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Fracture toughness study for a brittle rock subjected to mixed mode I/II loading

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Abstract

A semi-disk specimen containing an angled edge crack has been used in the past for conducting fracture tests on a brittle rock named Johnstone [Fracture testing of a soft rock with semi-circular specimens under three-point bending. Part 2—mixed mode. Int J Rock Mech Min Sci Geomech Abstr 1994b;31(3):199–212]. The test specimen is appropriate for investigating brittle fracture when the rock samples are subjected to the combined effects of tension and shear along the crack line. However, the experimental results reported in Lim, Johnston, Choi, Boland [Fracture testing of a soft rock with semi-circular specimens under three-point bending. Part 2—mixed mode. Int J Rock Mech Min Sci Geomech Abstr 1994b;31(3):199–212.] are inconsistent with all of the well-known theoretical criteria available for predicting mixed mode brittle fracture. In this paper, a modified criterion is used to provide accurate predictions for the reported experimental results. The modified criterion makes use of a three-parameter model (based on K_I, K_{II} and T) for describing the crack tip stresses. It is shown that the non-singular stress term T has a significant role when the rock fracture tests are conducted on the semi-disk specimens.

Keywords: Rock; Crack; Mixed mode I/II; Fracture toughness; Fracture criterion

1. Introduction

Cracked rock masses are usually subjected to complex loading conditions. Because of arbitrary orientation of cracks relative to the loading directions, brittle fracture in rocks may occur due to a combination of two major fracture modes, i.e. crack opening mode (mode I) and crack sliding mode (mode II). Therefore, many rock fracture researchers have investigated the fracture of rocks under mixed mode I/II loading. The mixed mode fracture toughness is a measure of the material resistance against the crack propagation when the crack is subjected to mixed mode I/II loading. In many practical applications of rock engineering, such as rock excavation, tunnelling, rock cutting process, hydraulic fracturing, rock slope stability analysis, rock blasting, etc.; fracture toughness of rock material is an important parameter for rock failure analysis or for increasing the performance of rock cutting tools. The extraction of complete envelopes for mixed mode fracture toughness require test specimens which allow fracture tests under pure mode I, pure mode II and a wide range of intermediate mixed modes I and II loading. There are a number of methods and test specimens for obtaining the fracture toughness of brittle materials for all mode mixtures from pure mode I to pure mode II [1–16]. The centrally cracked Brazilian disk specimen subjected to diametral compressive load [2–5], the single edge cracked rectangular plate subjected to four-point bending [6–9], the compact shear and tension specimen [10–12] and the edge cracked semi-circular specimen in three-point bending [1,13–16] are to name a few. These specimens have been used by rock fracture investigators to obtain mixed mode I/II fracture toughness for geomaterials such as rocks. However, no standard procedure has been established for mixed mode fracture testing. Indeed, the available standards for evaluating the fracture toughness of rock

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materials suggested by the International Society of Rock Mechanics (ISRM) are confined only to pure mode I fracture toughness tests [17,18].

Semi-circular bend (SCB) specimen (see Fig. 1) is one of the favorite test configurations for conducting mixed mode fracture toughness experiments on rock materials. As shown schematically in Fig. 1, the specimen is a semi-circle with a radial edge crack of length a introduced from the center of semi-circle. For conducting fracture tests, the specimen is located inside the three-point bend fixture and is loaded by a vertical compressive force (P) up to the fracture load. Different combinations of modes I and II can be provided by changing three parameters: a/R (the ratio of crack length over the semi-disc radius), S/R (the ratio of half-distance between two bottom supports over the semi-disc radius) and β (direction of crack line relative to the vertical direction). When β is zero the specimen is subjected to pure mode I, independent of a/R and S/R. By increasing β, various mode mixities are achieved. Pure mode II deformation, takes place in specific angles β depending on a/R and S/R.

Simple geometry of specimen, little machining operations, application of compressive loads rather than the tensile loads, ability of conducting the fracture toughness tests in the full range from pure mode I to pure mode II, easy test set-up procedure with common fracture toughness testing apparatus, simple data requirement from test procedure, and the ability to prepare specimens from typical rock cores, are the major advantages of the SCB specimen. Therefore, this specimen has been frequently used by rock fracture investigators for conducting fracture toughness tests [1,13,15]. For example, Lim et al. [1] carried out a large number of mixed mode fracture tests on a synthetic soft rock using the SCB specimens. More details of their experiments are given in the next section. However, the results obtained from their fracture tests on the SCB specimens could not be appropriately interpreted by any of the well-known theoretical fracture criteria available in the literature. For instance, the maximum tangential stress (MTS) criterion [19] fails to predict the test results, especially for mode II dominated loading conditions. It is shown in this paper that improved predictions for mixed mode fracture toughness of this rock can be achieved if a modified MTS criterion is used. In the modified MTS criterion three parameters ($K_{\mathrm{I}}, K_{\mathrm{II}}, T$) are used for evaluating the fracture load in cracked specimens, where K_{I} and K_{II} are the modes I and II stress intensity factors, and T is a constant term in the series expansion for stresses around the crack tip. In the following sections, first a brief review of the experimental procedure employed by Lim et al. [1,16] to conduct mixed mode I/II fracture toughness tests on SCB specimens is presented. Then the mixed mode fracture toughness data obtained from the fracture tests are compared with those estimates obtained by using the modified MTS criterion.

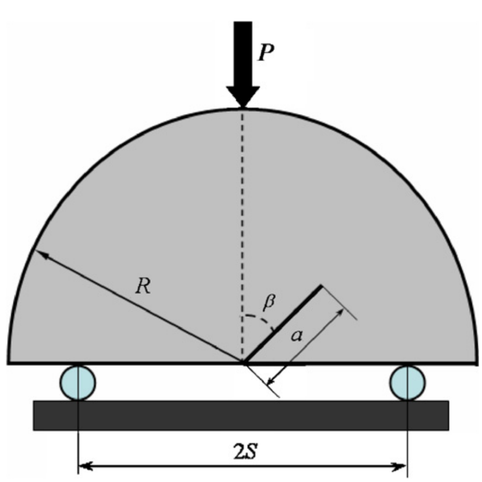

Fig. 1. Cracked semi-circular bend (SCB) specimen.

2. Review of fracture toughness tests

Lim et al. [1,16] studied mixed mode I/II fracture in a water saturated synthetic soft rock called Johnstone using the SCB samples. They used a large number of SCB specimens to conduct modes I, II, and mixed mode I/II fracture toughness experiments. For mixed mode I/II fracture tests [1] the following geometry parameters were used: $R = 49$ mm, $S = 24.5$ mm and $a = 17$ mm, giving $a/R = 0.35$ and $S/R = 0.50$. The thickness and the saturated water content for mixed mode samples were 20 mm and 17.7%, respectively. For mode I tests, Lim et al. [16] investigated the effects of different parameters such as the diameter and the thickness of specimen, the crack length, the ratio of S/R and the saturated water content on fracture toughness of the tested material. While the reported values of mode I fracture toughness (K_{Ic}) for Johnstone varied generally between 0.9 and 2.8 MPa mm$^{1/2}$ [16], the average value obtained from tests samples identical to the mixed mode samples was 2.2 MPa mm$^{1/2}$.

Different mode mixtures could be provided in the SCB specimen by changing the crack inclination angle β. The critical stress intensity factors for the SCB specimen can be written in terms of the fracture load P_{cr} as

$$K_{\mathrm{If}} = \frac{P_{\mathrm{cr}}}{2Rt}\sqrt{\pi a}\,Y_{\mathrm{I}}(a/R, S/R, \beta), \tag{1}$$

$$K_{\mathrm{IIf}} = \frac{P_{\mathrm{cr}}}{2Rt}\sqrt{\pi a}\,Y_{\mathrm{II}}(a/R, S/R, \beta), \tag{2}$$

where K_{If} and K_{IIf} are the modes I and II stress intensity factors corresponding to the onset of brittle fracture, and t is the thickness of specimen. The modes I and II geometry factors Y_{I} and Y_{II} are functions of $(a/R, S/R, \beta)$. The values of Y_{I} and Y_{II} for the SCB specimen have been calculated in the past by analytical and numerical techniques [13,20,21]. Lim et al. [20] and more recently Ayatollahi and Aliha [21] have analyzed this specimen using a large number of finite element models for various