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Mode Ⅱ fracture mechanism of direct shearing specimen with guiding grooves of rock①

RAO Qiu-hua(饶秋华)[1], SUN Zong-qi(孙宗颀)[1], WANG Gui-yao(王桂尧)[2],
XU Ji-cheng(徐纪成)[3], ZHANG Jing-yi(张静宜)[3]
(1. College of Resources, Environment and Civil Engineering, Central South University, Changsha 410083, P. R. China;
2. Department of River and Sea, Changsha Communications University, Changsha 410076, P. R. China;
3. Open Lab of Mechanics, Central South University, Changsha 410083, P. R. China)

[Abstract] Fracture mechanism of direct shear specimen with guiding grooves of rock was investigated experimentally and numerically in order to explore a favorable stress condition for creating Mode Ⅱ fracture and guide design of specimen configuration for determining Mode Ⅱ fracture toughness of rock, K_{IIC}. The experimental and numerical results demonstrate that Mode Ⅱ fracture can be successfully achieved in the direct shearing specimen with guiding groove because the guiding grooves added in the notch plane can generate a favorable stress condition for Mode Ⅱ fracture, i. e. tensile stress at the notch tip is completely depressed and shear stress at the notch tip is very high in the notch plane. The optimum design of the specimen configuration for K_{IIC} testing should aim to reduce tensile stress to be compressive stress or be lower than tensile strength and greatly increase shear stress at crack tip.

[Key words] Mode Ⅱ fracture; fracture mechanism; rock; direct shearing test; guiding groove
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1 INTRODUCTION

Mode Ⅱ (shear) fracture is one of typical failure patterns in rock engineering. It has attracted an increasing attention in recent years, through both theoretical study of fracture criterion[1~4] and laboratory testing of fracture toughness[5~8]. Although a number of testing methods have been proposed to measure Mode Ⅱ fracture toughness of rock, K_{IIC}, there is no standard method available for K_{IIC} to date. The reason is that these methods are based on applying a pure shear load to the specimen regardless of fracture pattern. However, the pure shear loading is not certain to results in a true Mode II fracture. For example, in direct shearing specimen, the newly initiated crack is usually propagated deviating from original notch plane and the fracture is of Mode Ⅰ. Numerical calculations show that under pure shear loading both tensile and shear stresses exist at notch tip and they have the same order of magnitude[9]. Since tensile strength of rock is much smaller than its shear strength, Mode Ⅰ easily occurs. When guiding grooves are introduced to the direct shearing specimen, Mode Ⅱ fracture can be successfully achieved.

In this study fracture mechanism of the direct shearing specimen with guiding grooves is investigated experimentally and numerically in order to explore an appropriate stress condition for creating Mode Ⅱ fracture and provide a guidance of specimen configuration design for determining K_{IIC}.

2 TEST ARRANGEMENT

Rock type used in this study is marble. Its mechanical properties, i. e. the tensile strength σ_t, uniaxial compressive strength σ_c, internal friction angle ϕ, cohesion C, elastic modulus E and Mode Ⅰ fracture toughness K_{IC}, were obtained by ISRM (the International Society for Rock Mechanics) standard testing methods. These values are listed in Table 1.

Table 1 Mechanical properties of rocks

Rock type	σ_t/MPa	σ_c/MPa	ϕ/(°)
Marble	2.6	66	48
Rock type	**C/MPa**	**E/GPa**	**K_{IC}/(MPa·m$^{1/2}$)**
Marble	17	23	0.91

Fig. 1 shows the configuration of the direct shearing specimen with guiding grooves and loading form. The pure shear load is applied to the notch plane through two angle-steel plates anti-symmetrically glued on the specimen. Table 2 gives dimensions of the specimen. Straight through notch, 0.8 mm wide

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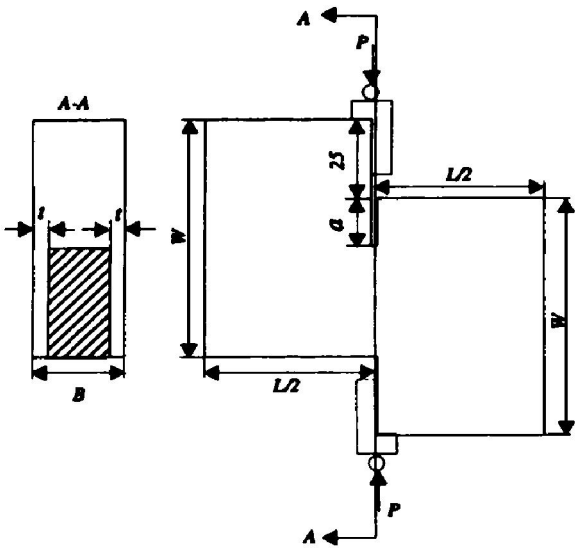

Fig. 1 Direct shearing specimen with guiding grooves (unit: mm)

and guiding groove, 8.5 mm deep, was cut by a diamond disc saw. Great care should be taken in preparing the notch and guiding groove in order to avoid any damage to the specimen. All tests were carried out on a servo-controlled Instron 1342 press with a capacity of 100 kN under position control. The peak load was recorded and the fracture surface was carefully examined by a scanning electron microscope (SEM) after tests.

Table 2 Dimensions of direct shearing specimens with guiding-grooves

Specimen No.	$L \times W \times B$ /mm	a /mm	$2 \times t$ /mm	$B - 2 \times t$ /mm
M1	100 × 75.1 × 30.0	16.0	2 × 8.5	13.0
M2	100 × 74.8 × 30.0	19.0	2 × 8.5	13.0
M3	100 × 75.2 × 29.8	15.1	2 × 8.5	12.8
M4	100 × 75.0 × 30.3	16.0	2 × 8.5	13.3
M5	100 × 75.6 × 30.3	21.5	2 × 8.5	13.3
M6	100 × 75.2 × 30.0	16.0	2 × 8.5	13.0
M7	100 × 74.8 × 30.5	14.5	2 × 8.5	13.5

3 TEST RESULTS

Fig. 2 shows the fracture trajectory of the direct shearing specimen with guiding grooves. It is seen that under pure shear loading the crack is initiated and propagated nearly in the notch plane. It may be considered that Mode II fracture occurs in this specimen.

For the direct shearing specimen with guiding-grooves, the shear stress intensity factor K_{II} can be calculated by the following formula[10], if the thickness of the specimen B is substituted with the net thickness of the specimen, $B - 2t$.

$$K_{II} = 2P \left| \frac{1.30 - 0.65(a_1/W)}{(B-2t)\sqrt{\pi a}\sqrt{1-a_1/W}} + \frac{0.37(a_1/W)^2 + 0.28(a_1/W)^3}{(B-2t)\sqrt{\pi a}\sqrt{1-a_1/W}} \right| \quad (1)$$

where a_1 is apparent length of the notch and $a_1 = a + 25$ for single-notched specimen (Fig. 1).

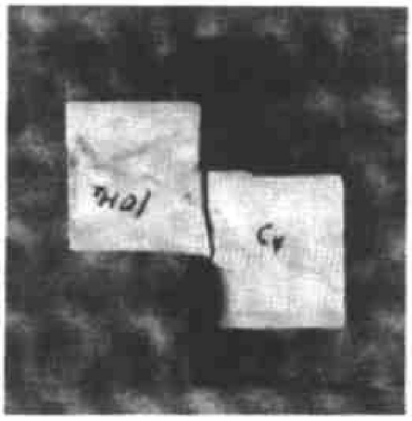

Fig. 2 Fracture trajectory of specimen

Table 3 shows the results of peak load and Mode II fracture toughness K_{IIC}. It is found that the measured K_{IIC} is much larger than K_{IC} and about 2~4 times of K_{IC}. It may be considered a reasonable value of Mode II fracture toughness of rock.

Table 3 Results of direct shearing specimen with guiding-grooves

Specimen No.	Peak load /kN	Crack initiation angle/(°)	Fracture toughness /(MPa·m$^{1/2}$)	$\frac{K_{IIC}}{K_{IC}}$	Fracture mode
M1	3.80	0	2.66	2.92	Mode II
M2	4.13	0	2.94	3.23	Mode II
M3	5.00	0	3.55	3.90	Mode II
M4	4.00	0	2.74	3.01	Mode II
M5	5.70	0	4.00	4.40	Mode II
M6	5.10	0	3.57	3.92	Mode II
M7	3.82	0	2.58	2.84	Mode II
Mean value			3.15	3.46	

4 DISCUSSION

Fracture mechanism of the direct shearing specimen with guiding grooves can be investigated by stress and SEM analyses.

4.1 Stress analysis

Finite element method is used to calculate stress distribution in the specimen. Three-dimensional brick elements were adopted and the whole specimen was modeled. Figs. 3 and 4 illustrate typical contours of maximum principal stress σ_1 and maximum shear stress τ_{max} in the notch plane and in the longitudinal plane through the root of the guiding groove, respectively, where tensile stress is defined as positive.

It is found that σ_1 and τ_{max} at the notch tip are equal to −2 MPa and 8 MPa in the notch plane and 0.5 MPa and 4 MPa in the longitudinal plane. That

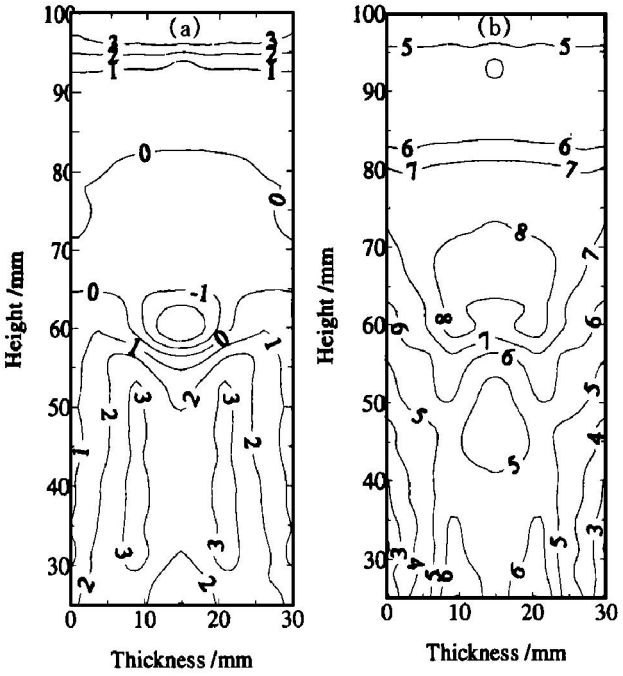

Fig. 3 Stress contours in notch plane
(The notch tip is at 60 mm)
(a) $-\sigma_1$, MPa; (b) $-\tau_{max}$, MPa

means the guiding groove added in the notch plane can completely depress the tensile stress at the notch tip and compressive stress appears in the notch plane. Furthermore, the guiding groove can create a very high shear stress in the notch plane. Since σ_1 in the longitudinal plane is lower than tensile strength of rock and τ_{max} in the longitudinal plane is smaller than that in the notch plane, the newly initiated crack propagates in the notch plane rather than in the longitudinal plane. The fracture is caused by the high shear stress in the notch plane and thus of Mode II.

4.2 SEM analysis

For the direct shearing specimen with guiding grooves, the fracture surface has a slightly saw-like shape, see Fig. 5. Fig. 6 shows its SEM fractographs in details. It is observed that the upper saw surface *A* is formed by the cleavage fracture and has a few tearing ridges (Fig. 6(a)). A number of tearing ridges appears in the step surface *B* (Fig. 6(b)). In the bottom saw surface *C*, there are much more tearing ridges and short streamline patterns (Fig. 6(c)). That means when the crack propagates from the former saw surface to the next one, the number of tearing ridges increases and a large quantity of energy is dissipated during the fracture process. Therefore a large value of K_{IIC} is obtained. On the whole the fracture surface is formed by shearing deformation.

The reason for this special fracture surface pattern may be attributed to the effect of the compressive stress existing in the notch plane on the direction of the maximum shear stress τ_{max}. Fig. 7 gives the contours of the angle θ_τ, i. e. the direction of τ_{max}, with respect to the notch plane, where the clockwise direction of θ_τ is defined as positive. It is found that the

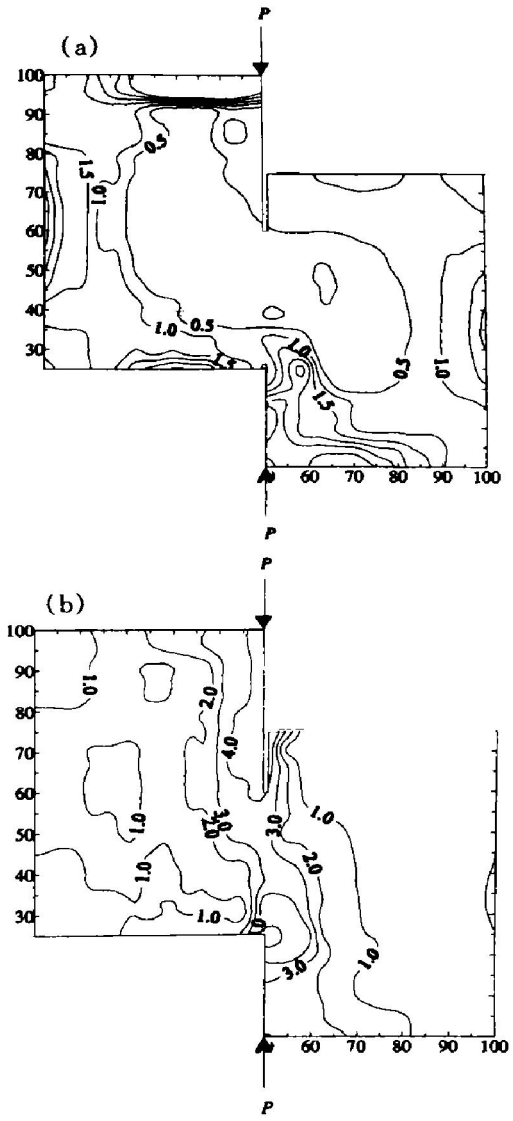

Fig. 4 Stress contours in longitudinal plane through root of guiding-groove
(a) $-\sigma_1$, MPa; (b) $-\tau_{max}$, MPa

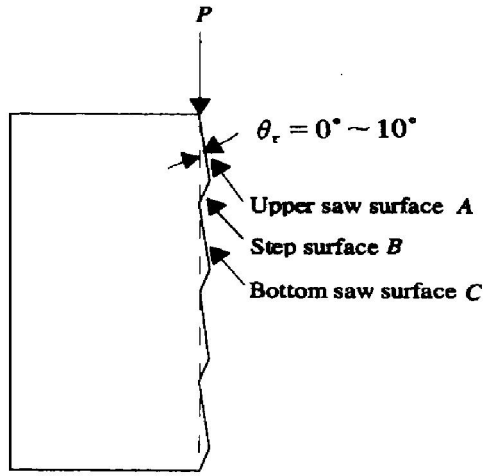

Fig. 5 Fracture surface pattern of specimen

existence of the compressive stress in the notch plane makes θ_τ is in the range between $-10°$ and $10°$, i. e. the direction of τ_{max} deviates at $\pm 10°$ from the notch plane. Since τ_{max} in the notch plane is very high and σ_1 is completely depressed, in comparison with those in the longitudinal plane, the crack is initiated and propagated in the direction of τ_{max} in the notch plane.

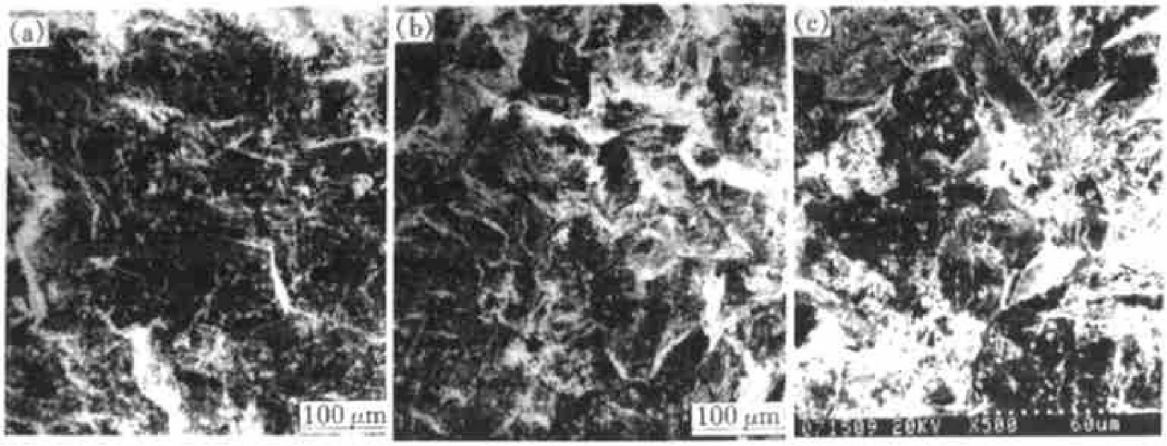

Fig. 6 SEM fractographs of fracture surface of specimen
(a) —Upper saw surface *A* (×100); (b) —Step surface *B* (×100); (c) Bottom saw surface *C* (×500)

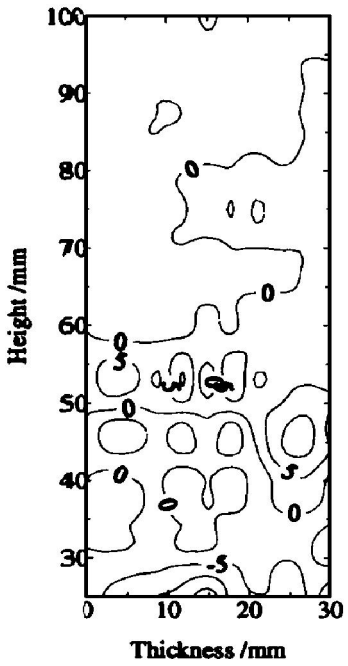

Fig. 7 Contours of θ_τ with respect to notch plane
(The notch tip is at 60 mm)

The fracture trajectory varies within − 10° and 10° deviating from the notch plane and therefore forms a slightly saw-like fracture surface.

5 CONCLUSIONS

1) Mode Ⅱ fracture of rock can be successfully achieved in the direct shearing specimen with guiding groove. The guiding grooves added in the notch plane can not only completely depress the tensile stress at the notch tip, but also create a very high shear stress in the notch plane, and thus enable the newly initiated crack propagates in the notch plane.

2) Stress distribution at the crack tip plays an important role in fracture mode. The optimum design of specimen configuration for achieving Mode Ⅱ fracture should aim to depress the tensile stress and create a very high shear stress at the crack tip.

3) The principal microscopic characteristic of Mode Ⅱ fracture is the existence of many tearing ridges and streamline patterns in the fracture surface, which is caused by the action of shear stress.

4) The measured K_{IIC} in the direct shearing specimen with guiding groove is much larger than K_{IC}, which is about 2~ 4 times of K_{IC}, and may be considered a reasonable value of Mode Ⅱ fracture toughness of rock.

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