of two materials of different mechanical properties. Other examples are composite materials, plates reinforced by adhered stringers of another material, inclusions in sheets, or simply structures consisting of two sheets of different materials joined by lap-joints.

Among the problems encountered in actual use of composite bodies is the problem of debonding, i.e., separation at the interfaces of the constituents. This problem is important because debonding drastically reduces the load-bearing capacity.

The investigations that have been completed have been concerned with composite bodies containing small flaws <u>at</u> or <u>near</u> the bond interfaces, for both <u>static</u> and <u>dynamic</u> conditions.

A flaw in a stressed body gives rise to a significant increase of the stress level, particularly in the vicinity of a sharp edge of the flaw. The flaw becomes unstable and may grow into a sizable fracture surface if the external loads increase beyond certain critical magnitudes. The analysis of the stability of flaws belongs to the realm of fracture mechanics. In a conventional analysis elastodynamic (or inertia) effects are neglected and the analytical work is quasi-static in nature.

Elastodynamic effects become of importance if the propagation of a crack is so fast, as for example in essentially brittle fracture, that rapid motions are generated in the medium. Elastodynamic effects in conjunction with fracture phenomena are also important if the external loads give rise to propagating mechanical disturbances (as for impact loads and explosive charges) which strike the crack and cause fracture. Spalling is an example of a fracture phenomenon caused by the rapid application of loads.

In the work that has been completed, it has been attempted to achieve three primary goals: first to establish a relatively simple model for the analysis of bond stresses and deformations near a crack in an interface between two materials, secondly, to establish a criterion for propagation of an interface crack, and thirdly to investigate the influence of dynamic effects on rapid propagation of a crack in or near a bond-plane.

From the analytical point of view, the general character of the fields of stresses and displacements near the tip of an interface crack depends on the manner in which the conditions change from the interface bond to the crack faces. Usually it is assumed that a single point of singularity (the crack tip) forms the transition from continuous stresses and displacements ahead of the crack tip (perfect bond) to traction-free conditions on the crack faces. Unfortunately a linearly elastic analysis based on a single point of transition gives rise to oscillatory singularities in the stress field [1,2]*. Furthermore, there will be a wrinkling of the materials near the crack tip causing them to overlap in a small vicinity near the tip. See also Refs. [3,4].

In research recently completed the author and co-workers have developed a more realistic model for loss of adhesion at the tip of an interface crack, in which the bond in a small zone near the crack tip is allowed to yield under the high stresses that are to be expected near an interface flaw. Since this yielding may be assumed to take place in an infinitesimally thin zone (the interface) it can very conveniently be related to an appropriate distribution of cohesive tractions, which is then defined by the nature of the adhesive bond. The fracture criterion that was adopted assumes that the elongation of the bond fiber at the trailing edge of the cohesive zone (which corresponds to the crack opening displacement at that point) must exceed a critical value for propagation of the crack. Results are reported in a paper that is currently in press [5]. See also [6].

In addition the elastodynamic near-tip fields for a crack propagating rapidly parallel to a bond-plane, at a short distance from that plane have been investigated. A paper is in press [7].

2. Participating Scientific Personnel

Work on the subject Grants was carried out under the direction of

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*Numbers in brackets refer to the list of abstracts in Section 4

Dr. J. D. Achenbach, Professor of Civil Engineering and Applied Mathematics. Also contributing to the research efforts for periods of time have been: Dr. R. P. Khetan, Dr. L. M. Keer, Dr. Maria Comninou and Dr. S.-H. Chen.

3. Advanced Degrees

Dr. S.-H. Chen was employed (part-time) as a Research Assistant on the subject Grants. His work resulted in a Ph.D. Dissertation entitled "Static and Dynamic Fracture Analysis for Bonded Dissimilar Materials." Dr. Chen is now employed by John Deere & Co., in East Moline, Illinois. His degree was granted in August 1979.

4. Abstracts of Published Papers:

1. "Elastodynamic Near-Tip Fields for a Rapidly Propagating Interface Crack" by J. D. Achenbach, Z. P. Bažant and R. P. Khetan, Int. J. Eng. Sc. 14, p. 797-809.

Abstract: The elastodynamic stress field near a crack tip rapidly propagating along the interface between two dissimilar isotropic elastic solids is investigated. Both antiplane and inplane motions are considered. The antiplane displacements and the inplane displacement potentials are sought in the separated forms $r^q F(\theta)$, r and θ being polar coordinates centered at the moving tip. The mathematical statement of the problem reduces to a second-order linear ordinary differential equation in θ, which can be solved analytically. Formulation of the boundary and interface conditions leads to an eigenvalue problem for the singularity exponent q. For the inplane problem, root q is found to be complex. Thus, the stresses exhibit violent oscillations within a small region around the crack tip, and the solutions have physical significance only outside this region. The angular stress distributions are plotted for various crack speeds, and it is found that at high enough speeds the direction θ of maximum stress moves out of the interface. This result indicates that a running interface crack may move into one of the adjoining materials.

2. "Elastodynamic Near-Tip Fields for a Crack Propagating Along the Interface of Two Orthotropic Solids", by J. D. Achenbach, Z. P. Bažant and R. P. Khetan, Int. J. Eng. Sc. 14, 1976, p. 811-818.

Abstract: The elastodynamic stress field near a crack tip rapidly propagating along the interface between two dissimilar orthotropic elastic solids is solved numerically, for inplane motion. The cartesian displacements are sought in the separated forms, $r^p U(\theta)$ and $r^p V(\theta)$, r and θ being polar coordinates centered at the moving tip. This reduces the mathematical statement of the problem to two complex second-order linear ordinary differential equations for complex functions $U(\theta)$ and $V(\theta)$. By means of the finite difference method, a matrix eigenvalue problem of the type $\Sigma A_{ij}(p)x_j = 0$, is obtained where $A_{ij}(p)$ are polynomials of the complex variable p and x_j are complex unknowns. An iterative numerical scheme for determining Im(p) is developed and the roots of p as well as angular stress and displacement distributions are calculated and plotted for various material combinations. Comparisons with exact solutions for the case of dissimilar isotropic solids indicates good accuracy of the numerical solution. The orthotropic nature of the materials is shown to have a significant effect on stress maximums.

3. "The Interface Penny-Shaped Crack Reconsidered," by L. M. Keer, S. H.-Chen and Maria Comninou," Int. J. Eng. Sc. 16, pp. 765-772, 1978.

Abstract: The penny-shaped crack at the interface between two bonded dissimilar media is reconsidered on the basis of recent developments on the elimination of oscillatory singularities. This is accomplished by assuming an annular frictionless contact zone at the crack circumference and reducing the problem to a Fredholm integral equation. Expressions for the strain energy, crack opening force and bond stresses are obtained and numerical results given for specific material combinations.

4. "Asymptotic Fields at the Transition Zone of a Propagating Interface Crack," by Maria Comninou and J. D. Achenbach, Mech. Res. Comm. 5, pp. 285-290, 1979.

Abstract: In the present paper we investigate the influence of a small transition zone on the elastodynamic fields near a rapidly propagating crack tip. At the leading edge of the transition zone the conditions are assumed to change from perfect bond to mixed conditions, which then in

turn change to traction free conditions at the trailing edge of the transition zone. The leading and trailing edges can conceivably propagate at different velocities. An asymptotic analysis of the fields at the leading and trailing edges of the transition zone shows that the stress fields have simple square-root singularities, which are familiar from near-tip fields in a homogeneous solid. These square-root singularities can be accommodated easily in expressions for elastodynamic energy-release rates, which then provide the basis for an elastodynamic criterion for bond failure.

5. "Loss of Adhesion at the Tip of an Interface Crack," J. D. Achenbach, L. M. Keer, R. P. Khetan and S.H.-Chen, J. of Elasticity, in press.

A model is constructed to analyze adhesive bond failure at the tip of an interface crack. The model is based on the assumption that there are zones of bounded cohesive tensile and shear stresses near a crack-tip. Within the context of certain broad a-priori assumptions on the distributions of certain stress and displacement components in the cohesive zones, the requirement that all stresses in the two materials remain bounded provides a method to compute the specific details for these zones. It is assumed that bond failure occurs when the extension of the bond fiber at the crack tip exceeds a critical value. For an interface crack in a uniform tension field computations for two alternate formulations suggest that this failure criterion is independent of the precise distribution of the cohesive stresses, but rather depends only upon their averaged values. Combined loading with a dominant tensile component has also been analyzed. If the critical extension of bond fibers and the maximum value of the cohesive tensile stress are known, the model provides the maximum allowable interface stresses for given crack dimension and material parameters.

6. "The Intersection of a Pressurized Crack with a Joint," by L. M. Keer and S.H.-Chen, to appear.

Abstract: A model is described for considering the partial slip that occurs when a vertical, pressurized crack intersects a horizontal joint. Within the slip region the resistance to slip is accounted for by prescribing the interfacial shear stress. Results are obtained for various crack loadings, and the crack growth is investigated.

7. "Steady Motion of a Crack Parallel to a Bond-Plane," by S.H.-Chen, L. M. Keer, and J. D. Achenbach, Int. J. Eng. Science, in press.

The combined effects of high crack-tip speed and the proximity of a bond-plane on the elastodynamic stress-intensity factor are investigated in this paper. The model-problem that is considered concerns the steady propagation of a crack of length 2a, parallel to a bond-plane with a half-plane of different material properties. By using a moving coordinate system and applying Fourier transform techniques and superposition methods, the mixed boundary-value problem is reduced to a dual singular integral equation with Cauchy-type kernels, which is solved numerically. Stress intensity factors and cleavage angles are computed with the material constants, crack-interface distance and the crack-tip speed as variables. It is found that the effect of the bond-plane is more intense for smaller crack-interface distance and larger crack-tip speed.

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

A summary and a bibliography are presented of the investigations on the rapid propagation of interface flaws in composite bodies, which were carried out at Northwestern University under the sponsorship of the U.S. Army Research-Office during the period July 1, 1975 - September 30, 1979.

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