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Experimental analysis of mixed mode crack propagation in brittle rocks: The effect of non-singular terms

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ABSTRACT

The fracture behavior of Neyriz marble is investigated both experimentally and theoretically by using two different test configurations: (1) the center cracked circular disk specimen subjected to mode I loading, and (2) the edge cracked triangular samples under mixed mode loading. The experimental results show that there is a noticeable difference between the values of mode I fracture resistance obtained from these two test configurations. The aim of this paper is to justify this difference by using a modified maximum tangential stress criterion which takes into account the effects of non-singular stress terms (T-stress, A_3 and B_3) in addition to the singular terms. The same criterion is then extended to estimate the mixed mode fracture resistance of triangular specimen from the mode I fracture resistance obtained from the circular specimen. It is also shown that the criterion provides better estimates for the experimental data when uses A_3 in the calculation of the fracture process zone length.

1. Introduction

A good understanding of the mechanical behavior of rock materials is important in many practical applications of rock engineering such as construction of dams, hydraulic fracturing of gas and oil wells, tunneling, rock cutting, excavation and fragmentation. Fracture toughness is an important mechanical property in rocks and other engineering materials which describes the rock resistance against crack propagation under static loading. The cracked rock masses and structures 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). Thus, it is very useful to investigate mixed mode I/II brittle fracture in rocks. Various test specimens have been used in the past for mixed mode fracture experiments. The edge cracked beam subjected to three or four point bend loading [1], the compact tension-shear specimen [2], the center cracked circular disk (CCCD) specimen [3], the cracked semi-circular specimen under three-point bending [4] and the edge cracked triangular specimen [5] under three point bending are some of the specimens used frequently for mixed mode fracture tests on rocks. The experimental results in previous studies have indicated that the values of fracture resistance obtained from these test configurations depend significantly on the specimen type not only in pure mode I, but also in mixed mode loading. For example, Aliha et al. [6] showed that the fracture resistance obtained from the semi-circular bend (SCB) specimen under mixed-mode loading is less than the

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Nomenclature

a	crack length in ECT specimen and half-crack length in CCCD specimen
A_3, B_3	constant coefficients of the third terms in the Williams series expansion
A_3^*, B_3^*	non-dimensional forms of A_3 and B_3
BD	Brazilian disk specimen
CZM	cohesive zone model
CCCD	center cracked circular disk specimen
ECT	edge cracked triangular specimen
FEOD	finite element over-deterministic method
f_t	tensile strength of material
K_I	mode I stress intensity factor
K_{II}	mode II stress intensity factor
K_I^*, K_{II}^*	non-dimensional forms of K_I and K_{II}
K_{If}	mode I fracture resistance
K_{IIf}	mode II fracture resistance
L	characteristic dimension
MTS	maximum tangential stress criterion
MMTS	modified MTS criterion
P	applied load
P_f	fracture load
R	radius of CCCD specimen
S	half the distance between the bottom supports in ECT samples
SED	strain energy density
r, θ	crack tip co-ordinate
r_c	critical distance from crack tip
B	specimen thickness
T	T-stress
T^*	non-dimensional form of T
TCD	theory of critical distance
w	width of ECT specimen
α	crack inclination angle
$\sigma_{\theta\theta}$	tangential stress component
$\sigma_{\theta\theta c}$	critical tangential stress

one calculated from the CCCD samples. A similar study by Khan and Al-Shayea [7] revealed that there is a considerable difference between the values of fracture resistance in a Saudi Arabian limestone determined using the same test configurations (SCB and CCCD). Therefore, geometry effect can be considered as an important issue when dealing with mode I or mixed-mode fracture in rocks.

Meanwhile, there are several criteria for predicting the onset of mixed mode fracture in brittle materials from their mode I fracture resistance K_{If}. The maximum tangential stress (MTS) criterion [8], the maximum energy release rate or G criterion [9], the minimum strain energy density (SED) criterion [10] and the cohesive zone model (CZM) [11] are to name a few. These criteria are not able to consider the geometry effects on mixed mode fracture behavior of rocks, because each criterion proposes an individually unique curve for predicting the onset of fracture for any given rock material.

The main objective of this paper is to present a procedure for predicting the mixed mode fracture resistance of rocks and other similar geo-materials by considering the geometry effects. The procedure is based on a modified MTS criterion which takes into account three higher order terms T, A_3 and B_3 in the Williams series expansion of the crack tip stresses in addition to the singular term. In order to assess the proposed procedure, the mode I fracture resistance of Neyriz marble is determined experimentally using two different test configurations. The first test configuration is the center cracked circular disk (CCCD) specimen subjected to diametral compression and the second one is the edge cracked triangular (ECT) sample under three-point bend loading which has been suggested recently by Ayatollahi et al. [5]. It is shown that there is a significant difference between the values of mode I fracture resistance obtained from these two test configurations. It is also aimed to interpret this discrepancy by using the modified MTS (MMTS) criterion [12] extended to mixed mode loading. Moreover, the mixed mode fracture behavior of Neyriz marble obtained from the ECT specimens with different crack inclination angels is investigated by the MMTS criterion. In order to use the MMTS criterion, the coefficients of higher order terms in stress field around the crack tip (T, A_3 and B_3) should be determined. Since the CCCD specimen has been frequently employed for investigating mixed-mode fracture in rocks, the dimensionless form of the higher order parameters are calculated comprehensively for the