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Fracture mechanism due to blast-imposed loading under high static stress conditions

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ABSTRACT

Using a dynamic-static experimental loading device and a digital laser dynamic caustic system, the effect rules for blasting induced main cracks responding to an initial static stress field are studied. The propagation rules of a 45° oblique crack subjected to different initial static stress fields and of cracks with different angles and initial static stress fields are also studied. The experiment results show that: (1) Under an initial static stress load, different stress concentrations are generated around boreholes, and the maximum tensile stresses are generated in the direction of the maximum principle stress of the borehole. The combined action of the initial static stress field and dynamic blasting stress field causes the longest crack to propagate in the direction of initial static stress preferentially. The initial static stress field changes the distribution characteristics of the blasting-induced cracks. (2) The level of the stress concentration increases, the propagation direction of the main crack is deflected along the direction of the principle stress, the propagation time of the main crack becomes shorter, the mode II fractures of specimens are more severe, and the maximum deflection angle of the main crack increases as initial static stress load increases. (3) As the angle between crack and initial static stress load direction increases, the propagation times of the main cracks decrease, and the occurrence of an obvious shear fracture occurs in the main crack more quickly. Also, with the increased angle between crack and initial static stress load direction, the peak values of the reflecting angles gradually increase, and the displacement along the pre-existing crack direction decreases showing the crack path becomes more flexural.

1. Introduction

Blasting operations in deep rock show different rock fracture characteristics than those in shallow rock. Deep rock destruction results from the combined action of high ground and blasting stress levels; therefore, the presence of high ground stress should not be ignored. However, the blasting theory and techniques for deep rock masses are not yet mature. Currently, many blasting parameters in deep rock masses are based on those for shallow rock masses and do not consider the effects of ground stresses, which can lead to unsatisfactory blasting results. Rock fracturing is a process of crack initiating, propagating and arresting under external loading. Therefore, the blast fracturing of deep rock is a process of crack propagation under the combined action of high ground and blasting stresses. Hence, studying how the ground stress fields affect blasting fracture processes is a basic research question and will enrich our understanding of the fracture mechanisms of deep rock masses, making this question important for the advancement of high-efficiency mining of deep coal resources.

In recent years, many experts and scholars have performed in-depth studies of rock-blasting and fracture mechanisms. However, due to the complexity of blasting, an analytical solution for even a simple blasting problem is quite difficult, so laboratory experiments and numerical analyses are the main methods for studying such problems. Kutter[1] and Rossmanith[2] experimental found that blasting-induced cracks propagate in the direction of the maximum principle stress. During field blasting tests in an underground chamber, Lu[3] finds that the in situ stress field has obvious effects on blasting parameter designs. Yang[4,5] uses caustic experiments to research the propagation laws of the main and secondary blasting cracks a combined dynamic-static stress field. The finite element method, boundary element method, finite difference method and discrete element method are the main computing methods that are appropriate for rock-blasting simulations. Many scholars[6–12] have thoroughly researched and attempted the application of such methods. Ma[13] used LS-DYNA to study the relation between ground stress fields and rock fractures and found that ground stresses obviously affect rock fractures; specifically, the ground stress has a guiding role in the propagation and distribution of blasting-induced cracks. Wang and Konietzky[14] uses a combined LS-DYNA and UDEC method to simulate

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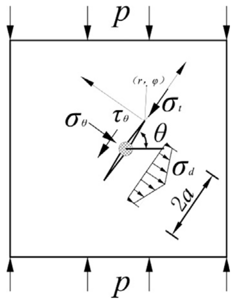

Fig. 1. Crack model under compression.

rock fractures in ground stress fields. Zhu[15–18] used RFPA-Dynamic simulation soft to study two holes blasting and cutting seam cartridge blasting under different in-situ stress conditions. According to these simulations, with the increasing of depth and in-situ stress, initiation and propagation of blasting induced crack is more difficult.

In this paper, we use a dynamic-static loading device and a digital laser dynamic caustic system to study the influence of blasting-induced crack propagation under different initial static fields. The kinematic and mechanical behaviour of blasting-induced cracks are analyzed to establish the relation between the distribution of blasting-induced cracks around the blast hole and the initial static stress field.

2. Theoretical analysis

Consider a plane elastic problem of a unit cell (infinite plate) containing a hole and a single pre-existing closed crack with length of $2a$ subjected to remote compressive stresses p in the lateral direction, as shown in Fig. 1. The orientation of the microcrack to the horizontal axis is given as the angle θ. The resolved shear stress τ_θ and the normal stress σ_θ on the crack face are given as

$$\begin{aligned} \sigma_\theta &= p\cos^2\theta \\ \tau_\theta &= p\sin\theta\cos\theta \end{aligned} \tag{1}$$

The stress intensity factors K_{I} and K_{II} at the crack tip are

$$\begin{aligned} K_{\mathrm{I}} &= -\sigma_\theta\sqrt{\pi a} = -p\sqrt{\pi a}\cos^2\theta \\ K_{\mathrm{II}} &= -\tau_\theta\sqrt{\pi a} = -p\sqrt{\pi a}\sin\theta\cos\theta \end{aligned} \tag{2}$$

where K_{I} and K_{II} are both negative. Under compressive loading, there is no physical meaning to the "opening" mode mentioned previously. K_{I} is negative and therefore causes the closure of cracks. A negative value of K_{II} implies only an opposite direction to the shear stress component and consequently, a different angle of incipient crack extension, which will be discussed later.

In blasting mechanics, the crack is loaded by a blasting stress wave and detonation gas pressure. To simplify the blasting model, an equivalent dynamic stress σ_d, which is a linear stress load, is applied to the crack, yielding a stress intensity factor of K_{I} at the crack tip,

$$\begin{aligned} K_{\mathrm{I}} &= \sigma_d\sqrt{\pi a} \\ K_{\mathrm{II}} &= 0 \end{aligned} \tag{3}$$

By superimposing the stress intensity factors from (2) and (3) and according to Williams,[19] the linear elastic stress components around the crack tip are written as infinite series expansions as follows:

$$\begin{aligned} \sigma_r &= \frac{1}{2}\sqrt{\frac{a}{2r}}\left[\sigma_d(3-\cos\phi)\cos\frac{\phi}{2} - p\sin\theta\cos\theta(3\cos\phi-1)\sin\frac{\phi}{2}\right] \\ \sigma_\phi &= \frac{1}{2}\sqrt{\frac{a}{2r}}\cos\frac{\phi}{2}\left[\frac{1}{2}\sigma_d\cos^2\frac{\phi}{2} + 3p\sin\theta\cos\theta\sin\phi\right] \\ \tau_{r\phi} &= \frac{1}{2}\sqrt{\frac{a}{2r}}\cos\frac{\phi}{2}[\sigma_d\sin\phi - p\sin\theta\cos\theta(3\cos\phi-1)] \end{aligned} \tag{4}$$

Following Erdogan and Sih,[20] the maximum tangential stress criterion suggests that, in a brittle material, crack propagation initiates along the direction φ, which corresponds to the maximum tangential stress at the crack tip. The angle φ can be found from $\frac{\partial\sigma_\varphi}{\partial\varphi} = 0$,

$$p\sin 2\theta\left(2\cos\frac{\varphi}{2}\cos\varphi - \sin\frac{\varphi}{2}\sin\varphi\right) = \sigma_d\sin\frac{\varphi}{2}\cos^2\frac{\varphi}{2} \tag{5}$$

Eq. (5) states that the direction of fracture initiation is determined by the static compressive stress p and the dynamic stress σ_{d}. When $\sigma_{\mathrm{d}} = 0$, the crack is a II-mode crack and the φ is 70.5°; when $p = 0$, the crack is a I mode crack and φ is 0°; and when p and σ_{d} are not zero, the crack is mix-mode and φ is determined by

$$n = \frac{p}{\sigma_d} = \frac{\sin\frac{\varphi}{2}\cos^2\frac{\varphi}{2}}{\sin 2\theta\left(2\cos\frac{\varphi}{2}\cos\varphi - \sin\frac{\varphi}{2}\sin\varphi\right)} \tag{6}$$

The relation between φ and θ is shown in Fig. 2.

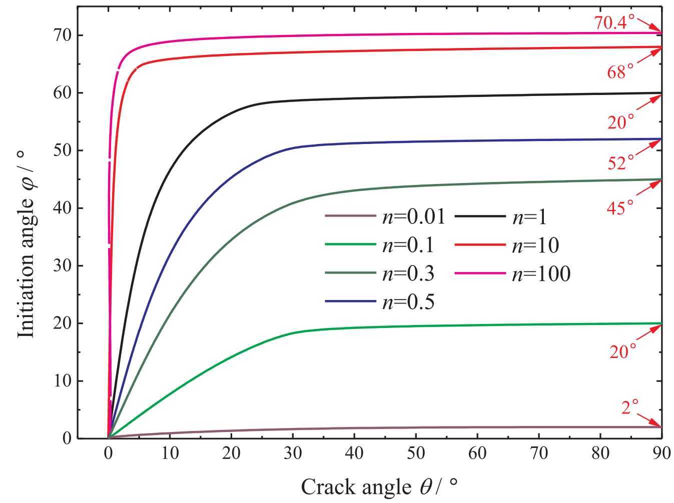

Fig. 2. Relation between φ and θ.

3. Principle of caustics

Caustics[21] is a useful experimental mechanics method on resolving stress concentration problem, such as crack and impact. When a component is subjected to a force, the thickness and refractive index of the component will change, affecting the direction of the propagation of light through the component. Due to the change of the refractive index, the parallel lights become scattered when penetrating such a component. This creates dark areas called caustic spots in the reference plane, and the boundary of a caustic spot is called caustics.

3.1. The caustics at the crack tip

Considering a plate with cracks in the dynamic stress field, a caustic is generated at the crack tip. Eq. (7) is the calculation formula for the static stress intensity factor K_{I} at a mode I crack under static loading, and Eqs. (8) and (9) are the calculation formulas of the dynamic stress intensity factors K_I^d and K_{II}^d for mode I-II cracks under dynamic loading.

$$K_I = \frac{2\sqrt{2\pi}}{3z_0 d_{eff} cg^{5/2}}\cdot D_{\max}{}^{5/2} \tag{7}$$

$$K_I^d = F(\nu)\cdot K_I \tag{8}$$

$$K_{II}^d = \mu\cdot K_I^d \tag{9}$$

Where $D_{\max}$ is the maximum diameter of the caustics along the crack propagation; g is a constant of the stress intensity factor; d_{eff} is the thickness of the specimen; c is the optical constant of the specimen; z_0 is the distance between the specimen and the reference plane; $F(\nu)$ is a