THE USE OF CIRCUMFERENTIALLY-CRACKED BARS FOR THE MEASUREMENT OF FRACTURE TOUGHNESS

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The circumferentially cracked bar (CCB) specimen can be used to measure fracture toughness of ferritic steels when the compact-tension and single edge-cracked bend specimens are inappropriate. This paper reviews the fracture toughness data available in the literature with a view to providing advice for incorporating the CCB specimen in testing procedures. The analytical relationships used to derive the stress intensity factor, limit load and $J$-integral for the CCB specimen are also reviewed. The relationships are compared with finite element analyses to assess their accuracy and limits of applicability. Practical experience is assessed and recommendations are given to enable the fracture toughness of a material to be measured using CCB specimens.

INTRODUCTION

Fracture toughness properties used in structural integrity assessments are conventionally obtained from compact-tension (CT) or single edge-cracked bend (SECB) specimens. The circumferentially-cracked bar (CCB), illustrated in Fig. 1, has been developed as an alternative for fracture toughness testing which may be used when conventional specimens are inappropriate or material availability is limited. The CCB specimen has a number of benefits: (i) the test method is similar to that used for tensile testing, (ii) test pieces are convenient and comparatively inexpensive to produce, and (iii) no plane stress regions are produced around the crack front, ensuring that a high degree of constraint is maintained at the crack tip.

This paper briefly reviews the available analytical, numerical and experimental information for the CCB specimen and provides guidance for the fracture toughness testing of homogeneous materials.

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FRACTURE BEHAVIOUR

Stress Intensity Factor Functions

A number of functions are available for a CCB specimen in the literature. Of these, Murakami (1) gives:

\[
\frac{K_I}{K_0} = \left(1 - \frac{a}{R}\right)^{-\frac{1}{2}} \left[ 0.5 \left(1 + 0.5 \left(\frac{b}{R}\right) + 0.375 \left(\frac{b}{R}\right)^2 - 0.363 \left(\frac{b}{R}\right)^3 + 0.731 \left(\frac{b}{R}\right)^4 \right) \right] \tag{1}
\]

where \(K_0 = \frac{P \sqrt{a} \pi R^2}{2}\). This function has been compared with finite element (FE) data derived by O'Dowd (2) and gives the closest agreement, better than 3%, with the FE results for \(0.1 \leq a/R \leq 0.9\) (Fig. 2).

Limit Load Solutions

The limit load \(P_L\) can be related to the yield stress \(\sigma_y\) by \(P_L = \sigma_y \pi R^2 m(a/R)\) where \(m(a/R)\) is given by Miller (3):

\[
m(a/R) = \begin{cases} 
1 - a/R & \text{for } a/R < 0.65 \\
2.85(1 - a/R)^2 & \text{for } a/R \geq 0.65
\end{cases} \tag{2}
\]

Eqn (2) is compared with the results from elastic perfectly plastic FE analyses (2) in Fig. 3. For \(a/R \geq 0.65\), agreement with the FE results is good. For \(a/R < 0.65\), the agreement is less good but conservative.

\(J\)-integral Functions

A number of \(J\)-integral functions for the CCB specimen are given in the literature, e.g. Rice et al. (4). The specimen behaviour has recently been evaluated analytically to show that \(J\) can be evaluated from the plastic component of the area under the load vs. load-point displacement record, \(U_p\), Neale (5):

\[
J = K_i^2 \frac{(1 - \nu^2)}{E} + \frac{U_p}{2\pi b^2} \quad \text{for } a/R < 0.65 \tag{3}
\]

TESTING CONSIDERATIONS

Fatigue precracking of CCB specimens can be performed under tension, Itoh et al. (6), or in rotating bend, Lucon (7). Although \(K_i\) and \(P_L\) solutions are known in
tension, variations in axial alignment can result in eccentric cracks. In rotating bend, dynamic solutions are necessary to establish the precracking loads. To avoid plastic damage to the specimen these need to be established.

In a test, the applied load and load-point/gauge length displacement are measured and the fracture toughness derived using either eqns (1) or (3). It is suggested that the initial crack depth, \(a_0\), be measured according to the eight-point procedure defined in Fig. 4. Crack growth, \(D_a\), ahead of the initial crack depth is measured at the same eight points. Variations in crack depth and the degree of eccentricity may be quantified by comparing individual values of \(a\) with \(a_0\). It is suggested that for the valid measurements of toughness \(a\) should be in the range \(0.9a_0 \leq a \leq 1.1a_0\).

Experimental Data

**Lower-Shelf Fracture Toughness.** CCB specimens have been used to measure fracture toughness for a range of materials, e.g. (7). In this regime, the maximum load at fracture is used to evaluate fracture toughness from functions such as eqn (1). Comparisons of CCB with CT data show reasonably good agreement particularly for larger specimens, Fig. 5. The apparent size effect may be due to an effective increase in plasticity for the smaller specimens with fracture in the elastic-plastic rather than the elastic regime.

**Transition Fracture Toughness.** CCB specimens have been used to measure the fracture toughness of ferritic steels in the transition regime, e.g. Gage et al. (8). Fig. 6 shows CCB data obtained for a 72W weld (columnar region). For some CCB tests, cleavage fracture followed a small amount of stable tearing. The CCB data generally lie above the corresponding CT data, probably reflecting the differences in sampling volume between the two specimen types.

**Upper Shelf Fracture Toughness.** CCB specimens have been used to measure the upper shelf fracture toughness of a Ni-Cr-Mo-V steel (6) and an A508 pressure vessel steel, Devaux et al. (9). For this latter material, close agreement was observed between the \(J\)-Resistance curves determined from CCB and CT specimens. The CCB specimens exhibited unstable fracture after a small amount of tearing, whereas the CT specimens exhibited fully ductile behaviour. This illustrates the high level of constraint, sufficient to promote unstable fracture, which is maintained in the CCB specimen at loads beyond general yield.

**DISCUSSION**

A number of size criteria have been proposed for the measurement of linear elastic fracture toughness using the CCB specimen. These may be expressed in the form:

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\[ a_i(R-a) \geq A_1 \left( \frac{K_i}{\sigma} \right)^2 \] .................................................. (4)

where \( A_1 \) is a factor relating to the minimum specimen dimensions \( a \) and \( (R-a) \). Values for \( A_1 \), derived from considerations of plastic zone size, \( r_p \), and/or test data, lie in the range 0.106 to 0.457, e.g. (5, 7). Until additional data and analytical results are available, it is recommended that \( A_1 = 0.265 \) should be adopted since this value is based on the consideration of both experimental data and \( r_p \) (7). For ductile fracture, CCB size criteria have not yet been established.

CONCLUSIONS

This paper has reviewed the use of CCB specimens for the measurement of fracture toughness. The following conclusions can be made:

(1) The stress intensity factor should be determined from eqn (1).

(2) Values of \( J \) may be derived from load vs. load-point displacement data using the partitioned \( J \) expression given as eqn (3).

(3) Although further work is required to establish the optimum test procedure, sufficient information is now available for a draft test method to be written.

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REFERENCES


(2) N P O'Dowd, private communication, 1995.


Figure 1 CCB specimen.  

Figure 2 Comparison of stress intensity factor functions
Figure 3  Comparison of limit load functions.

Figure 4  Suggested approach for the measurement of initial crack depth, $a_0$.

Figure 5  Variation of $K_I$ with specimen diameter: rotor steel at Rm. Temp. (7).

Figure 6  Fracture toughness transition data for 72W weld (8).