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A Fracture Test for Brittle Materials

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Abstract

It has become increasingly apparent that fracture toughness is an important material characteristic of ceramic materials, especially those subjected to high stresses due to mechanical loading or thermal shock. One aspect of their fracture behaviour is that in many cases their fracture toughness appears to increase as a crack propagates. This is known as the R*-curve effect. The current test methods in use were originally designed to obtain single parameters such as work of fracture or* K_{IC} *and are not particularly suitable for obtaining toughness curves. This paper presents a new fracture test that is specifically designed to measure the crack growth resistance curves of brittle materials. Some typical toughness curves for a range of materials are reported.*

1 Introduction

It has been observed for a number of years that some brittle materials do not show a constant toughness, instead the toughness increases as the crack propagates. This behaviour known as *R*-curve behaviour has been attributed to a number of mechanisms including microcracking,[1] crack bridging[2,3] and the release of residual stresses.[4]

The shape of the *R*-curve is important as it determines the onset of crack instability. A rising *R*-curve gives rise to multiple small cracks because, as one crack extends, the required stress intensity to propagate the crack will increase to a point where it is favourable to propagate a different crack. In contrast a flat *R*-curve (constant K_{IC}) will produce a single and possibly catastrophic crack. The extent to which the toughness increases also determines the residual strength after thermal shock:[5] the length of any cracks formed during the thermal shock is determined by the shape of the *R*-curve.

In order to investigate crack growth in these materials it is important to be able to propagate stable cracks. Various possible tests are commonly used:

1. *Indentation test.* A simple and rapid test for obtaining a fracture toughness value for small samples, with a fine scale microstructure. It is, however, difficult to determine the nature of any secondary cracks apart from in opaque materials and this makes measurement of the crack length difficult. Problems also exist with the geometry as it is difficult to model mathematically and hence any results for toughness increasing with crack length are difficult to interpret.
2. *Three- or four-point bend.* This test method is commonly used as it requires only a simple specimen, and loading jigs are readily available. However the stress intensity at constant load increases rapidly with crack length[6] and therefore it is necessary to measure the crack length very accurately to obtain meaningful results. The geometry of the specimen also does not allow significant crack growth to occur without the use of large specimens, making the test very inefficient in terms of material required.
3. *Double cantilever beam.* This test specimen can be loaded to provide a constant stress intensity as the crack grows, and so large amounts of crack growth are possible. In theory a straight crack should propagate down the centre of the specimen; in practice this is usually facilitated by grooving the specimen as otherwise the crack tends to deviate. This grooving complicates the calculation of the stress intensity factor and may also influence the formation of a damage zone around the crack tip.
4. *Double torsion.* The torsional loading produces a curved crack front so the crack length cannot be well defined. This therefore makes it difficult to measure *R*-curves.

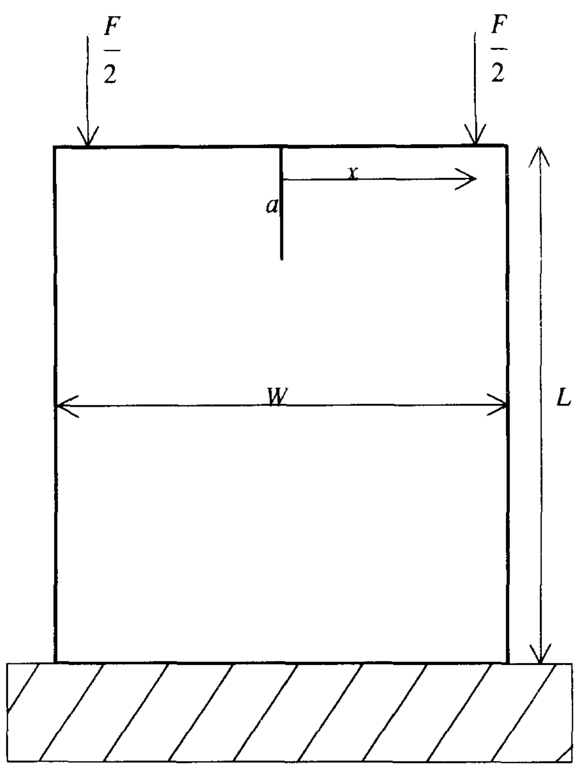

Fig. 1. The Browne/Chandler test geometry.

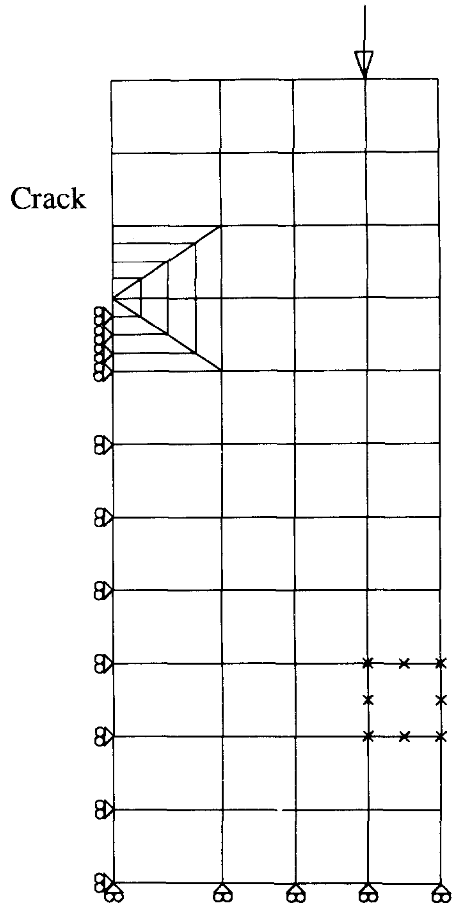

Fig. 2. Typical finite element mesh used in the analysis.

Browne and Chandler[7] developed a test with the geometry shown in Fig. 1. The specimen is bonded to a stiff block and a load is applied near the corner of the specimen, producing a moment about the centre of the specimen which forces the crack to propagate. At constant applied force this geometry shows a reducing value of stress intensity K as the crack propagates and hence an increase in the force required to propagate the crack, which removes the requirement of a stiff testing machine. During the initial experimental work the crack was found to grow straight down the centre of the specimen with no need for grooving. This is because there is a compressive stress parallel to the crack[8] due to the nature of the loading arrangement.

This specimen shape, at least for short cracks and those that approach the end of the specimen, does not lend itself to an analytical solution for all crack lengths and hence it is necessary to estimate the stress intensity using numerical methods. This paper presents the stress intensity curves for various specimen geometries and compares them with a well-known analytical solution for cracks of intermediate length, and reports the R-curves for a number of brittle materials obtained using this test.

2 Computer Modelling

A number of different geometries of the test have been modelled using finite elements in order to obtain the variation in stress intensity as the crack propagates. The program used in the analysis was FINEL, which has been developed at Newcastle University by Dr John Appleby of the Engineering Mathematics Department. A typical mesh was made up from eight-noded quadrilateral and six-noded triangular elements and one is shown in Fig. 2. The symmetry of the test piece allows half the specimen to be modelled, the crack being represented by unrestrained nodes along the axis of symmetry. Excessive mesh refinement near the crack tip was avoided by placing the nodes surrounding the crack tip at quarter points,[9] producing the necessary singularity.

The stress intensity at the crack tip was calculated by two methods. The first method used was the well-established energy method[10] where the crack extension force is calculated and from this K is obtained. The second method calculated K directly from the near-tip crack-opening displacement (u) which is obtained from the finite element analysis, using the relationship,[11]

$$K = \frac{Eu\sqrt{2\pi}}{4(1 - \nu^2)\sqrt{r}}$$

where ν is Poisson's ratio, E is Young's modulus and r the distance from the crack tip at which u is measured. The results from the two methods were

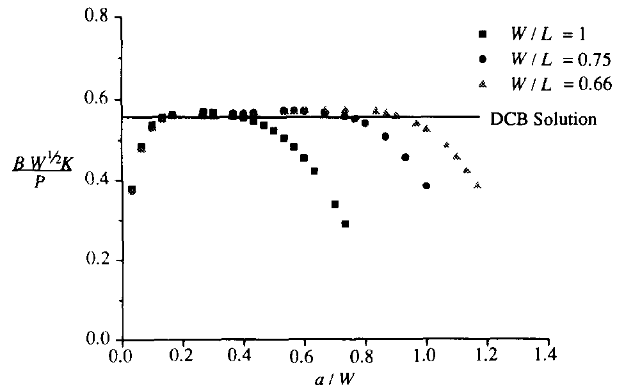

Fig. 3. Effect of varying the aspect ratio on the stress intensity curve ($x/W = 0{\cdot}36$).

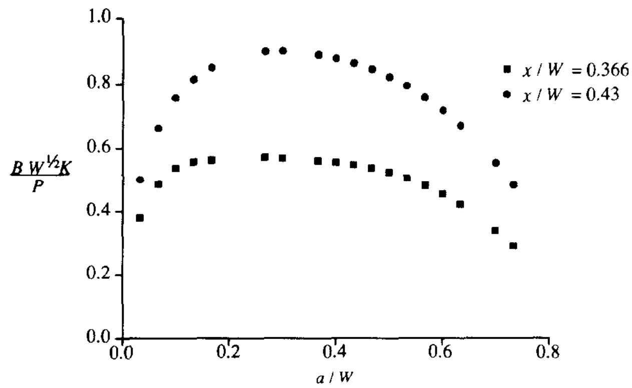

Fig. 4. Stress intensity curve for $W/L = 1$ with varying loading positions.

compared and were found to be very similar, thus the second method was used in the analysis because of its simplicity.

The aspect ratio of the specimen was varied, producing the results shown in dimensionless form in Fig. 3. It can be seen that the maximum stress intensity does not change as the aspect ratio varies; however, as the specimen becomes more elongated, the stress intensity remains at the maximum value for a greater amount of crack growth, reducing the stability of the loading arrangement. However, in materials which show *R*-curve behaviour it is still necessary to apply increased loads to propagate the crack and therefore elongated specimens can offer useful results for long cracks with a smaller volume of material. The effect of changing the position of the loading point is to vary the position of the peak and its magnitude as is shown in Fig. 4. It can therefore be seen that, as the geometry changes, the stress intensity curve varies and thus it is necessary to have a suitable calibration curve for a particular loading geometry. A number of these are shown in Figs 3–5.

3 Analytical Solution

It can be seen from the results presented that, for elongated specimens, at intermediate crack lengths where the effect of the restraining block is small, the test geometry closely resembles the double cantilever beam geometry. This has an analytical solution for K under a constant applied moment which is given by,[12]

$$K = \frac{M}{d^{\frac{3}{2}}}\sqrt{\frac{12}{1-\nu^2}}$$

where M is the applied moment and d is the half width of the specimen. If we consider the equivalence of the specimens it can be shown that the

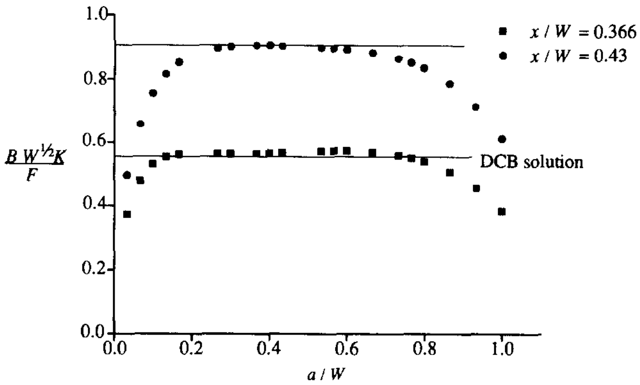

Fig. 5. Stress intensity curve for $W/L = 0{\cdot}75$ with varying loading positions.

stress intensity (per unit thickness) in the plateau region can be given by,

$$K = \frac{F}{\sqrt{W}}\left(\frac{x}{W} - \frac{1}{4}\right)\sqrt{2}\sqrt{\frac{12}{1-\nu^2}}$$

where the parameters are as shown in Fig. 1. The values obtained from the finite element analysis ($\nu = 0{\cdot}25$) and the analytical solution were compared and these showed good agreement (see Figs 3 & 5), suggesting that for elongated specimens within certain crack lengths it is not necessary to use an FE analysis to estimate the stress intensity values. For example a specimen with an aspect ratio of 0·66 and a crack with a/W ratios between 0·2 and 0·8 could be analysed using the above solution. More elongated specimens could also be analysed within the same a/W ratios using the above solution making FE analysis unnecessary.

4 Experimental

Various materials have been evaluated using this test. These materials have ranged from fine grained ceramics using specimens of 30 × 30 × 5 mm to concrete, rock and refractory materials with specimens of 100 × 150 × 20 mm. A typical loading arrangement is shown in Fig. 6. The sample was

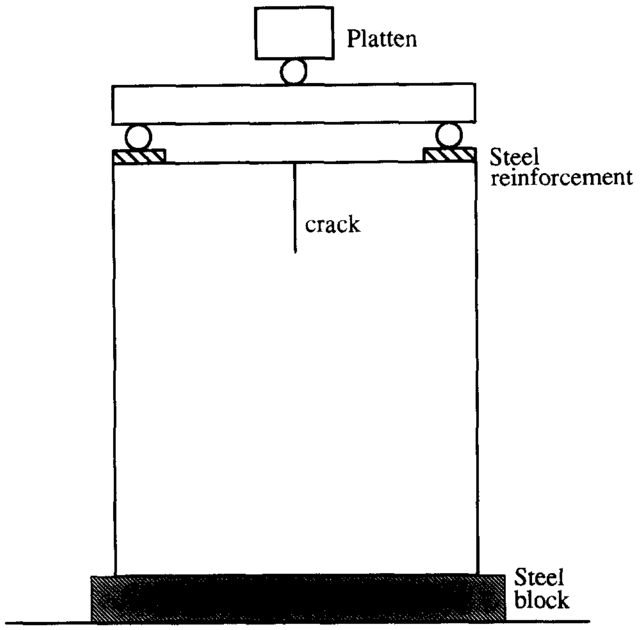

Fig. 6. The loading arrangement.

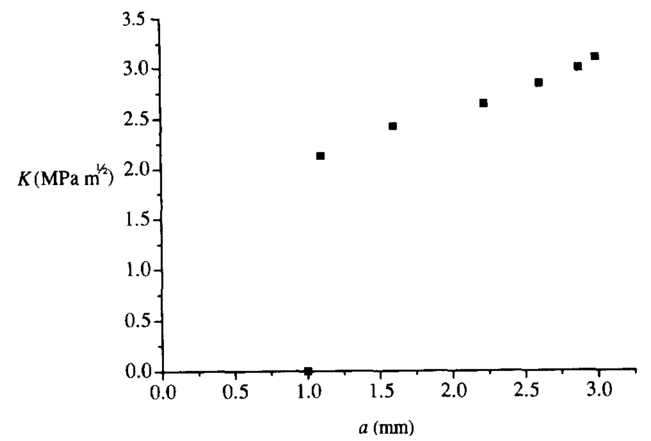

Fig. 8. *R*-curve for Pennant sandstone (sample size: 60 × 60 × 30 mm; initial crack length: 10 mm).

bonded with epoxy adhesive to a steel block and an initial crack was introduced simply by use of a saw, the thickness of which was chosen to be suitable for the material and size of sample, ranging from a fine 200 μm blade for glass-based ceramics to a 0·75 mm hacksaw blade for concrete and refractory specimens. The initial length of the crack was such that it was within the stable region of the stress intensity curve. The load is applied near the corner of the specimen, at a set distance from the initial crack using a set of rollers held in place by a jig in order to ensure even distribution of the load and allow for any imperfections in the geometry of the specimen. In practice it was also necessary to reinforce the corners of the specimen using steel blocks in order to prevent local crushing which occurs at the high loads required for crack propagation at longer crack lengths.

The specimens were loaded using a screw-driven compression machine, the load being applied incrementally and the crack length measured for a given load. The crack length was measured using a number of methods including by eye, use of a travelling microscope and also by the change in the resistance of an electrical paint film applied to the surface of the specimen. From the crack length and applied load, using the calibration curves established in Section 2 it is possible to calculate the stress intensity at the crack tip and thus form the *R*-curve. Previous work on concrete has suggested toughnesses ranging from 0·2 MPa $m^{1/2}$ [13] to 2·5 MPa $m^{1/2}$ [14] and the results obtained from this test (Fig. 7) lie within this range. The results obtained for Pennant sandstone (Fig. 8) agree well with Meridith[15] who reported a toughness of 2·56–2·66 MPa $m^{1/2}$. Results obtained from a soda lime glass show a constant toughness of 0·63 MPa $m^{1/2}$ which agrees well with results in the literature.[13]

5 Conclusions

A new method for determining the fracture toughness as a crack propagates has been shown to

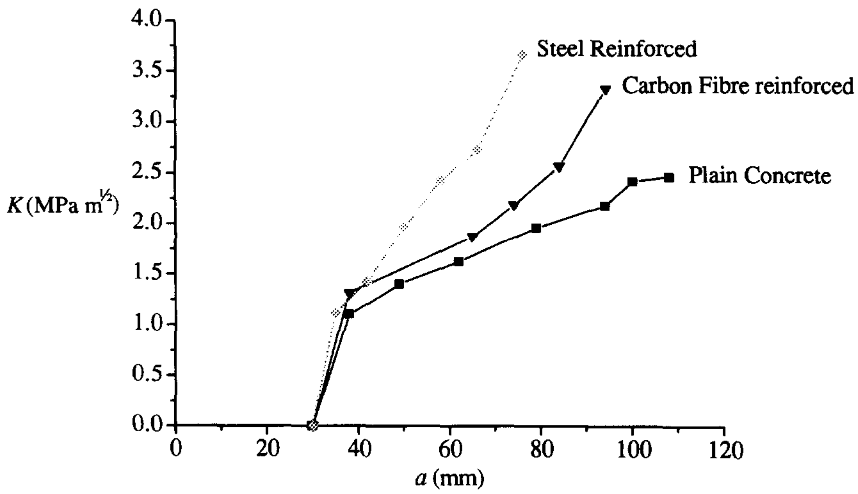

Fig. 7. *R*-curves for concrete with various types of reinforcement (sample size: 150 × 100 × 20 mm; initial crack length: 30 mm).

work on a variety of materials, with samples of varying geometries. The test, while closely resembling the double cantilever beam test, avoids many of the problems inherent in the DCB test, and can offer increased stability for materials with slight *R*-curve behaviour, by suitable choice of specimen shape and initial crack length.

Stress intensity curves can be calculated by the use of finite elements, the results of which show good agreement with an analytical solution based upon the double cantilever beam test geometry.

Acknowledgements

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