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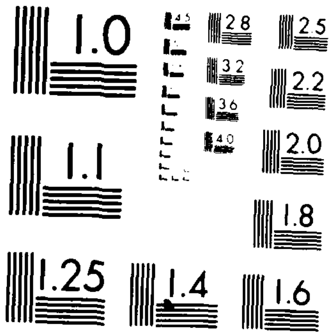

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MIXED MODE I AND II FULLY PLASTIC CRACK GROWTH: SUMMARY REPORT

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Technical Report

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

If a structure cracks, it is desirable that any crack growth be fully plastic to provide large deflections, both for stability by load-shedding to other parts of the structure, and for facilitating crack detection before failure of the entire structure. Unstable fractures are not only serious in themselves, but they may lead to a transition to brittle cleavage fracture that can propagate through parts of the structure that are much more lightly loaded. (cont.)

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Materials tests traditionally involve symmetric specimens, in which the crack advances between two slip bands into undamaged material. In practice, asymmetries often occur for cracks near welds, fillets, or shoulders. Then the deformation is focused into a single band, along which the crack advances into pre-damaged material. A measure of fully plastic crack toughness is the crack growth ductility, defined as the extension required (as a fraction of the original ligament) per unit load drop (as a fraction of maximum load). The crack growth ductility thus provides a measure of the stiffness of the surrounding structure that is required for stability of the entire structure.

The main result of this work is to show that in typical structural alloys with low strain hardening, asymmetries reduce the crack growth ductility by a factor of two to three. Asymmetries have little effect on the displacement for initiation, or on the crack growth ductility of higher hardening alloys, such as annealed, hot rolled, or normalized steels.

Mixed Mode I and II Fully Plastic Crack Growth: Summary Report

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Summary

If a structure cracks, it is desirable that any crack growth be fully plastic to provide large deflections, both for stability by load-shedding to other parts of the structure, and for facilitating crack detection before faliure of the entire structure. Unstable fractures are not only serious in themselves, but they may lead to a transition to brittle cleavage fracture that can propagate through parts of the structure that are much more lightly loaded. Materials tests are traditionally carried out on symmetric specimens, in which the crack advances between two slip bands into undamaged material. In practice, asymmetries often occur for cracks near welds, fillets, or shoulders. Then the deformation is focused into a single band, along which the crack advances into pre-damaged material. A measure of fully plastic crack toughness is the crack growth ductility, defined as the extension required (as a fraction of the original ligament) per unit load drop (as a fraction of maximum load). The crack growth ductility thus provides a measure of the stiffness of the surrounding structure that is required for stability of the entire structure.

The main result of this work is to show that in typical structural alloys with low strain hardening, asymmetries reduce the crack growth ductility by a factor of two to three. Asymmetries have little effect on the displacement for initiation, or on the crack growth ductility of higher hardening alloys, such as annealed, hot rolled, or normalized steels.

The demonstration and description of this loss of ductility, the studies aimed at understanding it, and some related exploratory results in ductile fracture are discussed with reference to the preceding and current progress reports or the resulting papers.

1. An Approximate Equation for Fully Plastic Mode II Crack Growth from an Asymmetric Weld Defect (McClintock and Slocum 1985, also TR01). A model assuming the crack grows directly along the slip band allows developing an approximate equation that predicts that the crack growth ductility varies directly as the critical fracture strain γ_c and inversely as the logarithm of the total crack advance per unit fracture nucleus spacing ρ. The equation provides a basis for predicting large-scale, fully plastic fracture from small specimens, but fails to predict the large loss of ductility observed in low strain-hardening alloys.

2. Tests and Interpretation of Mixed Mode I and II Fully Plastic Fracture from Simulated Weld Defects (Kardomateas and McClintock, TR06). Most fracture tests use symmetric specimens, with the crack advancing into the relatively undamaged region between two plastic shear zones. A crack near a weld or shoulder, loaded into the plastic range, may have only a single shear band, however, along which the crack grows into prestrained and damaged material with less ductility than the usual symmetrical configurations. Tests on six alloys show that the crack growth ductility, defined as the minimum displacement per unit ligament reduction, is less in the asymmetric case than in the symmetric one by a factor of 3 for low-hardening alloys (with strain hardening exponents $n \approx 0.1$). This means that with the low-hardening (typically high strength) alloys, the surrounding structure must be 3 times stiffer for fracture-stable design. For higher hardening alloys ($n \approx 0.23$) the crack growth ductility is less in the asymmetric case by a factor of at most 1.2. The crack initiation ductility (here approximately the crack tip displacement CTD) is relatively unaffected by asymmetry, but it cannot always be relied on for ductility, (e.g. in low cycle fatigue). Therefore tests such as these on crack growth ductility are needed for help in design and maintenance of

structures.

3. Fractographic Observations in Asymmetric and Symmetric Fully Plastic Crack Growth (Kardomateas 1986, also TR04). Electron micrographs suggest a mechanism of fracture consisting of fracture on one plane alternating with slip on one or two others. The usual symmetric case shows more equiaxed voids, while the low ductility asymmetric case shows more elongated voids. An "apparent crack ductility" is defined as the ratio of the sliding off area to the total area including the hole growth area. This apparent crack ductility is much higher than the more macroscopic crack growth ductility, but ranks the symmetric and asymmetric specimens of high and low hardening in similar order.

4. Displacement Fields for Mixed Mode Elastic-Plastic Cracks (Kardomateas, 1986, also TR05). The displacement fields for deformation theory, power law plasticity are found from the Shih strain fields for the mixed mode case. These are needed to extend the McClintock and Slocum model to the more realistic case where the shear band is of finite width and the crack progresses to the tensile side of the shear band. The displacement fields should be useful in many other applications as well.

5. Shear Band Characterization of Mixed Mode I and II Fully Plastic Crack Growth (McClintock and Kardomateas, 1986, TR07). A characterization locally by the directions and amounts of fracture and slip on two or three planes provides relations between those microscopic quantities and macroscopic ones, including the crack flank lengths and directions, the overall slip direction, the deformation of the back surface, and the crack growth ductility. The crack growth ductility is of practical importance in determining the stiffness of the surrounding structure that is needed to prevent unstable fracture.

Applied to six different structural alloys with strain-hardening exponents from 0.1 to 0.2, the model gave crack growth ductilities within 10% for the symmetrical configurations, where the values ranged from 0.25 to 0.4, and were unrelated to the strain-hardening exponent. Correlations with back angle were within 25%, with one exception.

For the asymmetrical configurations that occur near welds or shoulders, the crack growth ductility for the low hardening materials drops to 0.07 to 0.11 for the low-hardening alloys. The predicted values were uniformly high by a factor of two, thus giving a good relative ranking of materials. Correlations with the end-to-end displacement direction and with the lower projected ligament length and flank angle were all within 10%.

This slip plane model of fully plastic crack growth therefore provides a useful correlation between macroscopic measurements, made on the specimens after fracture, and the important loss of crack growth ductility that occurs in asymmetric configurations with materials with low strain-hardening.

6. Finite Element Study of Plane Strain, Fully Plastic, Mixed Mode I and II Crack Growth (Chap. 5 of Kardomateas, 1985). Neglecting blunting of the crack tip led to a serious underestimate of the strain to initiation. Early growth, studied by successive removal of four elements reaching unit damage, shows crack growth within 20% of that observed experimentally. Further interpretation of the results is under way.

7. On Fully Plastic Flow past a Growing Mixed Mode I, II Crack and its Relation to Machining Mechanics (Chap. 6 of Kardomateas, 1985). The assumption of a finite crack opening angle, found in both fully plastic crack growth and machining, leads in a linearly strain-hardening material to the paradox of flow past rigid flanks, but a logarithmic singularity in mean normal stress at the crack tip. Such a singularity could be relieved by strains of an elastic order of magnitude, leaving the rigid-plastic deformation field that was found relatively exact. This hypothesis is substantiated by considering the elastic-plastic field for a growing crack (Ponte-Castañeda 1985), for which the strain γ at a radius r was given in terms of the yield strain γ_y at a characteristic radius R by

$$\gamma = \gamma_y (R/r)^s ,$$

where $s < 0.1$ for typical alloys. Taking R to be 10mm and γ_y to be 0.003, the radius r at which the elastic-plastic singularity would dominate even a relatively small plastic fracture strain of $\gamma = 0.1$ is

$$r = 10\text{mm}(0.003/0.1)^{1/0.1} = 10\text{mm}(0.03)^{10} = 5.9\times 10^{-15}\text{mm} \quad !$$

Even with a much larger assumption of R, the result indicates that a rigid-plastic solution would dominate throughout the fracture process zone, which is of the order of 0.01 to 0.1mm.

8. Fully-Plastic Crack Growth in Asymmetric Plane-Strain Bending (McClintock and Wu, TR08). Since bending involves more triaxiality and less ductility than the tensile loadings discussed above, studies were made of asymmetric bend specimens. Extensive studies of specimen design, using slip line theory, showed that cantilever loading of shoulder configurations was necessary to limit the flow to a single slip line, producing the desired asymmetry. In bending, two ductility measures are needed; first a structural crack growth ductility, defined as the relative displacement at the load point per unit fractional load drop, and second, the local crack growth ductility defined as the local displacement per unit of crack growth. Tests on medium strength, low hardening steels (HY-80 and HY-100) showed that, for the limited triaxiality that could be produced, the local crack growth ductility under bending was reduced below that for tension by a factor of 1.5 for both symmetric and asymmetric specimens.

9. *A Wedge Test for Quantifying Fully Plastic Fracture* (McClintock and Wineman, 1986). A test using two wedges splitting a small, doubly grooved specimen allows measurement of stable, fully plastic crack initiation and growth under variable amounts of triaxiality. In wedge tests, 25mm cubes of 1018 hot rolled steel in three different orientations exceeded the limit load predicted by plastic slip-line fields. The tests gave crack tip initiation displacements of 0.7-0.8mm, regardless of

orientation. Since microscopic examination of the fracture surfaces indicated that the wedges suppress blunting, the presence of non-zero initiation displacements suggests that a fracture process zone of finite thickness must be established before crack growth. During growth, a specimen with rolling direction normal to the crack plane had a crack growth ductility (minimum displacement per unit ligament reduction) of 0.006-0.009, compared to ductilities of 0.016-0.027 for specimens with rolling direction parallel to the crack front or parallel to the growth direction. The lower ductility with the crack normal to the rolling direction appears to be due to a smoother fracture surface without zigzagging between inclusion stringers.

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