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Numerical study on time dependent and time independent fracturing processes for brittle rocks

Xiang Li [a,*], Heinz Konietzky [b], Xibing Li [a]

[a] School of Resources and Safety Engineering, Central South University, Changsha 410083, Hunan, China
[b] Chair for Rock Mechanics, Geotechnical Institute, TU Bergakademie Freiberg, Gustav-Zeuner-Str. 1, 09596 Freiberg, Germany

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ABSTRACT

Based on the physical observations of fracturing processes in brittle rocks, numerical modeling schemes are proposed considering material heterogeneity and initial microflaws at the element scale. Linear elastic fracture mechanical theory is adopted to define the mechanical conditions of a microcrack within each element, where failure criterion based on stress intensity factor is introduced. The kink model and wing crack propagation model are developed to describe the initiation and growth of microcracks. Numerical simulations are implemented under distinct loading types, where factors influencing model response are studied. Typical fracture patterns are observed under distinct external loads. The numerical models are able to reproduce the fracturing process of heterogeneous brittle rocks spatially and temporally. The simulation results have shown good agreement with laboratory observations. Conclusions were drawn and possible future work is discussed for the improvement of the current model.

1. Introduction

The existence of microflaws (microcracks) in rocks, such as pores, voids and mineral grain boundaries, is known to have significant influence on their mechanical behavior [1]. In fact, the inelastic response of such quasi-brittle materials including rock, concrete and ceramic under load is explained by the microcracking process involving initiation, propagation and coalescence of microcracks [2]. The coalesced microcracks finally form macroscopic fractures which lead to the loss of load bearing capacity and the eventual failure of the material. The above mentioned process is observed and widely acknowledged in both short and long term inelastic deformation and fracturing mechanisms of brittle rock [3–6]. Considerable constitutive models have been established to investigate the failure process of rock [7]. These models are generally divided into phenomenological models [e.g. 8–11] and micromechanics-based models [e.g. 12–27]. Phenomenological models are characterized by empirical internal variables and can be calibrated to fit the experiments, however, the physical mechanisms of the fracturing process are not accounted for. Whereas micromechanical based models are able to consider micro-mechanisms such as microcrack growth together with microscopic kinetics.

In this study, micromechanical numerical models are established to simulate both time dependent and time independent fracturing processes, up to the final macroscopic failure (formation of macroscopic tensile crack or shear band) of brittle rock. It is assumed in this modeling approach that the final failure of the rock is the result of the partially parallel growth and

* Corresponding author.
E-mail address: lixiang2006lixiang@hotmail.com (X. Li).

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Nomenclature

a	half crack length
b	shape parameter Weibull probability density function
D	diameter of the disc for Brazilian test
E	Young's modulus of a zone
G	shear modulus of a zone
K	stress intensity factor at the tip of the kink
K'	bulk modulus of a zone
K_{I}	Mode I stress intensity factor
K_{IC}	Mode I fracture toughness
K_{II}	Mode II stress intensity factor
K_{IIC}	Mode II fracture toughness
K_{ISO}	component of stress intensity factor derived from the two wing cracks
K_{SLI}	component of stress intensity factor derived from the sliding of the initial main crack
K_{TEN}	component of stress intensity factor derived from the tensile normal stress on the main crack
l	length of each wing crack
l_{eq}	wing crack's equivalent length
n	stress corrosion index
P	external line load in Brazilian test
R	gas constant (Boltzmann constant)
T	absolute temperature
u	activation energy
v	crack growth velocity
β	main crack's orientation to the abscissa
θ	kink angle
θ'	angle between the main crack and the wing crack
θ_1	kink angle at maximum circumferential stress
λ	scale parameter in Weibull probability density function
μ	Poisson's ratio of a zone
μ'	friction coefficient
υ_{o}	material constant
σ_{eff}	effective shear stress on the main crack
σ_{H}	minor principal stress applied along the abscissa on one zone
σ_{n}	normal stress on the main crack
σ_{t}	shear stress on the main crack
σ_{V}	major principal stress applied along the ordinate on one zone
σ_{x}	tensile stress along the loading line of the plane disc in Brazilian test
σ_{XX}	stress along the abscissa on one zone
σ_{YY}	stress along the ordinate on one zone
τ	shear stress on one zone
τ_{i}	shear stress on the main crack

coalescence of many initially existing microcracks at the grain size level, rather than the growth of one or only a few single cracks. We base our model on the linear elastic fracture mechanical theory (LEFM) [e.g. 28], considering heterogeneity. For the time dependent fracturing process, stress corrosion and Charles theory are adopted to describe the subcritical growth of microcracks. The simulation scheme is developed for cohesive granular material such as rocks, which consists of mineral grains of different shapes, sizes, and mechanical properties, such as strength and stiffness.

2. Numerical modeling approach

In this section, the simulation approach for the established model is presented. The prescription of heterogeneity is described. The time independent and dependent model schemes are also introduced in detail.

2.1. Heterogeneity in macroscopic model

As an ensemble of distinct minerals and cementitious materials, natural rock is well accepted as a heterogeneous material [16,29], where the properties vary in different locations at grain size scale. The mechanical response of rock sample is greatly influenced by this material discontinuity together with structural heterogeneities, such as grain sizes and initial microflaws.

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