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Micromechanical model for the rate dependence of the fracture toughness anisotropy of Barre granite

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ABSTRACT

Laboratory measurements of mode-I fracture toughness of Barre granite under a wide range of loading rates were carried out with an MTS machine and a split Hopkinson pressure bar (SHPB) system using the notched semi-circular bend (NSCB) specimen. The fracture toughness anisotropy was found to decrease with the increase of the loading rate. A micromechanics model is utilized in this work to understand this experimental observation, invoking crack–microcrack interactions. Two micromechanics models are constructed based on the microstructural investigation of Barre granite samples using the thin-section method. In both models, the rock material is assumed to be homogenous and isotropic. The main crack (i.e., the pre-crack in the NSCB specimen) and the closest microcracks are included in the numerical analysis. Numerical results show that stress shielding occurs in the model where the two microcracks form an acute angel with the main crack and the nominal fracture toughness is bigger than the intrinsic one, while stress amplification occurs in the model where the microcrack is collinear to the main crack and the nominal fracture toughness is smaller than the intrinsic one. Assuming that the intrinsic fracture toughness of the rock material has the usual loading rate dependency, we are able to reproduce the decreasing trend of the fracture toughness anisotropy as observed from experiments.

1. Introduction

Due to long-term tectonic loadings, granites are abundant with microcracks and pores, and these microstructural discontinuities are believed to be responsible for the apparent mechanical properties anisotropy including compressive strength [1], tensile strength [2] and fracture toughness [3,4]. Barre granite, as a standard rock suite by the U.S. Bureau of Mines, has been well known for its anisotropy in mechanical properties [5] and the microstructure of it has been thoroughly investigated [3,4].

The mode-I fracture toughness (K_{IC}) of rocks is a critical parameter in rock mechanics and rock engineering applications involving fracture. It is considered to be an intrinsic material property of rocks to resist crack initiation and propagation and thus has been widely investigated in the rock community. International Society of Rock Mechanics (ISRM) proposed short rod (SR) and chevron bending (CB) method in 1988 [6] and cracked chevron notched Brazilian disc (CCNBD) method in 1995 [7] to standardize the methods for static fracture toughness measurements. For the dynamic measurement, ISRM recently adopted notched semi-circular bend (NSCB) method for characterizing the dynamic mode-I fracture toughness of rocks [8]. Because most rocks are anisotropic due to tectonic stresses, a thorough research of mode-I fracture toughness on its microstructure related anisotropy is necessary.

In our previous work [9], laboratory measurements of mode-I fracture toughness of Barre granite under a wide range of loading rates were carried out with an MTS machine and a split Hopkinson pressure bar (SHPB) system using the NSCB specimen. To quantify the anisotropy, the NSCB fracture samples were fabricated along three pre-determined material symmetrical planes, resulting in six sample groups. A clear loading rate dependence of the fracture toughness anisotropy of Barre granite was observed. The fracture toughness anisotropy was found to decrease with the increase of the loading rate. The question remains to be answered is the physical reason for this observed trend of the rate dependence of mode-I fracture toughness anisotropy.

Like other granitic rocks, Barre granite has lots of pre-existing microcracks and its mechanical responses should be controlled by its microscopic structures. The phenomenon of microcracking zone near the main crack tip and its effects on the propagation

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of main crack in brittle materials such as ceramics, rocks and concretes, have been discussed by many researchers [10–12]. Existing theoretical analysis has focused on the effect of microcracking on the stress field near the main crack tip. Due to the complexity of the problem, except for a few simple cases, closed-form solutions are not available. Researchers attempted to model this problem in two perspectives. One is the continuum mechanics model, which aims at building a constitutive framework in the continuously damaged material mimicking the overall effect of microcracking [13,14]. But due to the complexity of the interacting problem, no agreement has been reached among researchers on what is the best material model to simulate the configuration of crack–microcrack interaction. The second approach considers the multiple microcracks in the microcracking zone near the tip of a main crack as discrete entities; in which case, interaction is addressed using the stress function or assumed stress state invoking the superposition principle [15–17].

Although there are many interesting discussions on the effects of stress shielding and amplification of the main crack due to the presence of microcracks, few of them have strong experimental basis. Mode-I fracture toughness (K_{IC}) measurements on four types of granites [4,18] were carried out under the standard procedure outlined by ISRM, demonstrating different levels of anisotropy. However in the above studies, an isotropic material model was borrowed to determine the fracture toughness values. In our previous work [9], the mode-I fracture toughness of anisotropic Barre granite was systematically measured using NSCB method [8], where an orthotropic material model with material constants identified from literature was used to accurately characterize the true stress intensity near the crack tip from a macroscopic point of view.

We believe that the physical reason for the observed fracture toughness anisotropy is due to pre-existing microcracks and thus we use micromechanics modeling in the current study to explicitly consider microcracks. Microstructural observation with a newly developed technique of computer-aided image analysis program clearly is used to examine the density and orientation of microcracks around the tip of the main crack. From two images of thin sections corresponding to the two contrasting cases of fracture toughness measurements, two physical micromechanics models are constructed. Finite element analysis is then conducted to determine the effects of embedded microcracks on the disturbance of the stress field at the tip of the main crack. The numerical results are consistent with the experimental results, supporting the postulation that the preferred distribution and orientation of pre-existing mircocracks in the otherwise homogeneous and isotropic rock material are responsible for the rate dependence of the fracture toughness anisotropy.

2. Crack–microcrack interaction

The method of pseudo-tractions, proposed by Horii and Nemat-Nasser [19], further improved by Gong and Horii [20], has been proven to be an effective approach to the analysis of the crack–microcrack interaction problem. Based on the complex potentials by Muskhelishvili [21] and the principle of superposition, this method can treat general problems with any number of interacting cracks or other inhomogeneities [20]. Herein, the concept of crack–microcrack interaction is demonstrated using the 0th-order and 1st-order solution of the pseudo-traction method by Gong and Horri [20].

Consider a general problem of a semi-infinite main crack and an arbitrarily located and oriented microcrack, as shown in Fig. 1. Denote the distance between the main crack tip and the center of the microcrack by d and the length of the microcrack by 2 c. The angle measured from the x-axis to the line connecting the tip of the main crack and the center of the microcrack is θ and the microcrack orientation is defined by the angle φ from x-axis to the x'-axis.

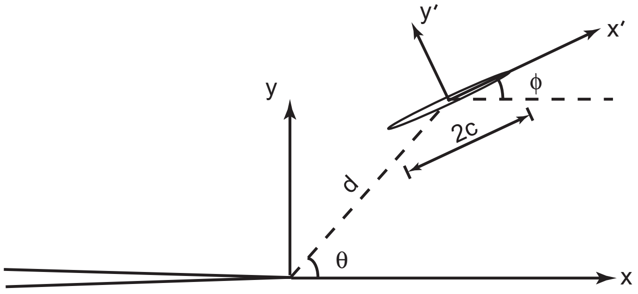

Fig. 1. One arbitrarily located microcrack near the tip of a semi-infinite crack.

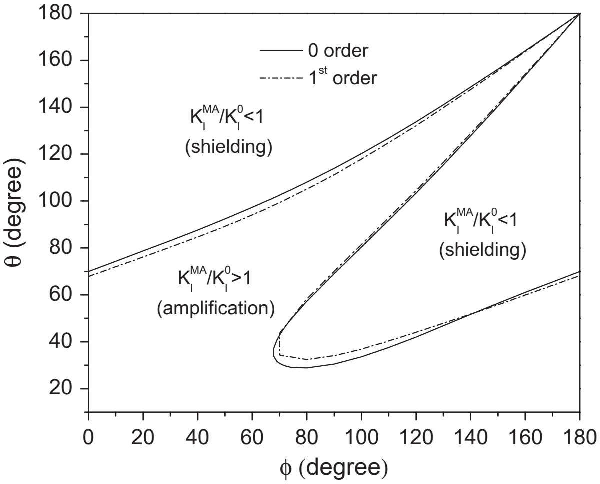

Fig. 2. The phase diagram of amplification and shielding effects of main crack due to the presence of a unique microcrack using solutions of 0-order and 1st-order approximation.

In this paper, K_I^0 denotes the stress intensity factor of the main crack without considering microcracks, i.e., the far-field stress intensity factor or the load, K_I^{MA} denotes the local stress intensity factor of the main crack. The method proposed by Gong and Horii [20] is used here to calculate the ratio between K_I^{MA} and K_I^0 with both 0th order approximation and 1st order approximation for the case where $d/c=2$. Because in our fracture tests on Barre granite [9], the resulting fracture mode is pure mode-I, thus in the current analysis, the far-field loading of K_{II}^0 is set to be zero. Using the first two terms of the formula given by Gong and Horii [20], the stress intensity factors of the main crack is calculated and showed in Fig. 2, in which the stress intensity factor at the tip of the main crack may be either increased (amplification, $K_I^{MA}/K_I^0>1$) or decreased (shielding, $K_I^{MA}/K_I^0<1$) with respect to that of the far-field, depending on the location and orientation of the microcracks. This effect of amplification or shielding of the stress intensity factor of the main crack due to the presence of the microcracks can be of vital significance to the anisotropy of rocks and hence can result in sizeable variations of the measured fracture toughness in the experiments, which will be fully explored in the following sections.

3. Construction of micromechanics models

3.1. Sample configurations in the NSCB tests

Fig. 3a illustrates the 3D block diagram showing longitudinal wave velocities. The three orthogonal material directions are