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Fracture prediction of rocks under mode I and mode II loading using the generalized maximum tangential strain criterion

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ABSTRACT

The effects of specimen geometry on mode I and mode II fracture toughness (i.e., K_{Ic} and K_{IIc}), and the ratio of K_{IIc} to K_{Ic} for a given rock material were derived on the basis of a generalized maximum tangential strain (GMTSN) fracture criterion, in which the effects of T-stress and radial stress on rock fracturing can be taken into consideration. To verify these theoretical predictions, laboratory tests using semi-circular bend (SCB) and center-cracked circular disc (CCCD) specimens were conducted. Experimental results indicate that the GMTSN criterion is capable of estimating the geometry dependence of K_{Ic} and K_{IIc}, the ratio of K_{IIc} to K_{Ic} and the fracture initiation angle of rocks. Moreover, the GMTSN criterion can provide better estimates for the experimental results than some other frequently-used fracture criteria. In addition, our study reveals that the SCB fracture test using asymmetric bottom supports can be identified as a suitable testing method to estimate the upper bound of mode II fracture resistance.

1. Introduction

Rock fractures are often encountered in a large number of rock engineering activities, such as mining, tunneling and hydro-electric projects. On one hand, to achieve safe and efficient completion of the engineering projects, rock engineering structures are often designed to have enough capability to avoid occurrence of catastrophic fracture; on the other hand, in oil and gas exploitation, more fractures/cracks are expected to be generated in rocks to increase production. Therefore, understanding the rock fracture mechanism is important, and the rock fracture mechanics has thus been established and widely used in engineering applications [1,2].

In fracture mechanics, the critical stress intensity factor (SIF), also known as fracture toughness (K_c), can reflect the resistance of a material against fracture propagation and is thus widely investigated as a material property. It can be further divided into three basic categories according to different modes of loading. Mode I loading (i.e., tension/opening mode) tends to move cracks away from each other while driving the crack along their normal direction; mode II denotes sliding/in-plane shear mode, where crack faces slide with respect to each other along the direction perpendicular to the crack front; and mode III corresponds to tearing/out-of-plane shear. Accordingly, modes I, II and III fracture toughness (i.e., K_{Ic}, K_{IIc} and K_{IIIc}) can be applied as basic material parameters to classification of rock mass quality, numerical modelling of rock fracture process, and stability assessment of rock structures.

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Nomenclature

a	crack length
B	biaxiality ratio
CB	chevron bend
CCCD	center-cracked circular disc
CCNBD	cracked chevron notched Brazilian disc
E	Young's modulus
GMSED	generalized minimum strain energy density
GMTS	generalized maximum tangential stress
GMTSN	generalized maximum tangential strain
ISRM	International Society for Rock Mechanics
K_{eff}	effective stress intensity factor
K_I, K_{II}, K_{III}	modes I, II and III stress intensity factor
K_{Ic}, K_{IIc}, K_{IIIc}	modes I, II and III fracture toughness
K_{Ic}^*, K_{IIc}^*	reference mode I and mode II fracture toughness
m, n	parameters related to Young's modulus and Poisson's ratio
MSED	minimum strain energy density
MTS	maximum tangential stress
MTSN	maximum tangential strain
P	load on specimen
P_{max}	maximum load
R	radius of specimen
r_c	critical distance from the crack tip
S_1, S_2	distances between bottom supports and crack plane
SCB	semi-circular bend
SIF	stress intensity factor
SR	short rod
t	thickness of specimen
T	T-stress
T^*	normalized T-stress
v	Poisson's ratio
Y_I, Y_{II}	normalized mode I and mode II stress intensity factor
α	normalized critical distance
β	crack inclination angle
σ_{rr}	radial stress
σ_t	tensile strength
$\sigma_{\theta\theta}$	tangential stress
$\varepsilon_{\theta\theta}$	tangential strain
θ_0	fracture initiation angle

Most fracture modes in rocks are dominated by mode I, mode II, or the mixed mode I/II [3–5]; therefore, the determination of K_{Ic} and K_{IIc} of rocks has attracted much research attention. Many specimen geometries and laboratory techniques have been developed to quantify K_{Ic} or K_{IIc} of rocks, including the chevron bend (CB) specimen [6,7], the short rod (SR) specimen [6,8,9], the cracked chevron notched Brazilian disc (CCNBD) specimen [10–15], the edge-cracked semi-circular bend (SCB) specimen [16–25], the cracked chevron notched semi-circular bend specimen [26–30], the center-cracked circular disc (CCCD) specimen [31–35], the edge-cracked four-point or three-point bend specimen [36–40], the diametrically compressed ring specimen [41], the edge-notched disc bend specimen [42] and the single V-notched ring specimen [43]. Among these specimens, SCB and CCCD have relatively simple geometries, fracture processes of them can often be simplified as two-dimensional problems, and the SIF calculations are comparatively easy. Most importantly, laboratory experiments using SCB and CCCD specimens can easily be used to determine both K_{Ic} and K_{IIc} as well as mixed mode I/II fracture toughness [44].

Although K_{Ic} and K_{IIc} are often applied as constant material properties independent of the test specimen and loading condition, significant differences are often observed in K_{Ic} or K_{IIc} results of the laboratory-scale rock specimens with different geometries or loading schemes [44–46]. To explain the geometry dependence of K_{Ic} or K_{IIc}, and to predict the fracture onset of a rock structure, many fracture criteria and theoretical models have been proposed [47–62]. Among them, some nonlocal theories developed by integrating T-stress [63] into conventional fracture criteria (e.g., the conventional maximum tangential stress (MTS) criterion [64] and the conventional minimum strain energy density (MSED) criterion [65]), have recently been demonstrated to be praiseworthy for mixed mode I/II (including mode I and mode II) fracture evaluation of rocks. Ayatollahi and his co-researchers have conducted valuable works on the generalized MTS (GMTS) criterion [66,67] and the generalized MSED (GMSED) criterion [68,69], taking the T-stress into consideration. Using the GMTS criterion, they provided