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A numerical study of brittle failure in rocks with distinct microcrack characteristics

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ABSTRACT

A numerical model is presented to reproduce the stress induced fracturing process of brittle rocks. Material heterogeneity at the zone level of the model is considered, and distinct initial microcrack lengths and orientations are also included. The rock material is prescribed with a Weibull distribution, and the microcrack lengths and orientations are defined by distinct distribution functions. Stress intensity factor approach is adopted to characterize the stress condition of the microcracks, and is used as a failure criterion for the zones of the model. The mechanical response of rock specimens is investigated on models under different external loading conditions. Obvious nonlinear characteristics before the peak strength can be observed in models under uniaxial compression. Consistency can be found between simulation results and lab test data. The influence of microcrack conditions and heterogeneity levels on the simulation result is also investigated. The macroscopic failure modes of models are studied with different distributions of initial microcracks, and correlations are found between the microcrack conditions and fracturing processes. Especially, scattered zones and obscure fracture patterns are produced in the model defined by exponential and uniform distribution, compared with clear shapes of macroscopic fractures observed in models defined by normal or lognormal distributions. The simulations also show that the differences in the mean value of microcrack orientations obeying certain distribution result in distinct macroscopic fracture patterns, from shear bands at lower mean orientations to tensile fractures at higher mean orientations. Typical fracture patterns observed in laboratory are successfully reproduced in the model, which demonstrates the capability of the model in reproducing faithful rock behaviors through prescribing specific microscopic characteristics.

1. Introduction

It is widely accepted that the inelastic deformation of rock under external load is associated with the complex fracturing process involving initiation, propagation and coalescence of microcracks, which are pervasive in rocks.[1,2] Based on the consensus, the failure mechanism of rock has long been a focus of study for scientists and engineers. Gallagher et al.[3] studied microfracture propagation of sandstone with established two-dimensional photomechanical model, and used it to obtain the relation between stress concentrations of grains and propagation of microfracture. Costin[4] proposed a continuum model to describe the time dependent and time independent deformation and failure of brittle rock, where a criterion for crack growth is determined. Eberhardt[5] studied the influence of the mineralogy on the initiation of cracking based on the observations in uniaxial compression tests for brittle rocks. Bobet and Einstein,[1] Tang et al.[6] and Wong et al.[7] studied the multiple pre-existing fracture or flaws coalescence in rock-type materials under uniaxial compression. Golshani et al.[8] developed a micromechanics-based continuum damage model of brittle rock to analyze the macroscopic mechanical response of rock and predict numerically the changes of crack length and crack density in the inelastic deformation. Paliwal and Ramesh[9] derived an interacting microcrack damage model for brittle materials under compressive loading to predict peak stress and transition strain rate. Tang et al.[10] proposed a heterogeneous micromechanical model by applying RFPA to study the deformation and failure process of rock, and the numerical simulation results indicated that the heterogeneity has an important effect on the strength and failure characterization of rock. Shao et al.[11] proposed a micromechanical damage model by introducing subcritical damage laws to describe induced anisotropic damage in brittle rocks. Lu et al.[12] proposed a dual-scale conceptual model to analyze the time-independent fracturing evolution, where randomly oriented microcracks

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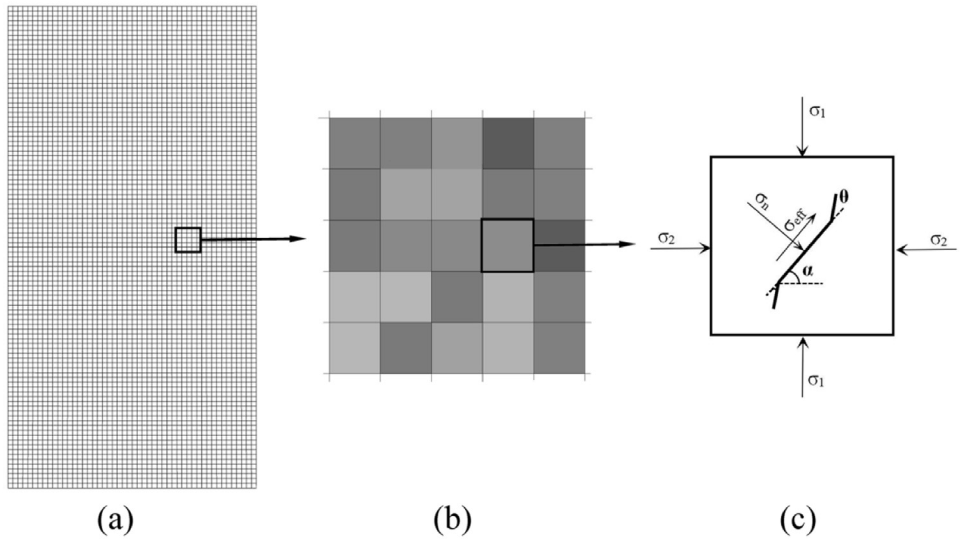

Fig. 1. Heterogeneous numerical model (modified from [23]): (a) geometry of the numerical model, (b) magnified view of certain area of the model, (c) initial microcrack propagation of a certain zone under compression.

Table 1
Material parameters.

Parameters	Value
Young's modulus E	48.1 GPa
Poisson's ratio μ	0.26
Bulk modulus K	33.40 GPa
Shear modulus G	19.09 GPa
Shape parameter β	15
Friction coefficient	0.3
Mean microcrack length / standard deviation (normal, lognormal and exponential distributions)	0.0005 / 0.0001
Mean microcrack orientation / standard deviation (normal, lognormal and exponential distributions)	45° / 1°
Microcrack orientation range (uniform distribution)	0°~180°
Mode I fracture toughness	1.88 MPa m$^{1/2}$
Mode II fracture toughness	4.87 MPa m$^{1/2}$

were included in the elements of the model.

Jia et al.[13] used Particle Flow Code (PFC 2D) to model the brittle fracture of carbonate rock under uniaxial compression, where each grain in actual rock is represented by a discrete particle and microcracks are represented by the broken bonds between particles. Based on Voronoi cells, Chen and Konietzky[14] developed a grain-based heterogeneous numerical model with the Discrete Element Method (implementation in UDEC) to simulate time-dependent fracturing process of granite, where both inter- and intra-granular fracturing can be reflected. The above investigations through tests and numerical models have been successful in grasping many of the characteristics of rock failure process under external load. However, simplifications were made in the previous studies that, the orientations were either generalized into groups in association with certain damage parameter which influences the inelastic behavior, or defined as randomly distributed. Thus, the influence of different microcrack orientations on the rock's mechanical response and resulting fracture patterns are largely overlooked.

Due to the importance of textural discontinuities (microcracks) in the failure process and mechanical behaviors of rock, the microcrack distributions should not be neglected for an accurate analysis of rock's response to load. For decades, attempts have been made in describing the microcrack distribution in the rocks. Based on the study of microcrack distributions of three types of granite, Kranz[15] proposed that initial microcrack orientations of rocks might follow normal distribution and initial microcrack lengths might satisfy lognormal or exponential distribution. Baecher[16] proposed that the microcrack length obey lognormal distribution by statistical analysis of rock mass fracturing. Dienes[17] also supported the assumption that microcrack lengths follow exponential distribution. With the inclusion of statistical distributions of microcrack lengths, Konietzky et al.[18] proposed a continuum damage model and used it as a cellular automaton to predict the life-time of rock. Li and Konietzky[19] extended the model by including the initial microcrack orientations in the modeling schemes. To reveal the effect of distinct microcrack distributions on the behavior of rock under load, this paper investigates the fracturing process of brittle rock using the developed numerical model, where the microcracks are described by the stochastic distributions reported above. In the following, the modeling schemes are first introduced, and the simulation results with distinct distributions of microcracks are given. Examples of different failure modes governed by fabric structures are also simulated to reveal the potential of the model in representing the macroscopic anisotropic phenomena in rocks.

2. Description of the numerical model

The proposed continuum damage model divides the rock specimen into elements (zones), where the microcrack lengths and orientations are described stochastically. Material heterogeneity is also implemented in the model at zone level. For one zone of the model, the mechanical behavior is thereby characterized by stochastic distributions of parameters of microscopic kinetics. When a zone is considered failed, post failure regime is applied to this zone, resulting in the total loss of shear or tensile load bearing ability for the zone. As a result, elasto-plastic stress redistributions will be caused in the region especially near the failed zone. The softening behavior of the zones can be considered as damage. In the proposed model local damage in each zone can be defined by the ratio between crack length to zone length. At the macro-scale damage can be defined as ratio between failed zone to total number of zones. The model is established using two-dimensional explicit finite difference code FLAC,[20] and the detailed modeling schemes are introduced as follows.

2.1. Assignment of material properties

To represent the heterogeneity in the rock material due to different minerals, the mechanical properties are assigned to the zones obeying Weibull distribution.[21] The Weibull distribution probability density function is expressed as: