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Estimation of Mode I Fracture Toughness of Rock by Semi-Circular Bend Test under Confining Pressure Condition

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Abstract

It is essential to understand the mode I fracture toughness of rock under in situ conditions found underground, such as confining pressure, for assessment of the stability of underground rock structures. Some researchers have performed several types of fracture toughness tests of rocks under confining pressure condition. However, the ordinary fracture toughness tests do not consider the effect of confining pressure in their estimation equations. A modified estimation equation for the mode I fracture toughness of rock under confining pressure condition was suggested in this study. This study was intended for the semi-circular bend (SCB) test, which is one of the ISRM-suggested methods for determining the mode I fracture toughness of rock. The SCB test under various confining pressures from 0 to 10 MPa was performed using Kimachi sandstone. A finite element analysis of the SCB test considering several confining pressure conditions was performed to calculate the stress intensity factor. Based on the numerical simulation results, the modification of the fracture toughness estimation was suggested. Applicability of the suggested estimation was discussed with comparing the mode I fracture toughness of the rock obtained in this study and previous research.

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Keywords: Mode I fracture toughness; Confining pressure; Semi-circular bend test; Kimachi sandstone

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1. Introduction

Fracture toughness K_c is one of the most important mechanical properties in fracture mechanics. It is considered to be the critical value of stress intensity factor K and indicates the resistance to fracture initiation. In rock engineering, K_c has been applied as a parameter for classification of rock materials, and interpretation and modeling of rock fracturing [1, 2]. It is essential to understand K_{Ic} of rocks under in situ conditions found underground, such as water content, temperature and confining pressure, for its application. Mode I (opening mode) is the most important mode of fracture initiation because it is the predominant loading condition over the fracture of rocks [1].

Many researchers have been conducting the fracture toughness tests under confining pressure [3–6]. It was found that K_c tends to increase with increasing confining pressure. However, some results show that K_c is not changed under several confining pressure values. In the experiments under confining pressure, the specimen is immersed in an incompressible fluid such as oil, and the fluid pressure is often used as confining pressure. The specimen requires jacketing to prevent contamination by the oil. The specimen in fracture toughness tests has a notch, and the previous results may show the different trends due to the different conditions of the pressure inside the notch as well as pore pressure. It also should be pointed out that the general fracture toughness tests [7–9] have not been theorized for the mechanical condition of the specimen under confining pressure. Some researchers have attempted modifications considering the effect of pressure inside the notch [4, 6]. Numerical simulation may support the estimation of the fracture toughness of rocks under confining pressure.

In this study, in order to understand the influence of confining pressure on the mode I fracture toughness of rocks, the fracture toughness test under various confining pressures from 0 to 10 MPa was conducted using Kimachi sandstone. The semi-circular bend (SCB) test [9], which is one of the ISRM-suggested methods for determining the mode I fracture toughness of rocks, was used. Numerical simulations of the SCB test considering several confining pressure conditions were performed. The experimental evaluation method for the mode I fracture toughness under confining pressure was discussed based on the numerical simulation results.

2. Semi-circular bend test

The geometry of the SCB specimen is shown in Fig. 1 (a). During the test, a three-point loading is applied to the specimen. The mode I fracture toughness K_{Ic} is evaluated using the following equations [9]:

Nomenclature

a	notch length of SCB specimen
K	stress intensity factor
K_c	fracture toughness
K_{Ic}	mode I fracture toughness
$K_{Ic}*$	apparent mode I fracture toughness
K_{If}	stress intensity factor at $P = P_{max}$
K_{I0}	stress intensity factor at $P = 0$
P	load applied to SCB specimen
P_f	fracture initiation load
P_{max}	maximum load
r	radius of SCB specimen
s	half of support span of SCB specimen
t	thickness of SCB specimen
Y_I	normalized stress intensity factor
σ_{cp}	confining pressure
σ_{cpo}	outer confining pressure
σ_{cpi}	inner confining pressure

$$K_{Ic} = Y_I \frac{\sqrt{\pi a}}{2tr} P_{max} \quad (1)$$

where a, r and t are the notch length, radius and thickness of the specimen, respectively, and P_{max} is a maximum load. The normalized stress intensity factor Y_I is a dimensionless function decided by specimen shape and its dimension. In case of the SCB specimen, Y_I is shown as a function of the ratios of a half of the support span to radius s/r and normalized notch length a/r [9].

The confining pressure was not considered in this estimation equation. In this paper, the fracture toughness under confining pressure estimated by Equation (1) is described as apparent fracture toughness K_{Ic}*.

3. Experiment under confining pressure

3.1. Specimen

Kimachi sandstone was used as a test material. The average grain diameter is 0.4–0.6 mm [10] and the porosity is approximately 20 % [11]. The other material properties are listed in Table 1. The geometrical dimensions of the SCB specimens are shown in Fig. 1 (a). In the specimen preparation process, firstly, a rock core was drilled from a rock block. Then, the core was cut into disks and each disk was cut into halves to form two semi-circular specimens. Finally, a straight edge notch was produced using a diamond blade with a thickness of 0.4 mm. The direction of the notch was normal to the sedimentation. The length of the notch is given by a/r = 0.5. After the preparation, the specimens were kept in an electric drying oven at 60^{o} C for more than 30 days.

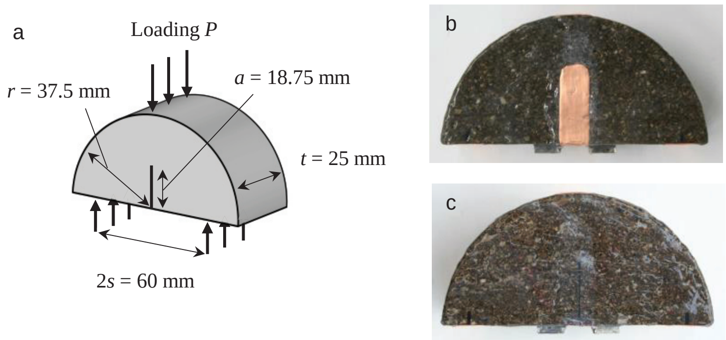

Fig. 1. SCB specimen; (a) the geometrical dimensions of the specimen and loading configuration, and (b) and (c) the picture of Specimen (O) and Specimen (I) (defined in Section 3.1), respectively.

Table 1. Material properties of Kimachi sandstone.

Material property	Value
Uniaxial compressive strength	59.3 MPa
Young’s modulus	7.7 GPa
Poisson’s ratio	0.22
Tensile strength	6.17 MPa
Elastic wave velocity	2.6–2.9 km/sec

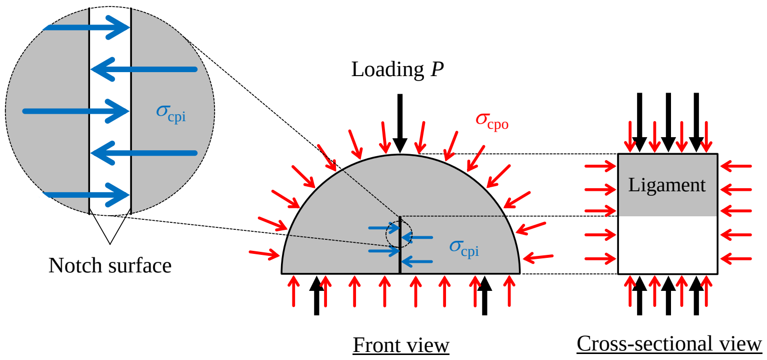

Fig. 2. Schematic of pressure applied to the SCB specimen.

The specimen was immersed in an oil vessel and subjected to the confining pressures during the test. The specimens were covered with silicone to prevent contamination of the oil. As shown in Fig. 2, the pressure applied to the notch surfaces is defined as an inner confining pressure σ_{cpi}, while that not to the notch surfaces is an outer confining pressure σ_{cpo} in this paper. σ_{cpo} is the hydraulic pressure of the oil vessel. In Specimen (O) shown in Fig. 1 (b), the notch was sealed by a copper sheet before the silicone covering. As a result, the silicone did not flow into the notch and the pressure was not applied to the notch surface, namely $\sigma_{cpi} = 0$. On the other hand, the silicone flowed into the notch in Specimen (I) as shown in Fig. 1 (c). A portion of the fluid pressure might have been applied on the notch surfaces through the silicone, namely $\sigma_{cpi} > 0$. However, this pressure value could not be measured directly. Moreover, it was found that the silicone layer did not affect K_{Ic} value; several SCB tests under atmospheric pressure conditions were performed using specimens with and without silicone coating and there were few differences in K_{Ic} values between them.

3.2. Experimental system and method

The tests were performed using a special testing system [6]. This testing machine facilitates loading a specimen in a three-point bending test while it is immersed in an oil vessel. The oil vessel can be raised to a hydraulic pressure of up to 30 MPa. The test was performed at room temperature, though the oil vessel can be heated up to 200^{o} C. The specimen was placed on the loading apparatus and loaded vertically through one upper and two support rollers. The support span 2s used is shown in Fig. 1 (a). Y_I was calculated as 6.67 in this study (a/r = 0.5 and s/r = 0.8) [9]. Moreover, one set of knife-edges were mounted at the notch mouth for attachment of a clip-type displacement gauge to measure a crack opening displacement (COD).

During the test, the loading apparatus with the specimen was immersed in the oil vessel and subjected to confining pressure. Before the test, the hydraulic pressure inside the oil vessel was raised stepwise by 2 MPa to the desired confining pressure. The SCB tests under atmospheric pressure conditions were also performed as a test under a confining pressure of 0 MPa. The specimen was loaded under displacement control using a loading rate of 0.01 mm/min. The displacement was measured by a differential displacement transducer. The load applied to the specimen was measured using a load cell installed on the system.

3.3. Results

The test results are summarized in Table 2. In the test using Specimen (O), σ_{cpi} was zero and σ_{cpo} (fluid pressure) was set to 0, 2, and 4 MPa. The test under the condition of σ_{cpo} higher than 4 MPa could not be performed because some σ_{cpo} of 4 MPa and 6 MPa tore the silicone layer and the oil flooded into the notch before the specimen fractured. In the test using Specimen (I), σ_{cpo} was set to six conditions: 0, 2, 4, 6, 8, and 10 MPa. σ_{cpi} could not be measured in this case. Fig. 3 shows typical load-displacement curves. The curve of Specimen (I) in Fig. 3 (b) is almost linear until a specimen fractured at the maximum load P_{max}. This value was used to estimate the apparent fracture toughness K_{Ic}* using Equation (1). On the other hand, as shown in Fig. 3 (a), there is a yield point at some load level in the curves in Specimen (O), and then the deformation behavior changes to ductility. This ductile behavior may be induced by confining pressure, and P_{max} does not indicate the load condition of fracture initiation in this case. Therefore, as shown in Fig. 3 (a), tangents for two linear parts were drawn and the load at the intersection of the lines was assumed as the fracture initiation load P_f. This value was used to estimate K_{Ic}* in the case of Specimen (O), as P_{max} in Equation (1).

As shown in Table 2, average K_{Ic}* tends to increase with increasing σ_{cpo}. However, the value of Specimen (O) is higher than that of Specimen (I). In Specimen (I), K_{Ic}* at σ_{cpo} of 2 MPa is higher than the others. In order to interpret the fracture toughness under confining pressure, numerical simulations for the SCB test considering several confining pressure conditions were performed.

Table 2. Results of experimental SCB test. P_{max} or P_f, K_{Ic}* and K_{Ic} are the average value of each specimen.

Specimen	Number of specimens	σ_{cpo} (MPa)	σ_{cpi} (MPa)	P_{max} or P_f (kN)	K_{Ic}* (MN/m$^{3/2}$)	K_{Ic} (MN/m$^{3/2}$)
O-0	3	0	0	0.75	0.64	0.64
O-2	3	2	0	3.06	2.57	1.10
O-4	2	4	0	5.80	4.88	1.95
I-2	5	2	-	2.47	2.14	-
I-4	4	4	-	1.74	1.48	-
I-6	4	6	-	1.93	1.65	-
I-8	4	8	-	2.02	1.73	-
I-10	4	10	-	2.46	2.08	-

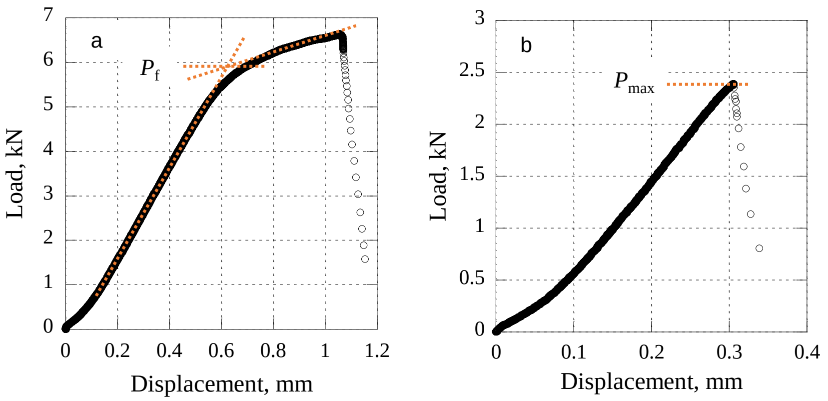

Fig. 3. Load-displacement curves; (a) Specimen (O-4), and (b) Specimen (I-2).

4. Numerical simulation considering confining pressure

4.1. Outline of the simulation

Using the maximum load P_{max} obtained from the experiment, the corresponding stress intensity factor K_I was calculated using a finite element code, Abaqus Unified FEA. Due to symmetry in shape and boundary conditions of the SCB specimen, only half of the structure was modeled and meshed as shown in Fig. 4. The load P was applied at the upper loading point. The dimensions of the model and the support span correspond to the specimen used in the experimental tests. K_I around the notch tip was calculated using the J-integral method. The computation was almost the same as that described in Kuruppu et al. [9], which derived the function of normalized stress intensity factor Y_I. Young's modulus and Poisson's ratio of Kimachi sandstone as shown in Table 1 were used in the calculations.

The outer confining pressure σ_{cpo} was set to six conditions as the same as the experimental ones. For each condition except σ_{cpo} = 0 MPa, $\sigma_{cpi}/\sigma_{cpo}$ was set to five conditions: 0, 1/3, 1/2, 2/3, and 1. In one series of simulations, P was applied to the model as the average value of P_{max} obtained from the experiments using Specimen (I) as listed in Table 2. The stress intensity factor calculated under the condition, described as K_{If} in this paper, was assumed to be the fracture toughness K_{Ic}. In other series, P was not applied to the model. This K_I value can be assumed to be the stress intensity factor induced due to confining pressure only, and is described as K_{I0}.

4.2. Results and discussion

Fig. 5 shows a part of the simulation results. In this figure, the plots at P = 0 and $P = P_{max}$ are K_{I0} and K_{If}, respectively. K_{I0} is zero under the conditions of $\sigma_{cpo} = \sigma_{cpi} = 0$ and $\sigma_{cpi}/\sigma_{cpo} = 1$. On the other hand, under $\sigma_{cpi}/\sigma_{cpo} < 1$, K_{I0} appears as a negative value because the stress concentration at the notch tip occurs as a compression. It decreases in proportion with $\sigma_{cpi}/\sigma_{cpo}$. The plots of K_{I0} and K_{If} under the same $\sigma_{cpi}/\sigma_{cpo}$ condition are connected to each other in this figure. It can be found that K_I increases with increasing P. The slope of all these lines is almost the same ranging from 887 to 891 $m^{-3/2}$.

The lines in Fig. 5 indicate the relation between K_I and P, and K_{Ic} may be on or an extension of the line at the critical value of P. Based on Equation (1) and the simulation results, the estimation equation for K_{Ic} under confining pressure suggested in this paper is represented as;

$$K_{Ic} = Y_I \frac{\sqrt{\pi a}}{2tr} P_{max} + K_{I0} \tag{2}$$

K_{I0} is zero under the condition of $\sigma_{cpo} = \sigma_{cpi}$. In this case, K_{Ic} can be estimated using Equation (1). On the other hand, when σ_{cpi} is smaller than σ_{cpo}, K_{I0} becomes a negative value due to the compressive stress concentration at the notch tip. Therefore, K_{Ic} under the condition of $\sigma_{cpi}/\sigma_{cpo} < 1$ can be estimated using Equation (2) instead of Equation (1).

Y_I is calculated as 6.67 at a/r = 0.5 and s/r = 0.8 [9]. On the other hand, using the slope of the lines shown in Fig. 5, Y_I values were estimated as from 6.90 to 6.95. The differences of Y_I values were under 5 %. Y_I calculated by Kuruppu et al. [9] can be used even though under confining pressure.

In the experimental SCB test using Specimen (O), σ_{cpi} was zero and K_{I0} was determined by the simulations; K_{I0} = -1.47 MN/$m^{3/2}$ for σ_{cpo} = 2 MPa, and K_{I0} = -2.94 MN/$m^{3/2}$ for σ_{cpo} = 4 MPa. K_{Ic} can be estimated using the K_{I0} value and the results are shown in Table 2 and Fig. 6. The apparent fracture toughness K_{Ic}* of Specimen (O) and Specimen (I) is also plotted as an open plot in Fig. 6. K_{Ic} (estimated by Equation (2)) of Specimen (O) is dependent on confining pressure σ_{cp} and increasing with increasing σ_{cp}. An approximation lines of this result and that of the study by Funatsu et al. [6], in which K_{Ic} was estimated under the confining pressure of up to 9 MPa using Kimachi sandstone, are drawn in this figure. These results are in agreement with each other.

As a future study, the results of Specimen (I) (under confining pressure of $\sigma_{cpi} < \sigma_{cpo}$) will require the estimation method. K_{I0} must be known not only the conditions of $\sigma_{cpo} = \sigma_{cpi}$ but also $\sigma_{cpi}/\sigma_{cpo} < 1$. It was found from the simulations that K_{I0} can be estimated by the differential confining pressure ($\Delta\sigma_{cp} = \sigma_{cpo} - \sigma_{cpi}$) and a crack opening displacement (COD) [12]. The detail will be published in near future.

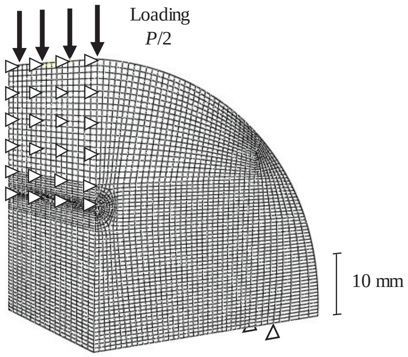

Fig. 4. Mesh design, boundary condition and loading configuration for simulating SCB specimen.

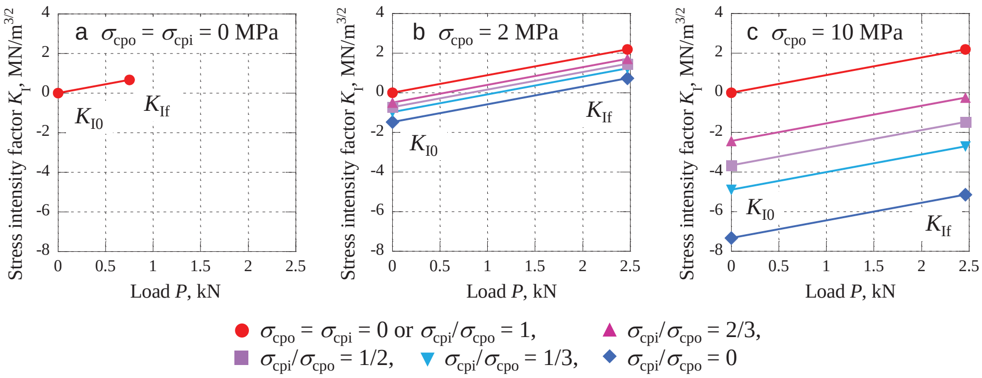

Fig. 5. Example results of SCB test simulation.

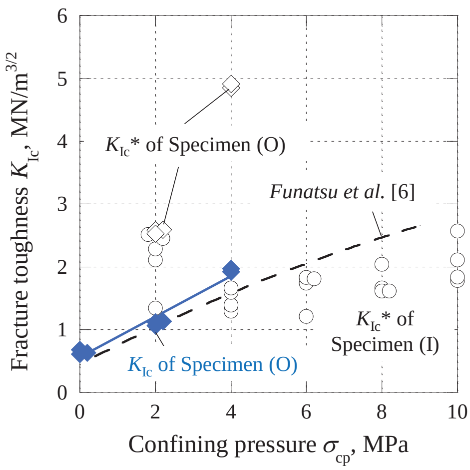

Fig. 6. Relation between fracture toughness and confining pressure.

5. Conclusions

In order to understand the influence of confining pressure on the mode I fracture toughness of rocks, the SCB tests under various confining pressures from 0 to 10 MPa were performed using Kimachi sandstone. Two types of specimen were prepared. In Specimen (O), the pressure applied to the notch surfaces (σ_{cpi}) is zero. In Specimen (I), there is not only the confining pressure applied except on the notch surfaces (σ_{cpo}) but also a certain value of σ_{cpi}. The numerical simulations of the SCB test considering several confining pressure conditions were also performed. The experimental evaluation method for the fracture toughness under confining pressure was discussed based on the numerical simulation results.

The fracture toughness evaluated by the ordinary SCB testing method tends to increase with increasing σ_{cpo}. However, there is a possibility that the mode I fracture toughness was not estimated appropriately because this evaluation method does not consider the effect of confining pressure. Based on the results of the numerical simulation, the mode I fracture toughness K_{Ic} under confining pressure can be estimated using the following formula;

$$K_{Ic} = Y_I \frac{\sqrt{\pi a}}{2tr} P_{max} + K_{I0} \qquad (2)$$

where Y_I is the normalized stress intensity factor, a, r and t are the notch length, radius and thickness of the specimen, respectively, P_{max} is a maximum load, and K_{I0} is the stress intensity factor under no applied load. Using this equation, K_{Ic} of the rock was estimated from the experimental results. As a result, K_{Ic} is dependent on confining pressure σ_{cp} and increasing with increasing σ_{cp}.

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