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Geometry effects and statistical analysis of mode I fracture in guiting limestone

M.R.M. Aliha [a,c], M. Sistaninia [b], D.J. Smith [c], M.J. Pavier [c], M.R. Ayatollahi [b,*]

[a] Welding and Joining Research Center, School of Industrial Engineering, Iran University of Science and Technology (IUST), Narmak, 16846-13114 Tehran, Iran
[b] Fatigue and Fracture Laboratory, School of Mechanical Engineering, Iran University of Science and Technology (IUST), Narmak, 16846-13114 Tehran, Iran
[c] Department of Mechanical Engineering, University of Bristol, BS8 1 TR, UK

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ABSTRACT

This paper describes the results of a series of tests conducted to study the mode I fracture toughness of a sedimentary soft rock (Guiting Limestone). Two types of tests were used: centre cracked Brazilian disc specimens subjected to diametral compression and edge cracked semi-circular bend specimens subjected to three-point bend loading. The experimental results showed that there was a noticeable difference between the sets of test data and that the mode I fracture resistance was significantly dependent on the geometry and loading conditions of the test specimen. The difference in fracture resistance between the tested specimens can be related to the effect of the higher order stress term A_3. A modified form of the maximum tangential stress which takes into account the effects of A_3 was shown to provide a good comparison with the test results. Furthermore, a statistical analysis demonstrated that the modified criterion is also able to predict the statistical parameters for each set of test data.

1. Introduction

The mode I or opening mode fracture toughness (K_{Ic}) is an important parameter for characterizing the fracture behaviour of rock and is a parameter used in many applications such as mining, tunnelling, underground excavation, rock cutting, hydraulic fracturing and blasting. The International Society for Rock Mechanics (ISRM) has suggested some standard procedures and test specimens for determining the mode I fracture toughness of rock including: the chevron notched round bar in bending; the chevron notched short rod in splitting and the chevron notched disc in diametral compression [1,2]. Due to the convenience of specimen preparation from rock cores, there is a preference to use cylindrical or disc shape samples for conducting fracture experiments. For example the centre cracked Brazilian disc (BD) specimen subjected to diametral compression [3–7] and the edge cracked semi circular bend (SCB) specimen under three-point bend loading have been used frequently to measure K_{Ic} for rock materials [6–10]. Although it may be expected that the measured fracture toughness is independent of the geometry and loading conditions in the test, previous studies have shown different test methods do not give consistent fracture toughness values (e.g. [6]). On the other hand, because of the inherent heterogeneity, porosity, bedding planes, texture, composition and anisotropy of rock materials, the presence of a large scatter in the experimental data is inevitable and makes firm conclusions difficult. In this research, the mode I fracture toughness of a soft limestone was studied experimentally and theoretically using both BD and SCB specimens. The test data were also investigated using a probabilistic analysis. It is shown in this paper that the apparent mode I fracture toughness of a given rock material tested with different configurations, crack lengths and loading types is not the same and may vary in a wide range. However, it is demonstrated that the differences between the fracture test data obtained from BD and SCB specimens can be characterised by higher order terms in the stress series expansion for mode I loading.

2. Experimental procedure

The geometry and loading conditions for the BD and SCB specimens used for mode I fracture tests are shown in Fig. 1. The BD specimen is a disc of radius R and thickness t which contains a centre crack of length $2a$. When the compressive force F is applied in the crack direction the crack tip conditions are equivalent to pure mode I. Similarly, the SCB specimen is a semi-disc of radius R and thickness t having a vertical edge crack of length a. Pure mode I deformation is obtained in the SCB specimen under three-point bending with a loading span of $2S$. The BD and SCB specimens can also be used for mixed mode I/II fracture

* Corresponding author. Tel./fax: +98 21 77240488.
E-mail address: m.ayat@iust.ac.ir (M.R. Ayatollahi).

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studies simply by changing the crack orientation relative to the loading direction [6,7,11–15]. Using the BD and SCB specimens, mode I fracture toughness experiments were performed on Guiting limestone, a homogenous sedimentary soft rock composed of calcite. Guiting limestone is porous, beige in colour and is widely available in the UK. For the sake of comparison, the same dimensions were used for the diameter and the thickness of the BD and SCB specimens: $2R=100$ mm and $t=30$ mm. The BD specimens were manufactured and then tested with a constant crack length but for the SCB specimens two different sets of crack lengths and loading support distances ($2S$) were used indicated hereafter by SCB-1 and SCB-2. Table 1 summarises the geometries of the BD and SCB specimens used in this work. A total number of 40 samples were prepared from a rock core. A fret saw with a thin saw blade of 0.4 mm thickness was used to introduce cracks into the specimens. The prepared samples were then tested using a 25 kN servo hydraulic Instron test machine. The tests were carried out under displacement control conditions with a constant crosshead speed of 0.08 mm/min. The BD samples were loaded using two flat platens and the SCB specimens were tested using a three-point bend fixture with the loading spans ratios (S/R) given in Table 1.

Fig. 2 shows the loading arrangements for sample BD and SCB specimens. For each specimen the load versus displacement curve was recorded until the final fracture. It was observed that all the samples showed a linear curve and fractured suddenly in a brittle manner initiating from the crack tip.

The critical stress intensity factor at the onset of fracture is denoted in this paper by the fracture resistance (K_{If}). Unlike the mode I fracture toughness (K_{Ic}), which is assumed to be a constant material property, K_{If} may be dependent on the type of specimen. The fracture resistance (K_{If}) of each tested BD and SCB specimen was determined from the following equations:

$$K_{If} = Y_{BD}\frac{F_c}{Rt}\sqrt{\frac{a}{\pi}} \quad \text{for BD specimen} \tag{1}$$

$$K_{If} = Y_{SCB}\frac{F_c}{2Rt}\sqrt{\pi a} \quad \text{for SCD specimen} \tag{2}$$

where F_c is the fracture load and Y_{BD} and Y_{SCB} are the geometry factors for the BD and SCB specimens. Eqs. (1) and (2) have been frequently used in the past for obtaining the fracture resistance of brittle or quasi brittle materials like rocks, polymers, concrete and asphalts by several researchers (e.g. [3,5–10,16–20]). The geometry factors are functions of the crack length ratio (a/R) and the span to diameter ratio (S/R). Analytical and numerical solutions are available for obtaining Y_{BD} and Y_{SCB} [5,16,20,21]. In this work the geometry factors were determined from Ayatollahi and Aliha [16] as $Y_{BD}=1.135$ (for $a/R=0.3$), $Y_{SCB\text{-}1}=2.05$ (for $a/R=0.3$ and $S/R=0.43$) and $Y_{SCB\text{-}2}=8.4$ (for $a/R=0.6$ and $S/R=0.8$).

Fig. 3 shows fracture toughness values obtained from each test result and their mean values for each of the three test geometries. While the scatter of results for each set of data was relatively large, the averages of K_{If} for the SCB-1 and SCB-2 specimens were noticeably higher than the BD results. The average K_{If} of the tested limestone is 0.24 MPa$\sqrt{m}$ for the BD, 0.33 MPa$\sqrt{m}$ for the SCB-1 and 0.37 MPa$\sqrt{m}$ for the SCB-2 specimens. Thus, these results show the noticeable influence of the geometry and loading conditions of the test specimen on the mode I fracture resistance of a given rock material. The main aim of the remainder of this paper is to demonstrate that the geometry effects on mode I fracture tests can be explained theoretically if a more accurate description for the stress field around the crack tip is used. In the next section, a theoretical model is presented for taking into account the geometry effects on mode I fracture results.

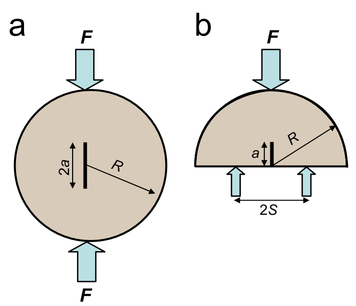

Fig. 1. BD and SCB specimens subjected to mode I loading; F is the applied force, R is radius of discs, a is the crack length and S is the half span length for the SCB specimen.

Table 1
Dimensional specifications of the test specimens.

Specimen	R (mm)	a (mm)	t (mm)	a/R	S/R	Number of test samples
BD	50	15	30	0.3	–	15
SCB-1	50	15	30	0.3	0.43	15
SCB-2	50	30	30	0.6	0.8	10

3. Fracture theory

A stress-based fracture criterion will be employed here to investigate the reason for the differences observed between mode I fracture resistance results of a BD and two SCB configurations. The stress field in the vicinity of a crack tip for mode I loading can

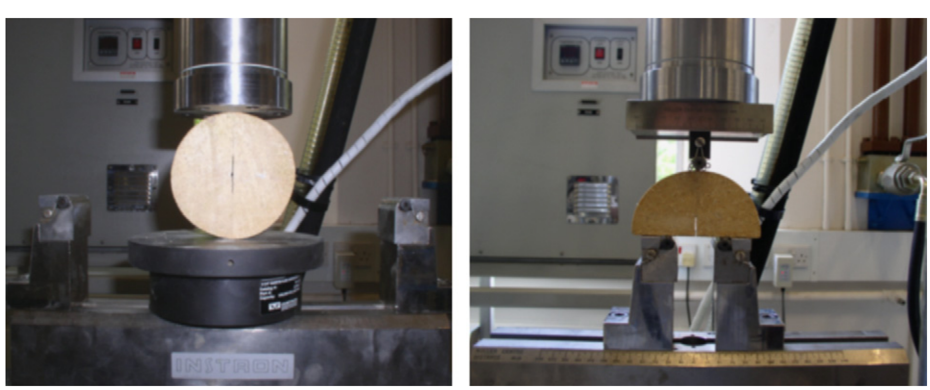

Fig. 2. Loading arrangements for the BD and SCB specimens.