THEORETICAL AND EXPERIMENTAL STUDIES ON FRACTURE PLANE CONTROL BLAST WITH NOTCHED BOREHOLES①

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ABSTRACT The results of theoretical studies and field tests on fracture plane control blast with notched boreholes have been introduced. In these studies, the single symmetrical notched borehole was simplified to a pressurized hole with two symmetrical cracks under the state of plane strain. In analyzing the growth and termination of the notch, only quasi-static pressure was considered. In the mean time, the rock to be blasted was considered to be isotropic. Based on the principles of fracture mechanics, the stress components near the tip of the notch were calculated, and the criteria for growth and termination of the notch were established. The growth direction of the notch was also predicted on the basis of strain energy density factor. An approach for estimating the amount of explosive for each hole and the spacing of holes was suggested. Furthermore, field tests were conducted to check the results from the theoretical studies.

Key words fracture plane control blast notched borehole fracture mechanics

1 INTRODUCTION

During recent years, quite a few investigators have worked on fracture plane control blast with notched boreholes. Successful applications have been reported from several sources[1]. So far, this technique has developed to an extent that it can be applied in producing a satisfactory presplit along the excavation contour in rocks.

However, the mechanism of how the notches control generation and growth of a fracture plane has not been fully understood. Also the amount of explosive for each hole and the spacing of holes are mostly based on trial and error.

As a result, the author attempts to explain the mechanism by employing fundamental principles of fracture mechanics and to establish an approach in estimating the amount of explosive for each hole and the spacing of holes.

2 MECHANISM

Although the fracture plane is achieved in a very short time frame, it is generated at two stages-growth and termination.

2.1 Growth of notch

The symmetrically notched borehole is the most common one to be employed in fracture plane control blast with notched boreholes, therefore, only such case is considered in this paper. The borehole can be simplified to a pressurized hole with two symmetrical cracks under the state of plane strain. In analyzing the growth and termination of the notch, only quasi-static pressure is considered, and the rock to be blasted is considered to be isotropic. On these conditions, the fracture mechanics model for notched borehole blasting is represented in Fig.1.

The stress field near the tip of a notch can be given as below[2-5]:

$$\sigma_r = \frac{K_I}{\sqrt{2\pi r}}\left[\frac{5}{4}\cos\frac{\theta}{2} - \frac{1}{4}\cos\frac{3\theta}{2}\right] \quad (1)$$

$$\sigma_\theta = \frac{K_I}{\sqrt{2\pi r}}\left[\frac{3}{4}\cos\frac{\theta}{2} + \frac{1}{4}\cos\frac{3\theta}{2}\right] \quad (2)$$

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$$\tau_{r\theta} = \frac{K_I}{\sqrt{2\pi r}}\left[\frac{1}{4}\cos\frac{\theta}{2} + \frac{1}{4}\cos\frac{3\theta}{2}\right] \quad (3)$$

where σ_r, σ_θ and $\tau_{r\theta}$ are the diametrical, tangential and shearing stresses, respectively; r and θ are the polar coordinates of a point around the tip of the notch. K_I is defined as dynamic stress intensity factor, it can be determined from following formula[6]:

$$K_I = Fp[\pi(r_0 + a_c)]^{1/2} \quad (4)$$

where p is the quasi-static pressure in the blast hole; r_0, its radius; a_c, diametral length of the notch; F, the correction coefficient.

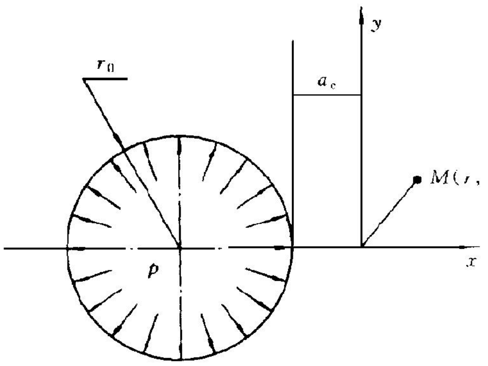

Fig.1 Fracture mechanics model for fracture plane control blast with notched boreholes

When the stress intensity factor is larger than the dynamic fracture toughness of the rock under the state of plane strain, the notch will extend, and a fracture plane will develop. The criterion for the growth of the notch can be described as below:

$$K_I = K_{ICD} \quad (5)$$

where K_{ICD} is the dynamic fracture toughness of the rock under the state of plane strain. It can be determined from the following empirical formula[7]:

$$K_{ICD} = 1.6\, K_{ICS} \quad (6)$$

where K_{ICS} is the static fracture toughness of the rock under the state of plane strain.

2.2 Growth direction of notch

The growth direction of the notch can be determined with reference to the criterion of strain energy density factor. The criterion states that the notch which has been simplified to a crack will grow further along the direction at which the strain energy density factor achieves its minimun value. The strain energy density factor can be expressed as bellow:

$$S = \frac{K_I}{4G}(3 - 4\mu - \cos\theta)(1 + \cos\theta) \quad (7)$$

where S is the strain energy density factor; K_I, the dynamic stress intensity factor at the tip of the notch (Eqn.(4)); G, the shearing modulus of the rock; μ, the Poisson's ratio; θ, the angle between the growth direction of the notch and the notch itself.

The conditions under which the strain energy density factor reaches its minimum value can be expressed as follows:

$$\partial S/\partial \theta = 0 \quad (8)$$

and

$$\partial^2 S/\partial \theta^2 > 0 \quad (9)$$

From Eqns.(8) and (7), the following results can be derived:

$$\theta = 0 \quad (10)$$

and

$$\theta = \arccos(1 - 2\mu) \quad (11)$$

Furthermore, the following expression can be obtained from Eqn.(7)

$$\frac{\partial^2 S}{\partial \theta^2} = \frac{K_I}{2G}[2\cos^2\theta - (1 - 2\mu)\cos\theta - 1] \quad (12)$$

so that, only when $\theta = 0$, can Eqn.(9) be satisfied. This implies that the notch will grow along the same direction as itself.

2.3 Termination of crack

With further growth of the notch, the explosion-generated gases continuously fill up the fracture. Simultaneously, the quasi-static pressure drops off very rapidly, leading to an eventual termination of the crack. The stress state near the blast hole at the time when further fracturing stops is shown in Fig.2. The criterion for termination of the further extension of the notch can be expressed as below[6]:

$$0.2\, p[\pi(r_0 + l)]^{1/2} \leqslant K_{ICD} \quad (13)$$

where l is the final length of the fracture.

3 ESTIMATION OF AMOUNT OF EXPLOSIVE IN NOTCHED BOREHOLE

The amount of explosive in a notched borehole can be estimated in the following way.

Firstly, the gas pressure can be calculated from the following formula:

$$p_g = \frac{\rho D^2}{2(K+1)} \qquad (14)$$

where p_g is the gas pressure generated by a detonating charge in Pa; ρ, the density of explosive in kg/m^3; D, the detonating velocity in m/s; K, the equivalent entropy coefficient of the explosive, typically 2.

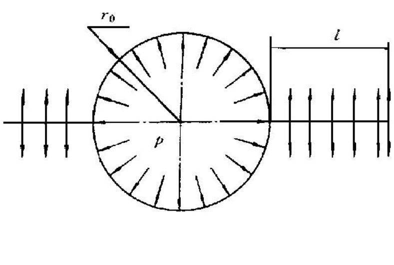

Fig.2 Stress state when further fracturing stops

Secondly, the quasi-static pressure can be calculated from the following:

$$p = p_c\left(\frac{p_g}{p_c}\right)^{\upsilon/k}\left(\frac{\Delta}{\rho}\right)^{\upsilon} \qquad (15)$$

$$\Delta = \frac{4Q}{\pi d^2 H} \qquad (16)$$

where p is the quasi-static pressure, Pa; υ, the gas expansion coefficient without any heat exchange (usually 1.4); p_c, the critical pressure generated by detonating the explosive (generally 2×10^9 Pa for No.2 explosive for rock blasting); Δ, the volume density of explosive in a borehole in kg/m^3; Q, the weight of explosive loaded in a borehole in kg; d, the hole diameter in m; H, the hole depth in m.

Thirdly, the symmetrically notched borehole is considered equivalent to the plane strain fracture problem under mode I loading. The stress intensity factor can be determined from the following expression:

$$K_I = 0.2p[\pi(d/2 + a_c)]^{1/2} \qquad (17)$$

where K_I is the dynamic stress intensity factor, N·m$^{-3/2}$; a_c, the diametrical length of a single notch in m.

Fourthly, in order to make the notches extend and avoid damage to the borehole wall by detonation, the stress intensity factor should be larger than the dynamic fracture toughness of the rock to be blasted, and the quasi-static pressure should be less than the dynamic compressive strength of the rock. Therefore, the following reqirement can be established:

$$\frac{K_{ICD}}{0.2[\pi(d/2 + a_c)]^{1/2}} < p < \sigma_{CD} \qquad (18)$$

where σ_{CD} is the dynamic compressive strength of the rock.

Finally, the amount of explosive in a borehole can be estimated from Eqn.(19):

$$\frac{\pi d^2 H\rho}{4}\left[\frac{K_{ICD}}{0.2p_c[\pi(d/2 + a_c)]^{1/2}} \times \left(\frac{2(K+1)gp_c}{\rho D^2}\right)^{\upsilon/k}\right]^{1/\upsilon} < Q < \frac{\pi d^2 H\rho}{4}\left[\frac{\sigma_{CD}}{p_c}\left(\frac{2(K+1)gp_c}{\rho D^2}\right)^{\upsilon/k}\right]^{1/\upsilon} \qquad (19)$$

4 ESTIMATION OF HOLE SPACING

Once the amount of explosive in a notched borehole has been estimated, the spacing of holes can be determined[8].

Firstly, since the spacing is much larger than the radius of the hole, the dynamic stress intensity factor has to be calculated from the following formula[9]:

$$K_I = \frac{pd}{[(\pi/2)W]^{1/2}} \qquad (20)$$

where W is the spacing between centres of the holes in m.

Then, by employing the criterion of fracture mechanics, the following expression for estimating the spacing can be obtained:

$$W = \frac{2}{\pi}\left(\frac{p}{K_{ICD}}\right)^2 \qquad (21)$$

5 FIELD TESTS

Five tests were conducted at Shuangfeng marble quarry in Hunan province, each consisting of five vertical holes which were 4 cm in diameter and 100 cm in depth. Each of the two symmetrical notches had a diametral length of 4 mm and a depth of 70 cm from the collar to the bottom. The properties of the marble formation are listed in Table 1.

The explosive cartridge, made from the No.2 Explosive for rock blasting was used. Its physical properties are listed in Table 2.

Table 1 Properties of marble formation

Dynamic uniaxial compressive strength/ MPa	Dynamic fracture toughness / ($N \cdot m^{-3/2}$)
72	7.3×10^5

Table 2 Properties of No.2 explosive

Density / ($g \cdot cm^{-3}$)	Detonating velocity / ($m \cdot s^{-1}$)	p_c/ Pa
1.0	3 000	2×10^9

Each explosive cartridge was 25 mm in diameter and 200 mm in length. After loading of the explosive cartridges, the boreholes were stemmed.

The estimated amount of explosive was calculated from Eqn.(19), and the estimated spacing of holes was calculated from Eqn.(21). Both of them were 49 ~ 100 g and < 1.02 m, respectively. The practical amount of explosive in each hole and spacing of holes in tests were 100 g and 0.5 m respectively. The test results showed that a presplit was formed in each test.

6 CONCLUSIONS

The following conclusions have been obtained from the studies.

(1) It has been shown that both generation and growth of a fracture plane can be easily accomllished by employing notched borehole blasting.

(2) The fracture mechanics model established in this paper gives a satisfactory explanation of how the notch controls the generation and growth of a fracture plane.

(3) The computation methods, suggested for estimating the amount of explosive in a notched borehole and spacing of holes, are based on the principles of fracture mechanics, and confirmed by a few field tests. Further field trials have to be carried out to validate these findings.

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