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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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Keywords: Fracture; Granite; Tensile crack; Numerical simulation; Anisotropy

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.

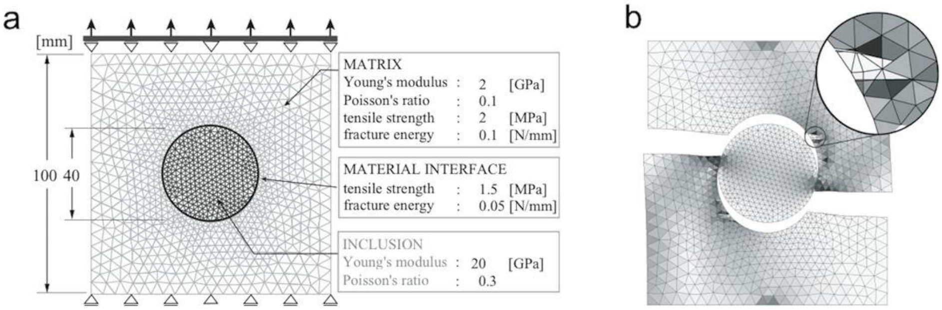

Fig. 1. (a) Microstructure of circular inclusion embedded in a matrix [6]; (b) Crack paths and distribution of von-Mises stress [6].

3. Numerical simulations of the SCB tests

We consider numerical simulations of the SCB test [5]. These simulations focus on the fracture process depended on the distribution of mineral grains. However, material constants of minerals are generally unknown, because very few attempts have been made at measurement of them. In the beginning, we examine the influence of these constant, such as Young's modulus and tensile strength of minerals, on the fracture process. After testing the fundamental performance depended on the constants, we shall provide an example of anisotropy caused by the distribution of grains. All the numerical analysis in this section is performed under the plane strain condition, because an experimental SCB sample had a thickness t =20 mm, as shown in Fig. 2(a) [5].

3.1. Numerical specimen

In the simulations, numerical samples are given by means of the X-ray CT image of African granite as shown in Fig. 2(b) shows the X-ray CT image near the tip of artificial notch included in the SCB sample. The image can observe the complex microstructure in the granite. In the image, a dense mineral is described as a white material. We assume that the microstructure in the granite is formed by two minerals. Both the minerals are assumed as linear elastic materials with the fracture criteria for cracking.

Fig. 2(c) shows a numerical specimen which is prepared using the X-ray CT image. In the specimen, the heterogeneous and anisotropic microstructure exists only on area near the tip of artificial notch. We assume that a material on the other area is a homogeneous material as the matrix.

The interface elements with Lagrange multipliers are introduced into the material interface between the mineral grains and the matrix in order to represent the debonding and to impose compatibility conditions until the interfacial fracture.

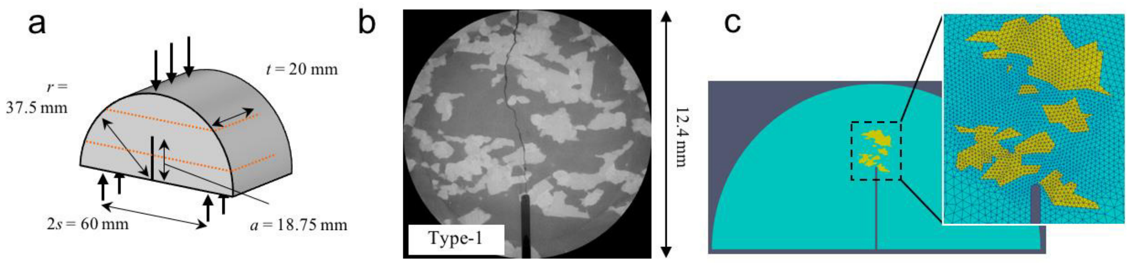

Fig. 2. (a) SCB test [5]; (b) X-ray CT image of a granite; (c) Numerical specimen (Type-1).

3.2. Analysis of material constants

We consider the SCB tests with various set of material constants to examine its influence on the fracture process. We utilize four sets of material constants as shown in Table.1, and they are applied to the numerical specimen shown in Fig. 2(c). In a case of test00, the constants of mineral grain and matrix are set with the same values. Though the numerical model includes the interface elements which may cause the debonding, its results are expected to behave as a homogeneous specimen. This example shows the fundamental performance of this method.

The Young's modulus, tensile strength and both of the mineral grains in test01, 02 and 12 are respectively set with larger value than these of the matrix. Their tests are conducted to observe the fracture process decided by these material constants.

Table 1. Sets of material constants (Poison's ratio = 0.1).

Test name	Matrix		Mineral grain		Interface
	Young's modulus [GPa]	Tensile strength [MPa]	Young's modulus [GPa]	Tensile strength [MPa]	Tensile strength [MPa]
Test00	30	5	30	5	5
Test01	30	5	50	5	5
Test02	30	5	30	8	5
Test12	30	5	50	8	5

Fig. 3 illustrates a crack path generated in the specimen of test00. The figure shows that the crack starts from the end of notch, and propagates in a vertical direction up to the loading point. It is note that the crack path is crossing straight the material interfaces which are artificial discontinuities in the numerical modelling. This result agrees well the fracture behavior of a homogeneous specimen.

Fig. 4 shows the evolving cracks in the case of test01, 02 and 12. The result of test01 presents that the increase of Young's modulus of the grains causes the crack paths to incline because a distribution of the stress is nonuniform. In the result of test02, the strong minerals prevent the crack from evolving straight in a vertical direction. As a result, the crack evolves along the material interface. When we focus on the crack generated in the matrix, it tends to propagate straight in a vertical direction. In the test12, the result provides the fracture process which combines the fracture mechanism in test01 and in test02. Comparing this result with the experimental result shown in Fig. 2(b), the fracture process in test12 presents the most similar result to the experiment.

Fig. 5 shows the relationship between the vertical applied load and displacement at the loading point. As can be seen, the curve for test12 exhibits a greater peak load than that of the others. This result presents that the Young's modulus of minerals distributed in the granites causes the shift of macroscopic strength.

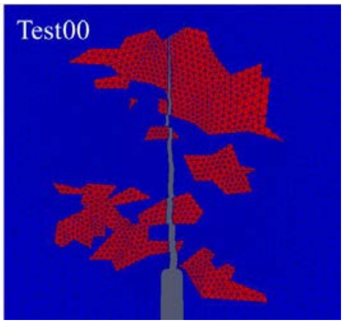

Fig. 3. Evolving crack in a homogeneous specimen of test00 (Type-1).

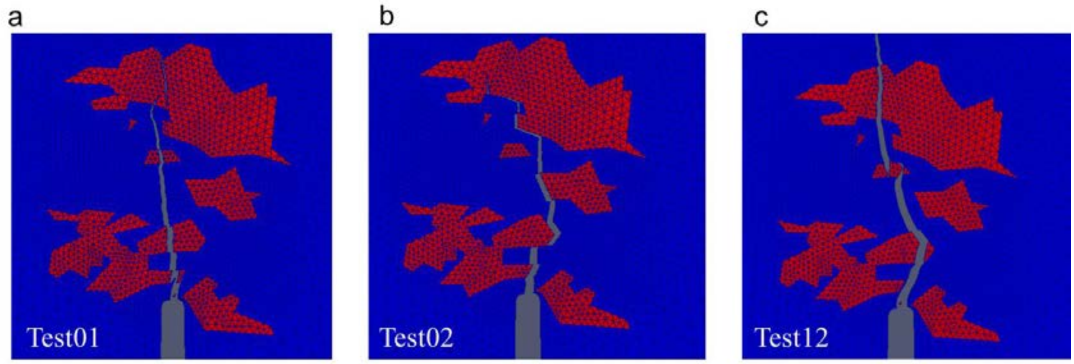

Fig. 4. Evolving crack in a nonhomogeneous specimen (Type-1) of (a) test01; (b) test02; (c) test12.

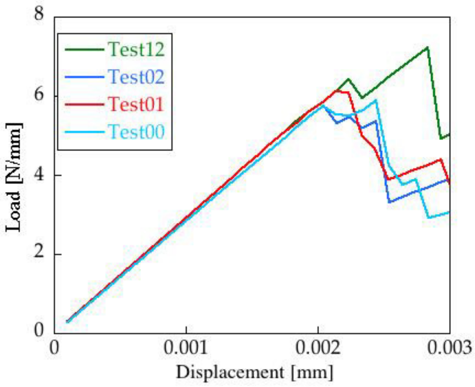

Fig. 5. Macroscopic load-displacement curves (Type-1).

3.3. Analysis of anisotropy

We consider the SCB tests using the 2 types of specimens to examine the anisotropy caused by the distribution of grains. We utilize a numerical model (Type-3) given by other X-ray CT image as shown in Fig. 6, in addition to the model (Type-1) shown in Fig. 2(c). The new model has a different anisotropic microstructure. Experimental SCB tests using these samples of the African granite have already been conducted by Kataoka et al. [5] to determine macroscopic properties of them. However, we have to set valid material constants of the mineral grains in numerical test. A parametric testing has been conducted to determine the valid constants by trial and error. In the parametric testing, the experimental result of Type-1 was compared with many numerical results. Table 2 shows the values of material constants determined by the parametric testing. There is no evidence that these values in Tab. 2 represent the exact properties of minerals in the granite, though the values of strengths seem to be close to the properties of minerals themselves rather than rocks.

Table 2. Material constants determined by parametric testing (Poison's ratio = 0.1).

Matrix		Mineral grain		Interface
Young's modulus [GPa]	Tensile strength [MPa]	Young's modulus [GPa]	Tensile strength [MPa]	Tensile strength [MPa]
21	120	42	130	120

Fig. 7 illustrates each of the evolving crack in Type-1 and 3. From these figures, both the generated crack in Type-1 and Type-3 agrees well the experimental fracture behaviors respectively, as shown in Fig. 2(b) and 6(a). Fig. 8 shows the numerical and experimental relationship between the vertical applied load and displacement at the loading point. On an order estimation by thickness t = 20 mm, the expected macroscopic strengths by the numerical tests agrees broadly the actual values reported in [5] (Fig. 9). This agreement provides that the anisotropic distribution of grains is the dominant factors causing the anisotropy of mechanical strengths on the granites.

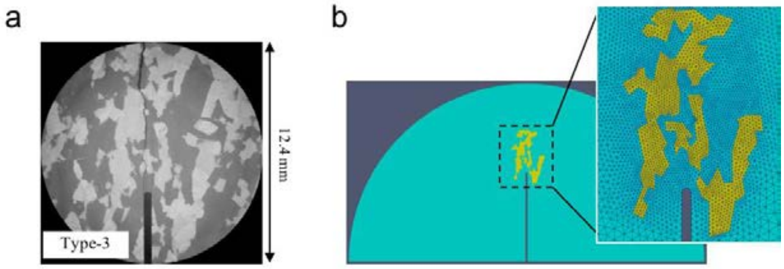

Fig. 6. (a) X-ray CT image of a granite; (b) Numerical specimen (Type-3).

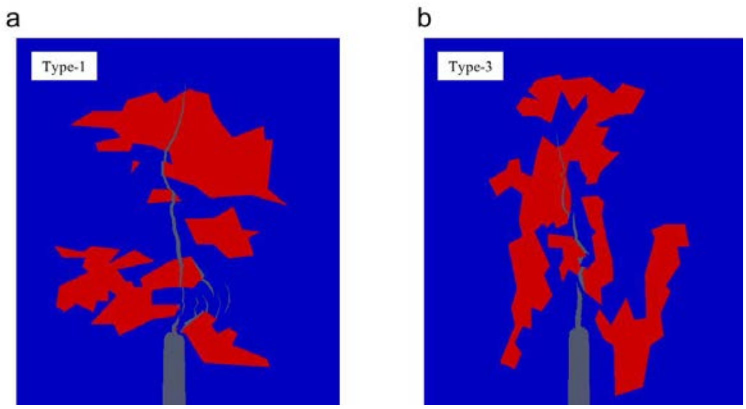

Fig. 7. Evolving crack in granites in (a) Type-1; (b) Type-3.

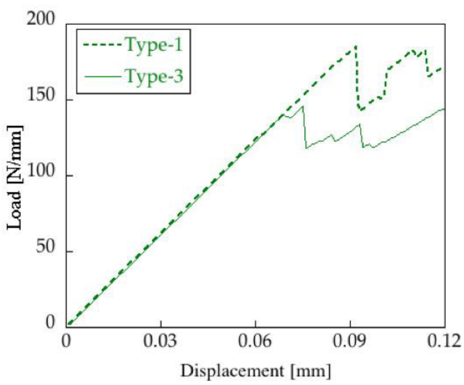

Fig. 8. Macroscopic load-displacement curves.

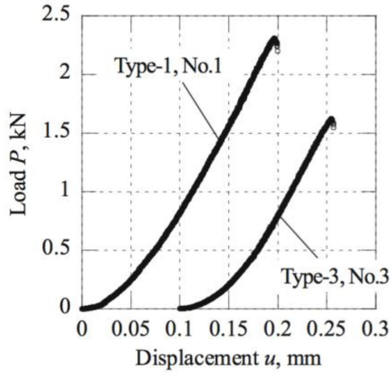

Fig. 9. Load–displacement curves reported in [5]. The curves of Type-3 are translated 0.1 mm in the positive direction of the horizontal axis.

4. Conclusions

We have conducted the fracture analyses based on the FCM in order to examine a fracture mechanism including crack initiation and propagation in the microstructure of African granite. After preparing the numerical specimens by means of the X-ray CT images, we considered the influence of material parameters, such as Young’s modulus and tensile strength through the numerical simulations with the assumed material parameters. We have successfully tracked the fracture process in the inhomogeneous specimens by our numerical approach. Then, we have performed the series of numerical SCB tests using the several specimens which have the different anisotropic microstructures to observe the anisotropy of macroscopic strength caused by the distribution of mineral grains. The results summarized as follows:

- The Young’s modulus of the minerals distributed in the granites is one of the dominant factors causing the anisotropy of the macroscopic strength as well as the tensile strength.
- The anisotropic distribution of grains causes the anisotropy of mechanical strengths on the granites without the microcraks.

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