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:

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

where $K_0 = P\sqrt{\pi a}/\pi R^2$. 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 $0.1 \le a/R \le 0.9$ (Fig. 2).

Limit Load Solutions

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

$$m(a/R) = 1 - a/R \qquad \text{for } a/R < 0.65$$
$$m(a/R) = 2.85(1-a/R)^2 \qquad \text{for } a/R \ge 0.65 \quad (2)$$

Eqn (2) is compared with the results from elastic perfectly plastic FE analyses (2) in Fig. 3. For $a/R \ge 0.65$, 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):

$$J = K_I^2\frac{(1-\nu^2)}{E} + \frac{U_p}{2\pi b^2} \qquad \text{for } a/R < 0.65 \quad (3)$$

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, Da, 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_i with a_0. It is suggested that for the valid measurements of toughness a_i should be in the range $0.9a_0 \leq a_i \leq 1.1a_0$.

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:

$$a,(R-a) \geq A_1\left(K_I/\sigma_y\right)^2 \qquad (4)$$

where A_1 is a factor relating to the minimum specimen dimensions a and $(R\text{-}a)$. 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.

ACKNOWLEDGEMENTS

This work was carried out as part of the R6 programme sponsored by Nuclear Electric plc (NE), AEA Technology (AEAT), British Nuclear Fuels Ltd and Scottish Nuclear Ltd. This paper is published with the permission of AEAT and NE. The authors are grateful to Dr R A Ainsworth (NE) for useful discussions and to Dr E Lucon (CISE) for information exchanged during this work.

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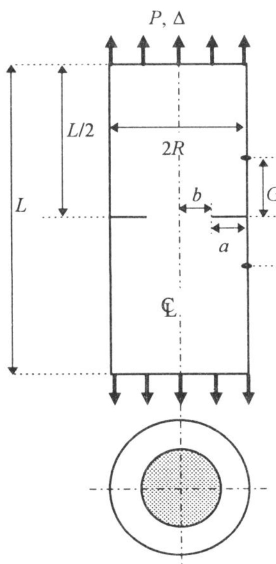


Figure 1 CCB specimen.

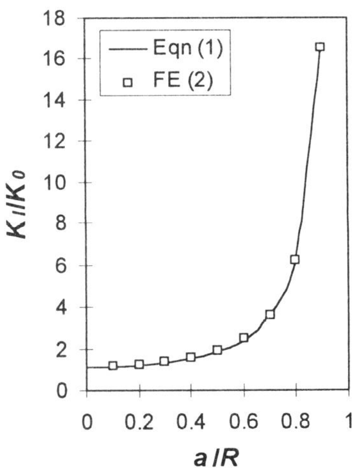


Figure 2 Comparison of stress intensity factor functions

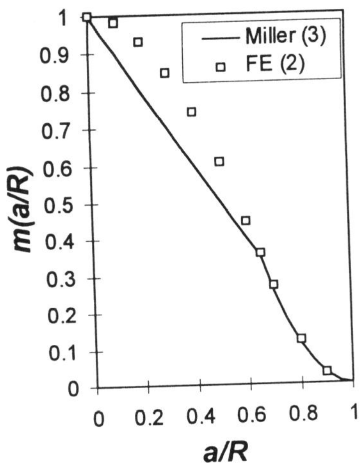
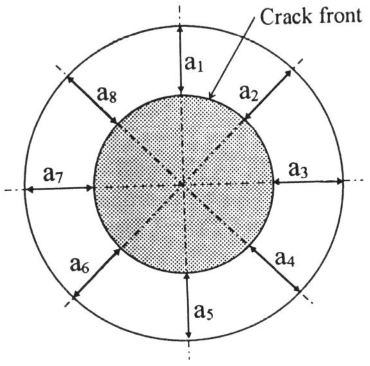


Figure 3 Comparison of limit load functions.



$$a_0 = \frac{1}{8}\sum_{i=1}^{8} a_i$$

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

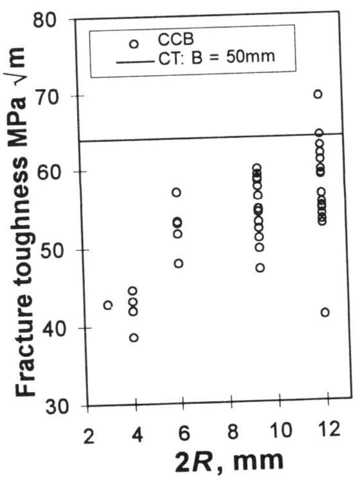


Figure 5 Variation of K_I with specimen diameter: rotor steel at Rm. Temp. (7).

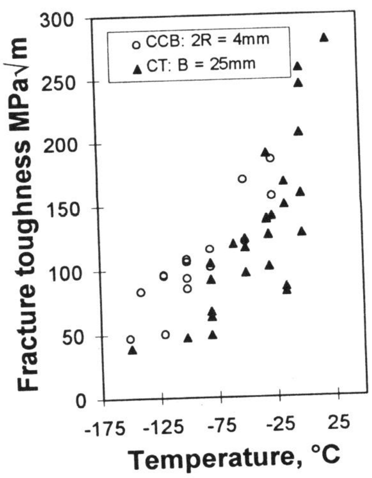


Figure 6 Fracture toughness transition data for 72W weld (8).