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Numerical Analysis of Tensile Crack Initiation and Propagation in Granites

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Abstract

Fracture analyses based on finite cover method (FCM) are conducted to investigate a fracture mechanism of granites. The analysis by the FCM, which is a cover-based generalized finite element method, has been extended for analyses of fracture process involving cracking within and/or between mineral grains in inhomogeneous rocks. A fracture process of numerical specimens which are prepared using X-ray CT image of African granites is studied. The analysis of material parameters, such as Young's modulus and tensile strength of minerals contained in the granites, is conducted to examine its influence on the fracture process and strength. Additionally, distribution of the mineral grains provides anisotropy for mechanical properties of granites. Comparison between numerical and experimental results presents that the important factors causing the anisotropy of macroscopic strength are the Young's modulus as well as the tensile strength of minerals distributed in the granites.

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1. Introduction

A fracture toughness is the most useful mechanical property in rock mechanics, describing resistance to fracture initiation [1]. Igneous rocks generally contain microcracks, representing mechanical weakness. The orientation and distribution of the microcracks are dominant factors affecting mechanical strengths of rocks, such as the fracture toughness [2–4]. However, taking into account fracture process of rocks governed by the microscopic crack

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initiation, the fracture process is decided by microstructural parameters themselves: a type of matrix and minerals, dimensions, and distribution of mineral grains. Any preferred orientation of the microstructure provides anisotropy for mechanical properties of granites. Kataoka et al. [5] has conducted Semi-Circular Bend(SCB) tests using African granite including observation of thin section and X-ray CT method to examine influence of the microstructure on the anisotropy of mechanical properties. They presented that the dominant factor causing the anisotropy of mode I fracture toughness is the distribution of mineral grains rather than inherent microcracks in the rocks.

To discuss of the anisotropy of properties involves evaluating a fracture process including crack initiation and propagation in the microstructures. In this research, we will conduct numerical analyses of tensile crack initiation and propagation to examine the fracture process of rocks in detail. The analyses are based on finite cover method(FCM) which is a generalized cover-based FEM. It is enable us to simulate progressive fracture process involving crack initiation and propagation within and/or between mineral grains in inhomogeneous rocks [6].

The SCB tests of numerical specimens which are prepared using X-ray CT image of African granites are performed. These numerical tests focus on the fracture process depended on the distribution of mineral grains. However, material parameters of minerals are generally unknown, because very few attempts have been made at measurement of them. As the first step in our analysis, we examine the influence of these parameters, such as Young's modulus and tensile strength of minerals, on the fracture process and macroscopic strength of granites. Analyses of the anisotropy caused by the distribution of grains are performed after the parametric testing for material parameters of minerals.

2. Fracture analysis by the FCM

The fracture analysis by the FCM [6] has developed to simulate the fracture process involving crack initiation and propagation within materials and interfacial debonding on material interfaces in heterogeneous solids and structures. The method can represent evolution of generated cracks independent of mesh alignment owing to distinctive features of the FCM as the generalized FEM. Also, interface elements with Lagrange multipliers are introduced to impose compatibility conditions on the material interface.

The judgement is made according to fracture criteria introduced separately for the material inside and the material interface. We utilize the Rankine type fracture condition based on positive principal stress, which is one of the most conventional and simplest ways to deal with the crack initiation inside the material. That is, the following condition is set for the crack initiation:

$$F = \sigma_{\max} - \sigma_{\mathrm{cr}} = 0 \tag{1}$$

where $\sigma_{\max}$ is the positive maximum principal stress that can be computed form the Cauchy stress, and σ_{cr} is the critical value of stress for generating crack. The crack initiation takes place when the positive principal stress reaches a material's tensile strength. Orientation of the generated crack is determined by the direction perpendicular to the major principal direction. In contrast, the fracture of material interface is assumed to occur when magnitude of positive traction vector on the interface reaches its strength limit. That is, by identifying the traction with the Lagrange multiplier, we can check the criteria of debonding. When the criteria for either the crack initiation or the debonding is met, the fracture which met the criteria take place by itself.

Fig. 1 shows an example to illustrate the applicability of the analysis for crack initiation and propagation by the FCM in heterogeneous solid. In this example, a two-phase material whose microstructure is formed by a circular inclusion embedded in a matrix. The loading and support condition are given in Fig. 1(a), along with the material parameters used in the numerical analysis. Here we assume that inclusion is strong enough that is will not exhibit failure. The numerical analysis is performed under the plane strain condition.

Fig. 1(b) shows the final configuration with the von Mises stress involving the appearance of the crack paths reported in [6]. As can be seen from the figure, the interface between the matrix and the inclusion are separated as a result of debonding. Also, the cracks which evolves along the interface intrude into the matrix when the limit of resistance of the matrix material comes at some time of loading. The paths of multiple cracks intruding into the matrix are independent of the mesh alignment. The FCM simulation enables us to trace smooth transition of the progressive fracture from the debonding of material interface to the separation of materials inside.