PLANE STRESS FRACTURE UNDER BIAXIAL LOADING

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ABSTRACT

Crack tip opening angle and J-resistance curves were used in a finite element model to predict stable crack growth and fracture under biaxial loading. Both the amount of stable crack growth and the predicted fracture loads were in good agreement with the experimental data. This indicates that plastic fracture resistance curves generated in uniaxial loading can be used in biaxial loading without major modification.

KEYWORDS

Plastic fracture, crack tip opening angle, J-resistance curve, finite elements, biaxial loading.

INTRODUCTION

Kanninen and co-workers (1979) developed J- and CTOA-based resistance curves for aluminum alloy specimens under uniaxial loading conditions. In an attempt to generalize this work, these plastic fracture analyses were applied to center-cracked panels with through-thickness cracks under biaxial tension. The objective was to ascertain if crack resistance curves obtained from simple specimens could be used in a finite element analysis to predict crack growth and fracture instability under loading conditions more nearly representative of service conditions. This paper presents the experimental data and the analysis results from this work.

EXPERIMENTS

Biaxial tests were performed on 7075-T73 and 2219-T87 aluminum alloy specimens of 6.35 mm thickness. Figure 1 shows the specimen design. The grip areas of the specimens were reinforced at back and front. Slits were cut to prevent load shedding of the load component transverse to the grips. The specimens were provided with a central notch consisting of a 3.18 mm diameter hole and two saw cuts from which fatigue cracks were grown over a distance of at least 6.35 mm. The total crack length ranged from 12.7 mm to 100 mm.

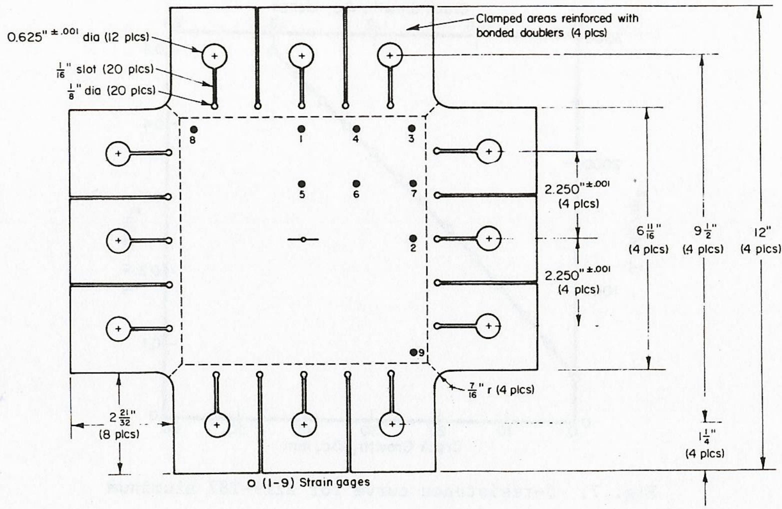


Fig. 1. Biaxial specimen

Crack opening displacement during these experiments was measured by a clip gage located in the center of the notch. Slow crack growth was measured by potential drop gages. Note that it was necessary to correct the potential drop records because gage cracking was caused by the large plastic strains in these tests.

While each specimen was equipped with biaxial strain gages at the Locations 1, 2, and 3 shown in Figure 1, one specimen was equipped with 9 biaxial strain gages. This specimen was loaded in the elastic range at a given biaxiality ratio with the gages being read at given load increments. After unloading, the same specimen was used for strain measurements at other biaxiality ratios. Subsequently, the crack size was increased and the procedure repeated. Data were obtained for four crack sizes at biaxiality ratios k = 0, 0.5, 1, and 2 ($k = P_x/P_y$, where x denotes the direction along the crack plane and y the direction normal to the crack plane).

TEST RESULTS

The edge-stress distribution (Figure 2 shows an example) was non-uniform due to the presence of the crack. But, it was in good agreement with the stress distribution computed assuming uniform displacement of the edges (rigid clamping). Biaxiality ratios for the edge stresses in a panel with a 12.7 mm crack indicate that, on average, the edge stresses show approximately the same biaxiality ratio as the loads. This is shown in Figure 3. Similar results were obtained for other crack sizes.

Most load-COD records (obtained concurrently with the strain gage measurements) were slightly nonlinear except in the case of the 12.7 mm crack. But, the average COD per unit of load depends almost linearly on biaxiality ratio. This is shown in Figure 4. For the uniaxial case and uniform edge stress, COD would be given by

$$COD = \frac{4\sigma a}{E} f(a/b) = 4\ \varepsilon_{nom}\ a\ f(a/b) \qquad (1)$$

where $\varepsilon_{nom} = \sigma/E$ is the remote strain. In the biaxial case, it is expected that COD will still be proportional to ε_{nom} so that, by taking $\varepsilon_{nom} = \sigma/E\ (1 - \nu k)$ and setting f(a/b) equal to one for simplicity,

$$\frac{COD}{\sigma} = \frac{4a}{E} (1 - \nu k) \qquad (2)$$

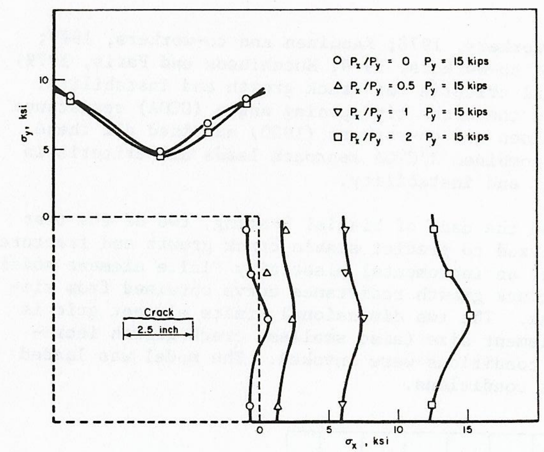


Fig. 2. Edge stress distribution in biaxial specimen with 2.5 inch crack

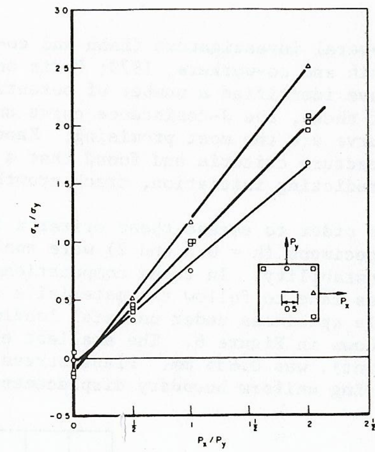


Fig. 3. Biaxiality of edge stresses for 0.5 inch crack

Figure 4 indicates that Equation (2) is in good agreement with the test data.

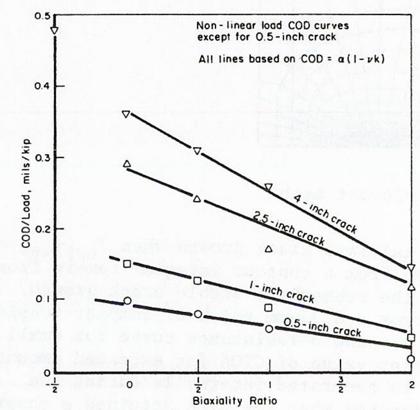


Fig. 4. The effect of biaxial applied stresses on COD

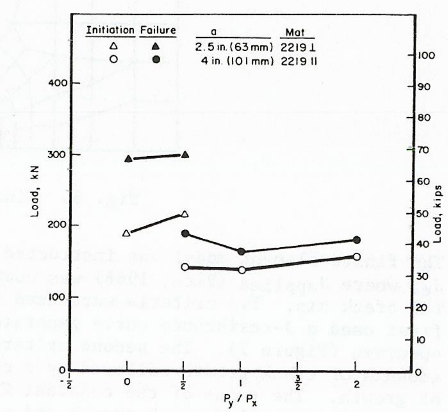


Fig. 5. Residual strength of 2219 aluminum specimens

The residual strength data for the 2219 material are plotted in Figure 5. These data show no systematic effect of biaxiality ratio on fracture behavior; i.e., all data are within the scatter normally found in these kinds of tests. Only the loads at the initiation of crack growth seem to show a systematic increase with biaxiality ratios.

FINITE ELEMENT ANALYSIS

Several investigators (Hahn and co-workers, 1978; Kanninen and co-workers, 1979; Shih and co-workers, 1979; Paris and co-workers, 1979; Hutchinson and Paris, 1979) have identified a number of potential criteria for crack growth and instability. Of these, the J-resistance curve and the crack tip opening angle (CTOA) resistance curve are the most promising. Kanninen and co-workers (1980) examined all these fracture criteria and found that a combined J/CTOA approach leads all criteria in predicting initiation, crack growth, and instability.

In order to assess these criteria in the case of biaxial loading, two of the test specimens (k = 0.5 and 2) were analyzed to predict stable crack growth and fracture instability. In these computations, an incremental plasticity finite element model was made to follow the material's crack growth resistance curve obtained from simple specimens under uniaxial loading. The two dimensional finite element grid is shown in Figure 6. The smallest element size (also smallest crack growth increment), was 0.635 mm. Plane stress conditions were invoked. The model was loaded using uniform boundary displacement conditions.

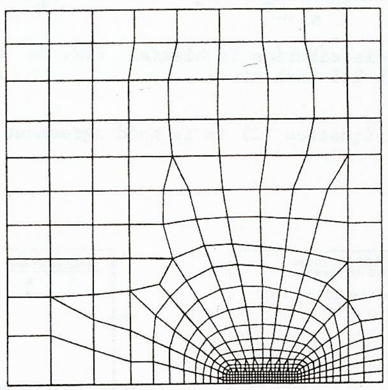


Fig. 6. Finite element mesh

The finite element model was instructed to initiate crack growth when $J_{applied} = J_c$, where $J_{applied}$ (Rice, 1968) was computed from a contour integral remote from the crack tip. Two criteria were used for the subsequent stable crack growth. The first used a J-resistance curve generated from a 6.35-mm thick 2T compact tension specimen (Figure 7). The second criterion was the J-resistance curve for small amounts of crack growth followed by a constant value of CTOA for extended amounts of growth. The value of the constant CTOA is generated internally during the initial J-controlled crack growth and was invoked when the CTOA attained a constant value (Kanninen et al, 1980).

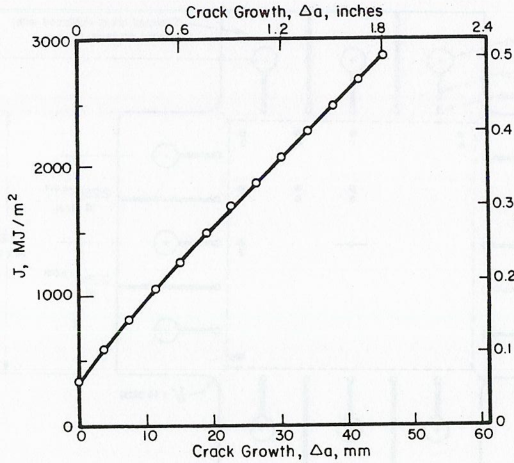
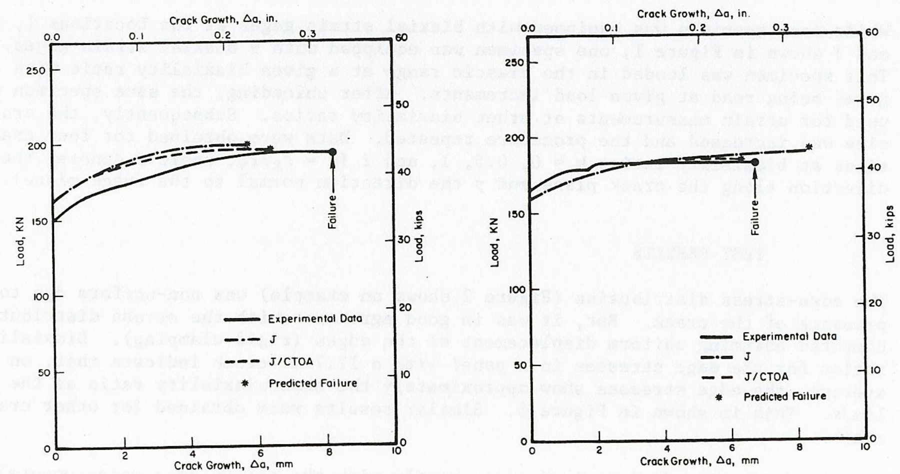


Fig. 7. J-resistance curve for 2219-T87 aluminum

Figure 8 shows a comparison between the experimental and the analytical results. It can be seen that, while very good agreement was obtained, the J/CTOA approach gave the better prediction, both in maximum load (assumed to be the point of instability) and amount of stable crack growth to reach the instability point. The internally computed values of CTOA were 0.12 radians (k = 0.5) and 0.11 radians (k = 2). These indicate that CTOA is slightly dependent on the biaxiality ratio which agrees with the observations of Adams (1973).



$P_x/P_y = 0.5$ $P_x/P_y = 2$

Fig. 8. Critical comparison between predicted and experimental crack growth and final fracture

DISCUSSION

Several investigators have addressed the effect of biaxiality on crack growth. However, very few useful test data are available (Adams, 1973; Radon and co-workers, 1978; Liu and Ditmer, 1978). The test data tend to show very little effect of biaxiality on residual strength and fatigue crack propagation. Analytical work has shown that the plastic zone sizes are affected by biaxiality. But, because it appears to be well established that there is no unique relation between plastic zone size and the various fracture criteria, this may not be particularly relevant. The effect of biaxiality on J (Lee and Liebowitz, 1977; Miller and Kfouri, 1979), on G (Eftis and co-workers, 1977; Miller and Kfouri, 1979), and on CTOD (Adams, 1973), has also been considered. A small dependence of J and CTOA on biaxiality ratio was found, under plane stress conditions.

CONCLUSIONS

For the plane stress conditions considered in this study, it appears that the resistance curves generated from tension specimens can be used to predict crack growth and fracture instability under biaxial loading. A possibly even more important result of this study is that resistance curves obtained from simple specimens can be used in the analysis of specimens (structures) of a significantly different geometry. The use of the J-resistance curve for the first part of crack growth and of an internally generated CTOA was also shown to be able to reliably predict stable crack growth, beyond the limits of J-controlled crack growth.

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