터널과 지하공간, 한국암반공학회
Vol. 7, 1997, pp. 284~292

TUNNEL & UNDERGROUND Vol. 7, 1997, pp. 284-292
J. of Korean Society for Rock Mech.

암석인장파괴와 관련된 지질공학적 특성연구

박 형 동

Study on the Engineering Geological Characteristics Related to the Tensile Failure of Rock

Hyeong-Dong Park

요 약 본 연구에서는 파괴형상의 특성을 이용하여 암석인장강도 측정실험법의 적용성을 평가하였다. 이를 위해 화강암 및 석회암 시료를 대상으로 하여 점하중 시험법, Brazilian 시험법, Hoop 시험법을 통해 인장파괴를 유도하였다. 각 파괴면의 형상을 분석하였고, Hoop 시험법의 경우 이론적인 응력분포와 함께 해석하였다. 파괴면 형상의 특징은 향후 시추코어의 파괴면 해석, 야외조사시 절리면의 파괴 해석 등에 이용될 수 있다.

1. Introduction

The mechanism of tensile failure in rock is an important part of fracture mechanics of rock not only because the rock is weaker under tension than under compression, but also because the coalescence of such tensile failure in a rock specimen under externally applied compressive forces attributes for the structural failure of rock under compression.[1~5]

Since tensile fracture is a fundamental basis for understanding the failure mechanism of rock, theoretical and laboratory studies have been carried out. From a theoretical viewpoint, tensile strength of rock is defined as the maximum tensile stress at which the rock fails.[6] Despite of this simple definition, it has not been possible to successfully measure the value experimentally. The main gap between theory and practice comes from the difficulties in practical work, i.e. (i) the stress at fracture initiation is not necessarily the same as that at fracture propagation, (ii) the volume of sample subjected to the critical tensile stress is different in each tensile test(Fig. 1). Therefore, there does not seem to be an experimental technique for defining the tensile strength of rock as a material property even though the International Society on Rock Mechanics suggested two standard methods, i.e. direct tension and Brazilian test.[7]

Compared to the conventional tensile testing methods, a recently developed hoop test[8] has been suggested as a much simpler test to perform due to no requirement of large loading frame. However it is not simple to prepare such hoop shaped sample by double coring. In addition, it has not been clarified that such failure was simply induced under tension.

Thus, the main purpose of this paper is to provide a theoretical basis whether the hoop test can introduce tensile failure of a rock specimen.

This paper are mainly focused on the followings: (i) the theoretical background of hoop test, (ii) the application of fractographic techniques to both the conventional tensile testing methods and hoop test using the fractographic observation, (iii) the comparison among the various tensile failure patterns and its application for studying the minimum requirement of the tensile test.

Full member, Professor
Division of Civil, Urban and Geosystem Engineering,
Seoul National University

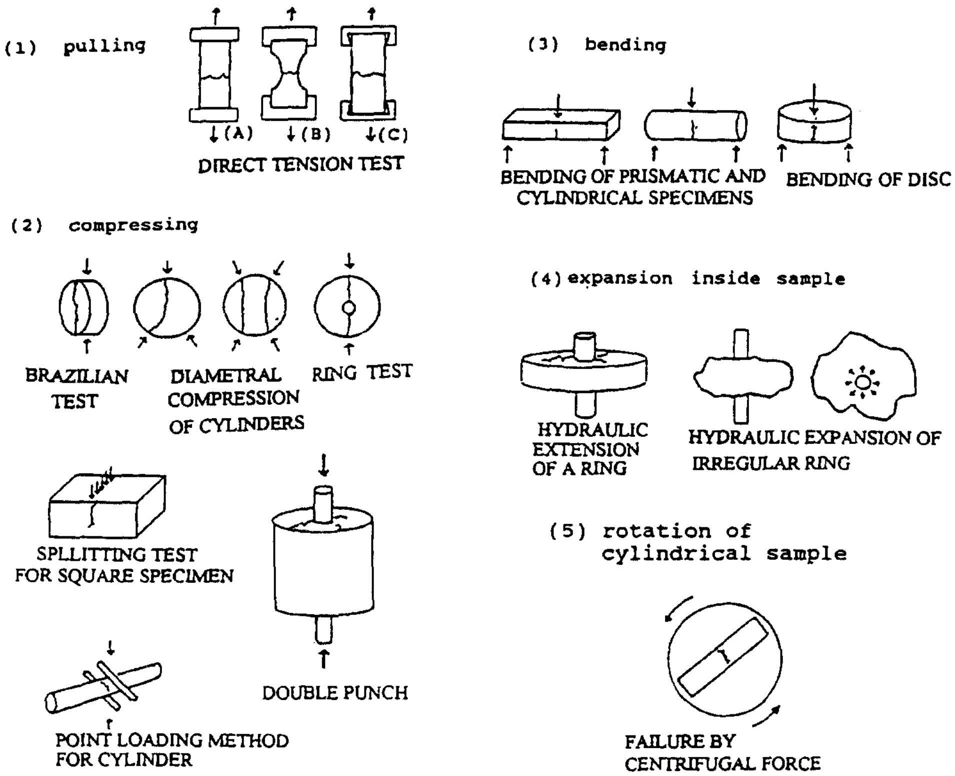

Fig. 1. Various tensile test methods (based on the previous works[9,10])

2. Review of the conventional tensile tests

Ideally, direct tension test is the simple and definitive test for the determination of tensile strength of rock. However, in practice, the ideal case of the theory is not easily achieved; (i) a local stress concentration occurs around the grip, (ii) any incorrect fitting of sample induces a bending moment, resulting in uneven stress distribution within the rock specimen and hence this makes the stress distribution within the sample uneven. The main advantage is that the overall strain value can be directly achieved without using any mathematical manipulation. Consequently, irrespective of being a suggested method, the experimental work using direct tension test is less frequently found in literature than other indirect test.

Brazilian test is basically an indirect tension test with an assumption that the maximum tensile stress is induced at the centre of disc and the failure occurs due to the maximum tensile stress irrespective of compressive stresses within the disc because the rock is weaker in tension than in compression. This test is frequently employed by researchers because it is easy to conduct and tensile strength (in theory) is easily calculated by the simple formula. In some cases, locally concentrated stresses near the contact points between the specimen and loading jig may significantly influence the validity of test results.[11, 12] Some methods for improving the test were suggested: (i) using a loading jaw with a contact angle of 10°(ISRM, 1981), (ii) using cardboard inserts between the loading platens and the sample,[12] (iii) using soft wood[13] which prevented local compressive failure around the loading point.[14]

3. Theory of hoop test

A recently developed hoop test simply consists of two semi-cylindrical loading platens and a loading jack which is connected to an oil pressure pump controlled by personal computer. A maximum pressure and loading rate are set and controlled. Failure generally occurs at the line parallel to the plane of platen opening (Fig. 2).

Under the assumption of perfect contact condition, the analytical solution of the hoop test was suggested as a similar form to the solution of bending in a curved beam.[17] The expression, which is the work of Boresi and Sidebottom (1985),[18] includes geometric parameters, i.e. inner radius (r_i), outer radius (r_o) and height (h) of hoop sample:

$$\sigma_{\theta\theta} = \frac{F}{A} + \frac{M_x(A - rA_m)}{Ar(RA_m - A)} \quad (1)$$

where, with reference to Fig. 3,

$\sigma_{\theta\theta}$: circumferential stress

F : normal traction

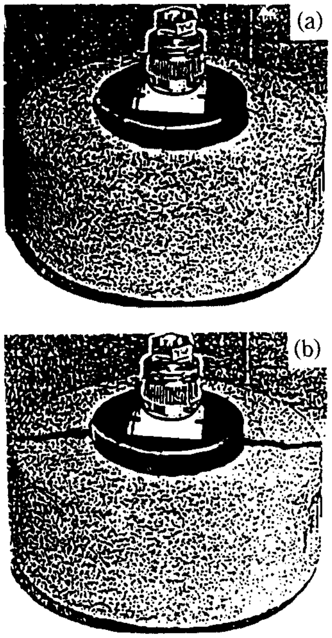

Fig. 2. Hoop test: (a) before and (b) after failure

A : cross-sectional area of the curved beam, $h(r_o\text{-}r_i)$

h : height of sample

r : distance from the centre

r_o : outer radius of sample

r_i : inner radius of sample

A_m : $h \cdot \ln(r_o/r_i)$

R : $(r_o+r_i)/2$

Mx : bending moment at a section forming an angle θ with the line extending from the planes of platen separation

Further details of calculations were not made, e.g. the calculation of bending moment (M_x), by those authors.[17] However, it is worth getting an approximation of such a mathematical expression using a relatively simple model. Such an analogous model is a closed ring subjected to a concentrated load.(Fig. 3)

The applied load V, N and M_x at a section forming angle θ with the face BC are as follows:

$$V = (F/2)\ \mathrm{SIN}\ \theta \quad (2)$$

$$N = (F/2)\ \mathrm{COS}\ \theta \quad (3)$$

$$M_x = M_o - (FR/2)\ (1 - \mathrm{COS}\ \theta) \quad (4)$$

where,

$$M_o = \frac{FR}{2} \cdot \left(1 - \frac{2A}{RA_m\pi}\right) \quad (5)$$

$$\simeq \frac{FR}{2} \cdot \left(1 - \frac{2}{\pi}\right)\ (\text{if } R/h > 2.0) \quad (6)$$

A general expression of M sub x can be achieved by substituting Eqn. 5 into Eqn. 4:

$$M_x = FR \cdot \left(\frac{\mathrm{COS}\ \theta}{2} - \frac{A}{RA_m\pi}\right) \quad (7)$$

Now, the stresses at any section of hoop can be calculated by substituting Eqn.7 into Eqn.1 and yields:

$$\sigma_{\theta\theta} = \frac{F}{A} + \frac{FR}{2} \cdot \left(\mathrm{COS}\ \theta - \frac{2A}{RAm\pi}\right) \cdot \frac{(A - rA_m)}{Ar(RA_m - A)} \quad (8)$$

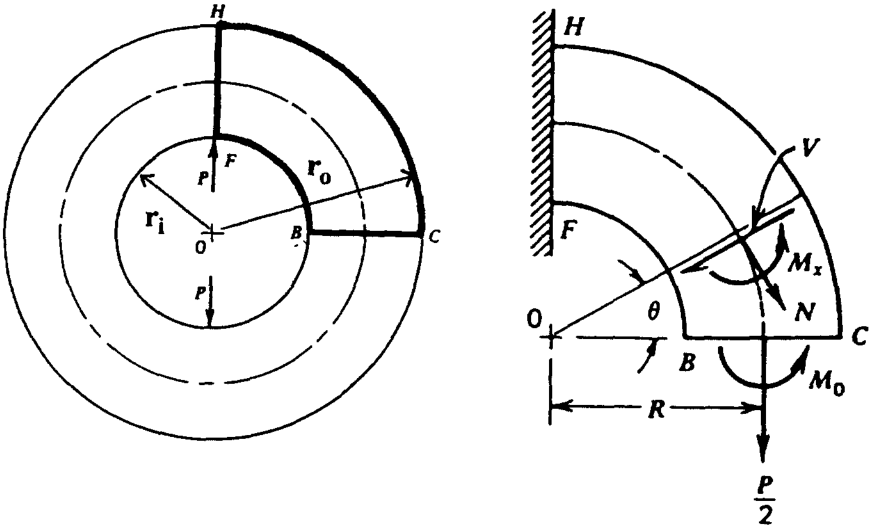

Fig. 3. Bending moment in a closed ring (hoop) subjected to a concentrated load (from Boresi and Sidebottom[18])

Eqn.8 can also be expressed in terms of geometric variables in hoop, i.e. r_i, ro and h, based on the notation expressed in Eqn.1.

The first term of Eqn.8 is an expression of the contribution of evenly distributed loads (i.e. direct tensile loads) to the hoop stress ($\sigma_{\theta\theta}$). The second term, which seems to be complex, is an expression of the contribution of bending moments to the hoop stress. To find the stress distribution, both along the plane parallel to the platen opening (θ=0°) and along a load line parallel to the direction of loading (θ=90°), a simple calculation was made with using an arbitrary constants: r_o=60 mm, r_i=30 mm, h=50 mm and F=500 N. For convenient comparison, $\sigma_{\theta\theta}$ can be normalized through σ_o (=F/A) and expressed as those shown in Table 1, 2 and Fig. 4.

From the above examples, it could be shown that (i) hoop stress is a superimposed result of direct tensile stress and bending moment induced stress and hence there exists two different states of stress, i.e. tension and compression, of which boundary can be defined as neutral point and (ii) the maximum tensile stress occurs at a point (r=r_i) on the plane parallel to the platen opening (θ=0°). However, large tensile stresses also occur in the

Table 1. Hoop stress calculated from analytical solution of curved beam, normalized through σ_o (=F/A), when θ=0° : all notations are referred in Eqn.1 and Fig. 3

r (mm)	Direct tensile stress (σ_a / σ_o)	Bending moment induced stress (σ_b / σ_o)	Hoop stress ($\sigma_{\theta\theta}$/σ_o)
30	1	2.2461	3.2461
35	1	1.2004	2.2004
40	1	0.4161	1.4161
45	1	-0.1939	0.8061
50	1	-0.6819	0.3181
55	1	-1.0812	-0.0812
60	1	-1.4140	-0.4140

Table 2. Hoop stress calculated from analytical solution of curved beam, normalized through σ_o (=F/A), when θ=90° : all notations are referred in Eqn.1 and Fig. 3

r (mm)	Direct tensile stress (σ_a/σ_o)	Bending moment induced stress (σ_b/σ_o)	Hoop stress ($\sigma_{\theta\theta}$/σ_o)
30	1	-3.5473	-2.5473
35	1	-1.8958	-0.8958
40	1	-0.6571	0.3429
45	1	0.3063	1.3063
50	1	1.0770	2.0770
55	1	1.7076	2.7076
60	1	2.2331	3.2331

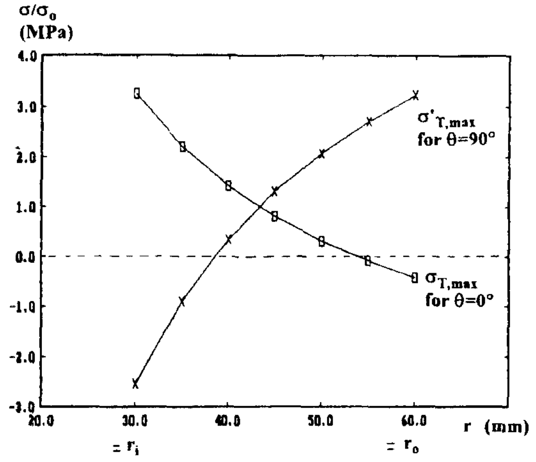

Fig. 4. Distribution of normalized hoop stress (tension being positive and compression, negative)

load line (θ=90°), parallel to the loading direction and if a weak plane existed at this location, failure could occur in this plane instead of the plane parallel to the platen opening. This could be the possible explanation of the reports of such failures.[19] However no research has been conducted on the validity of the test with such an occurrence of unexpected failure in an unknown failure mode.

4. Comparison of the experimental results in terms of fractography

Although the analytical approach has been proved to be useful for understanding the stress distribution in the hoop test,[14,17,20] no research has been conducted to analyse the failure patterns of the rock specimen in the hoop test, especially the link between the unexpected failure plane and the stress distribution in the load-line from analytical solution. To find the failure mode of the unexpected failure plane, a series of comparison have been conducted among the results from point load test, Brazilian test and hoop test using both fine-grained limestone and coarse-grained granite samples.

4.1 Basic principle and application of fractography

Fractography, as the science dealing with the description, analysis and interpretation of fracture surface morphologies and links them to the causative stresses, mechanisms and subsequent evolution of the fractures, can be a good tool when the failure pattern is in question.

An example which shows the basic principle of fractography can be shown as Fig. 5, i.e. the morphology of joint surface depends on the characteristic of joint propagation. Such a principle has been widely used in the interpretation of in-situ stress of core[21]

Another recent study shows that the reconstruction of fracture propagation can be easily obtained from the drawing of escarpments on the surface failed under tension.[23] The same descriptive technique has been adopted in this study to compare the failure patterns of conventional tensile testing and that of hoop test. Photography taken under the inclined light can be used to reveal the roughness of the surface.

4.2 Results from point load test

Failure plane of limestone samples shows the typical characteristic of fracture propagation, i.e. some crushed zone under the compressive loading point (Fig. 6) and the escarpment of tensile failure.

In medium-grained granite, such an escarpment

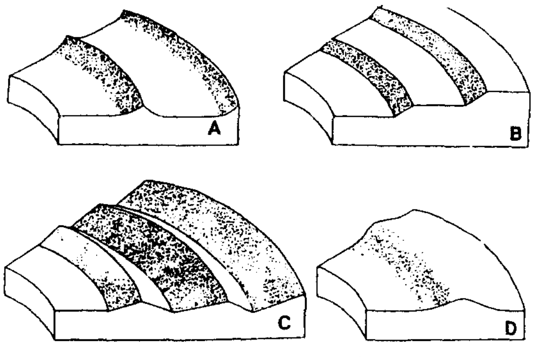

Fig. 5. Relationship between morphology and propagation of joint[22]

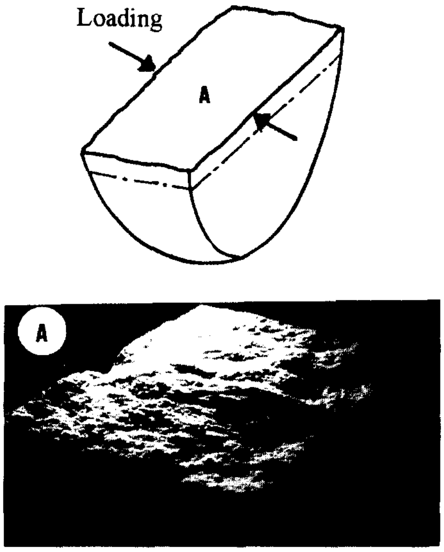

Fig. 6. Failure plane of limestone after point load test

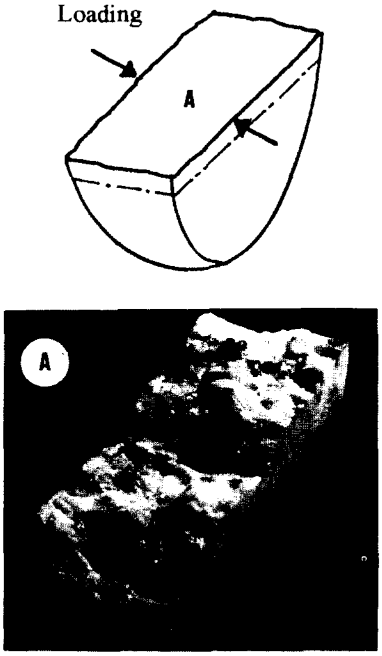

Fig. 7. Failure plane of medium-grained granite after the point load test

can not be easily found. However the breakage of each grain forms similar escarpment which finally resulted in typical rough surface(Fig. 7).

4.3 Results from Brazilian test

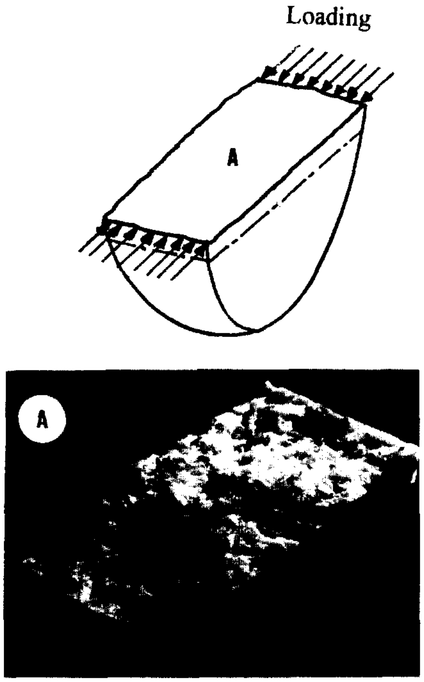

Fig. 8. Failure plane of medium-grained granite after Brazilian test

It was expected that little area could be observed as a result of compressive loading in Brazilian test. The failure surface shows that the typical roughness resulted from the breakage of the grain, which also confirms the tensile failure mode of the surface after Brazilian test(Fig. 8).

4.4 Results from hoop test

The validity of hoop test has been investigated since its invention.[14,19,20,24~25] However no investigation was conducted on the validity of the hoop test especially when the unexpected failure occurs.

The surface of normal failure plane of hoop test shows the typical roughness of tensile mode I, i.e. limestone (Fig. 9) and medium-grained granite (Fig. 10).

The unexpected failure planes of limestone and granite also showed the typical rough plane of tensile failure (Fig. 11, 12). No virtual difference was found between the expected failure plane and the unexpected failure plane in the case of limestone sample.

Slight difference in morphology of failure plane in granite (Fig. 12a) was attributed to the differences in the propagation speed, i.e. the interval of rib mark is highly dependent on the propagation speed. From this it can be assumed that each failure plane

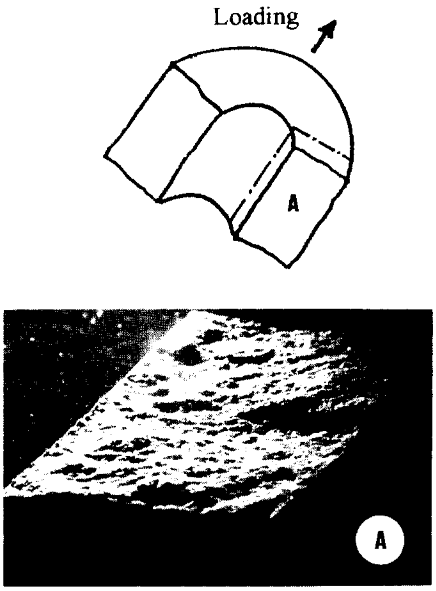

Fig. 9. Failure plane of limestone after hoop test

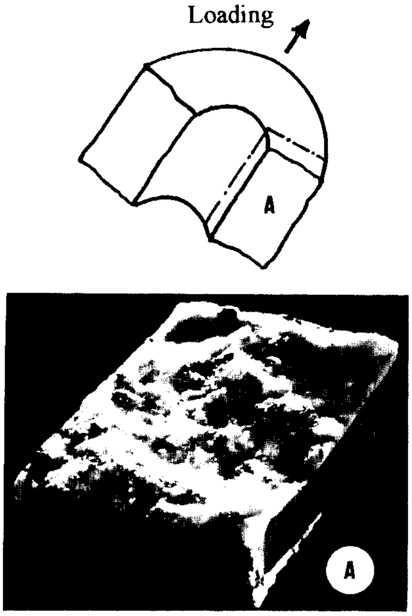

Fig. 10. Failure plane of medium-grained granite after hoop test

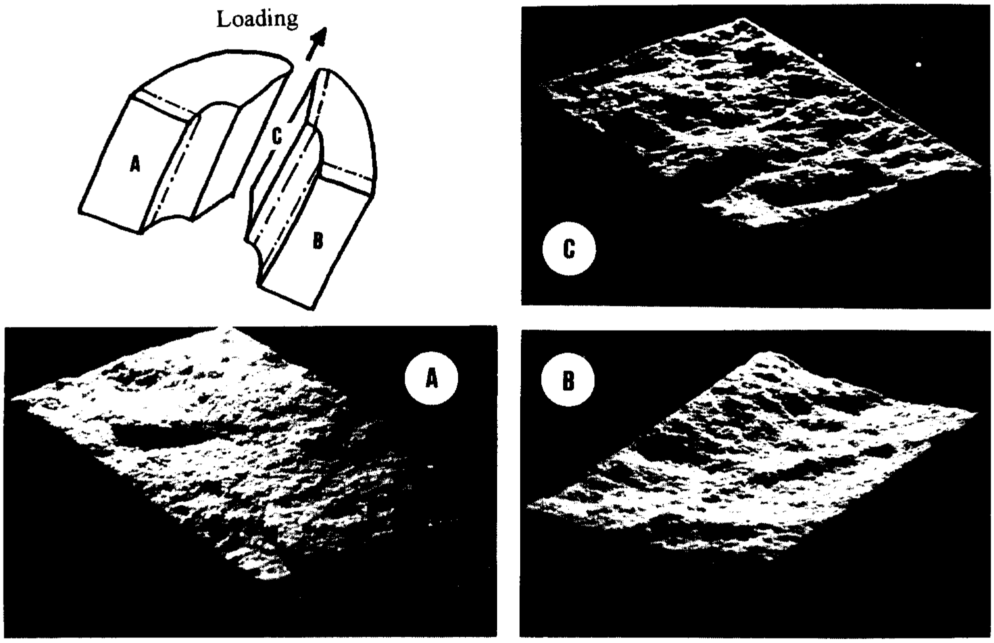

Fig. 11. Morphology of normal and unexpected failure planes of limestone after hoop test (a: unexpected failure plane, b, c: normally occurring failure planes)

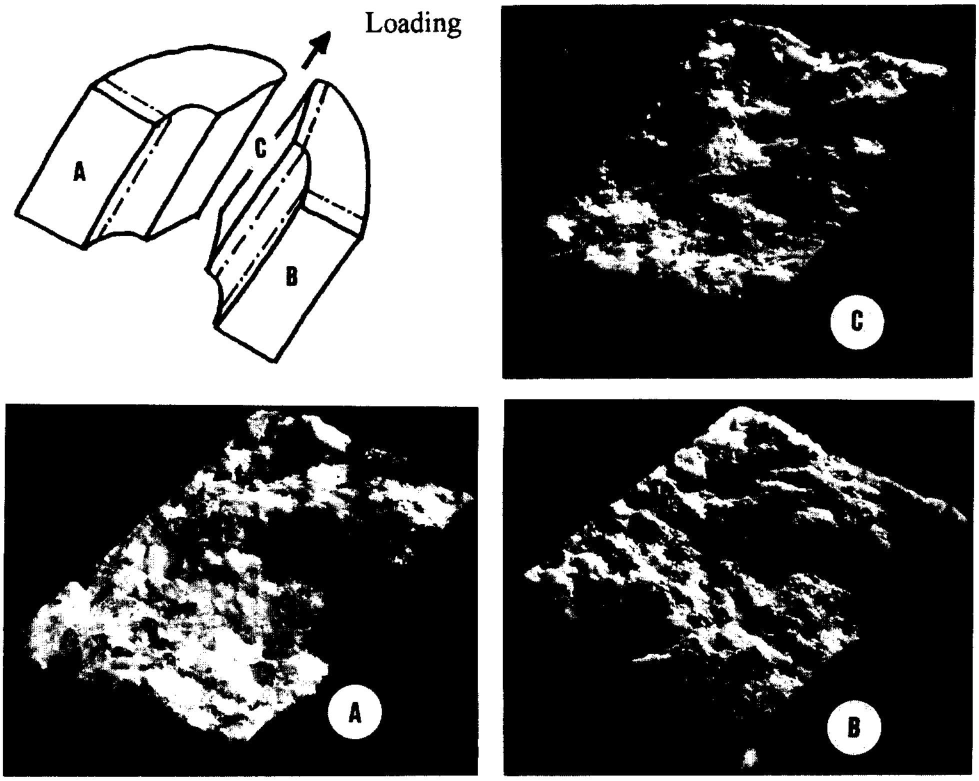

Fig. 12. Morphology of normal and unexpected failure planes of medium-grained granite after hoop test (a: unexpected failure plane, b, c: normally occurring failure planes)

was not created simultaneously since the propagation would accelerate after the failure of other planes.

Although such an order of failure occurrence has not been observed in this study, it was clear enough that the unexpected failure plane was also created by tensile stress.

5. Conclusion and suggestion to future study

From this study the following points could be drawn as final conclusions:

1) Hoop stress is a superimposed results of direct tensile stress and bending moment induced stress. The maximum tensile stress occurring at the inner wall on the plane parallel to the platen opening, is responsible for the initiation of the failure, which has been occurred as tensile mode.

2) Unexpected failure has been occurred in the line parallel to the loadline. A series of comparison among the failure surfaces in terms of fractography, confirmed that such failure plane was also initiated by tensile stress, i.e. typical rough surface of tensile failure plane.

3) The order of the occurrence of the failure planes in hoop test has not been easily determined by usual observation. For the determination of the exact order, it is suggested to conduct a series of hoop tests under high speed camera or using acoustic emission facility. In addition, the quantitative analysis of the roughness of the failure plane is recommended for the better interpretation of the failure mechanism of rock under hoop test. Further study can be focused on the application of the hoop test for the evaluation

of fracture toughness.

Acknowledgements

This paper was supported by NON DIRECTED RESEARCH FUND, Korea Research Foundation, 1996 (Project No: 04-E-0256).

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