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GEOMETRY EFFECT ON CRACK CLOSURE

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One of the early methods of determining fracture toughness was to measure crack opening displacement of a specimen which had a fatigue crack at the root of a notch. Drucker and Rice [1], however, conducted elastic-plastic analyses which suggested that the fracture toughness results which were obtained from this type of test would be dependent on specimen geometry; i.e., measurement of crack opening displacement could, therefore, differ for different specimen geometries.

More recently Larsson and Carlsson [2], Rice [3] and Leevers and Radon [4] presented results of analyses which indicated that the characterization of the stress state at a crack tip could not always be accurately predicted for different specimen geometries by use of the mode I stress intensity factor. They showed that a more accurate characterization could, however, be obtained by including the second term of the Williams series; i.e., the so-called T stress term.

Since about 1971, there has been considerable interest in a fatigue phenomenon described as closure. This actually involves prevention of closure by the presence of a plastic wake [5] or by roughness asperities on the fatigue crack surfaces [6]. The amount of crack opening displacement can be expected to affect the amount of interference which is produced by crack surface obstructions to closure. Acceptable methods for predicting closure effects must, of course, be valid for all specimen geometries and conditions of loading to be useful in the prediction of fatigue crack growth in components in machines and structural systems. For example, would a center cracked specimen under tensile loading and an edge crack specimen under bending have the same near crack opening contours if they were both loaded to develop the same value of stress intensity factor? Can, for example, closure predictions based on the use of data obtained on a center crack specimen be valid for all cracked bodies?

The objective of the studies described here was to examine the factors which prompted the preceding questions. To accomplish this, finite element analyses of three specimen geometries were performed. These were the center crack tensile (CCT) specimen, the single edge notched specimen under tensile loading (SEN-Tension) and the single edge notched specimen under bending (SEN-Bending). The loading which was applied in these numerical experiments was chosen to develop the same stress intensity factor for all three specimens. The near crack tip opening displacements were then determined for each of the specimens.

The three specimen geometries considered are shown in Fig. 1. In order to determine the magnitude of loading, which will develop the same stress intensity factor for each case, the result of analytical solutions for stress intensity factors found in [7] were used. They all were obtained by using least square method [8] and are detailed as in the following:

(CCT)

$$\frac{K_T^{CCT}}{\sigma_1\sqrt{\pi a}} = 1 + 0.128(a/W) - 0.288(a/W)^2 + 1.525(a/W)^3 \qquad (1)$$

(SEN-Tension)

$$\frac{K_T^{SEN}}{\sigma_2\sqrt{\pi a}} = 1.122 - 0.231(a/W) + 10.55(a/W)^2 - 21.71(a/W)^3 + 30.382(a/W)^4 \qquad (2)$$

(SEN-Bending)

$$\frac{K_B^{SEN}}{\sigma_{max}\sqrt{\pi a}} = 1.122 - 1.4(a/W) + 7.33(a/W)^2 - 13.08(a/W)^3 + 14.0(a/W)^4 \qquad (3)$$

By setting $K_T^{CCT}=K_T^{SEN}=K_B^{SEN}$, the loading ratios between the cases can be obtained in terms of specimen geometry dimensions and crack size.

The typical finite element mesh shown in Fig. 2 was used. It contained a total of 81 quadratic elements and 292 nodes. The mesh was modeled for all considered geometries. Due to the various symmetries, only one fourth of the CCT specimen and one half of the SEN specimens were modeled. The model used has W=76.2 mm and a height of 190.5 mm. The crack size was chosen to be a/W=0.4 because a/W becomes normally greater than 0.25 after precracking in fatigue crack growth testing. The region surrounding the crack tip was modeled with quadratic isoparametric elements with the mid-point nodes of the edges moved to the quarter point to produce the proper strain singularity at the crack tip. This modeling technique was suggested by Barsoum [9]. The values of the stress intensity factors determined by using the nodal displacements in the analytical expressions for displacements were confirmed by comparisons with available results. Typical elastic constants for aluminum alloys (E=72 GPa, ν=0.31, σ_{ys}=300 MPa) were used. The tensile load for σ_1 was used as three tenths of yield stress. From the previous analyses, σ_2 and σ_{max} were determined as $0.52362\sigma_1$ and $0.87791\sigma_1$ for a/W=0.4, respectively. In this study, only the elastic and plane strain cases were considered.

For the given geometries and loading conditions the results of the finite element analyses were 29.02 MPa$\sqrt{m}$ for the CCT specimen, 28.34 MPa $\sqrt{m}$ for the SEN-Tension specimen, and 28.00 MPa$\sqrt{m}$ for the SEN-Bending specimen. Differences between the numerical values are within 3 percent. Computed values of displacement are given in the table. Figure 3 presents plots of crack opening displacement near the crack tip for each case. From Fig. 3 it is clear that the trends for the crack surface contours for different geometries differ. The overall crack opening displacments for SEN specimens are greater than those for the CCT specimen. From the table, however, the trends are reversed in the area very close to the crack tip.

Knott [10] has indicated that the location of closure obstruction behind the crack tip can vary from 0.1016 mm for surface roughness and oxide obstructions to 5.08 mm for a plastic wake. An examination of the crack surface contours of Fig. 3 indicates that the available clearance for closure obstructions in this range differs for the different conditions. Although the differences are small, it should be noted that the effective heights of the obstructions are of the order of 0.005 mm for IN-718 materials [11]. An examination of the results in the table and in Fig. 3 indicates that the differences in the displacements are of the order of the obstruction height. Small clearance differences could, therefore, result in significant differences in the opening loads. Therefore, it is concluded that the amount of clearance for closure obstructions is dependent on specimen geometries.

The crack opening displacements for CCT and SEN specimens under tensile and bending loadings were obtained using the finite element method. The loadings were chosen to develop the same stress intensity factor for all three specimens. It was concluded that crack closure behavior is geometry dependent.

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Table 1. Computed crack opening displacement values for a/W=0.4

Distance from Crack Tip (mm)	Crack Opening Displacement (x 0.01 mm)		
	CCT	SEN-Tension	SEN-Bending
7.62	4.9376	5.3100	5.6937
5.715	4.3472	4.5737	4.8250
3.81	3.6154	3.7210	3.8560
2.8575	3.1529	3.2104	3.2968
1.905	2.5826	2.6022	2.6475
0.47625	1.2786	1.2687	1.2726
0.0	0.0	0.0	0.0

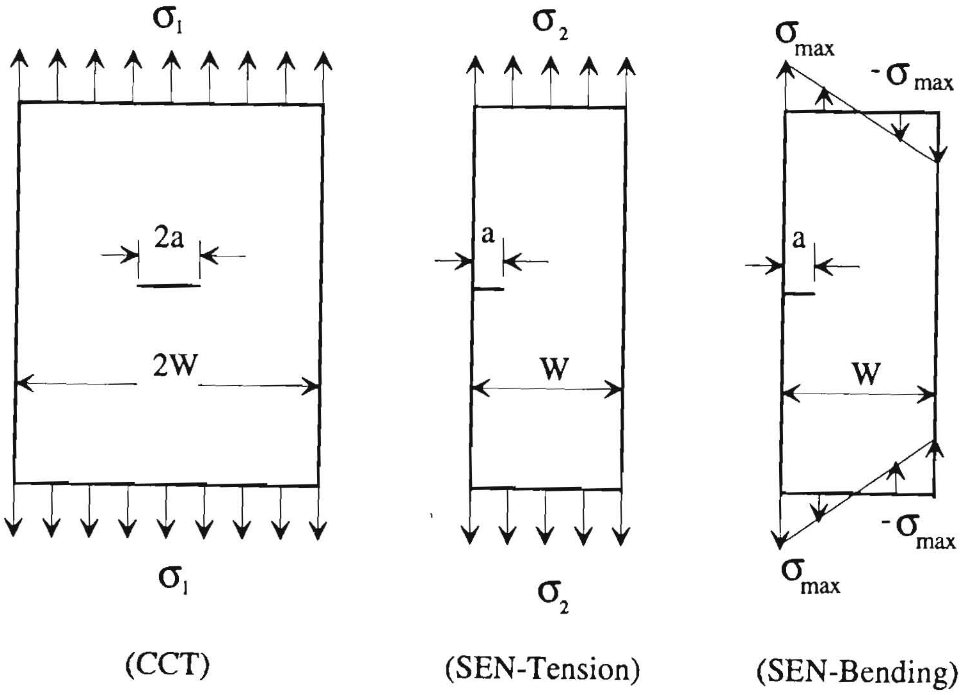

Figure 1. Specimen geometries and loadings.

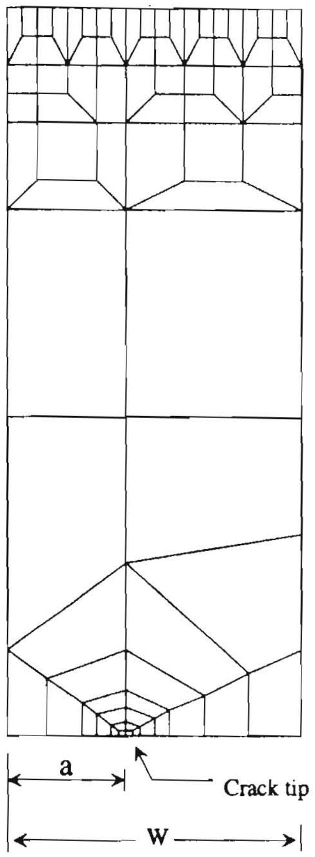

Figure 2. Typical finite element mesh.

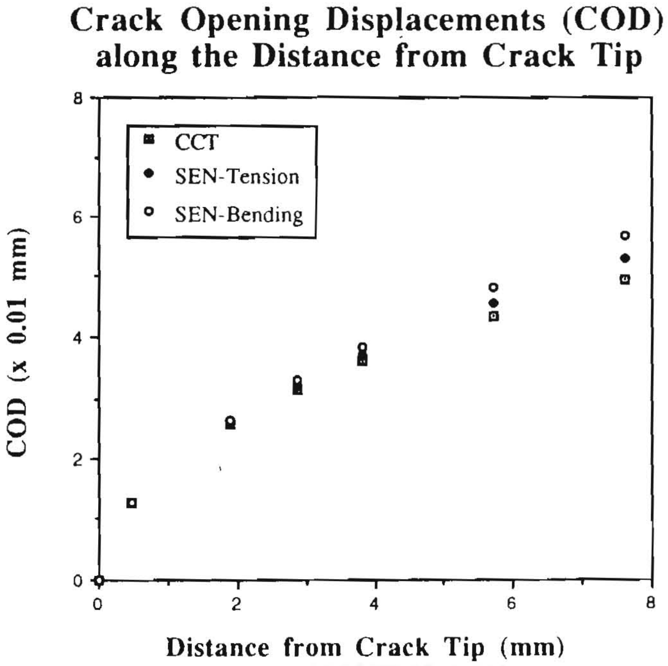

Figure 3. Crack opening displacement along the crack surface.