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Model experiment on dynamic behavior of jointed rock mass under blasting at high-stress conditions

Renshu Yang[a,b], Chenxi Ding[a,*], Liyun Yang[a], Cheng Chen[a]

[a] School of Mechanics and Civil Engineering, China University of Mining and Technology (Beijing), Beijing 100083, China
[b] State Key Laboratory for Geomechanics and Deep Underground Engineering (Beijing), Beijing 100083, China

A R T I C L E I N F O

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A B S T R A C T

The blasting response of jointed rock mass under high-stress conditions is studied in a laboratory experiment using model specimens. The crack initiation mode and initiation angle at the joint are analyzed, as well as the stress intensity factor and crack velocity. The blasting stress wave increases the stress concentration at the joint which promotes crack initiation and propagation. The dynamic behavior of the crack can be divided into two stages – the initiation stage and the propagation stage. The theoretical criterion based on the minimum strain energy density factor can well predict and explain the crack initiation behavior under blasting loading. The high-stress condition enhances the degree of shear failure of the crack initiation at the joint, which has significant effects on the dynamic behavior of subsequent crack propagation and leads to larger crack initiation angles.

1. Introduction

As shallow earth resources are being exhausted, the exploitation of coal and other mineral resources is expanding into greater depths. Thus, the mining environment is becoming more complex and challenging for mining engineers. Deep mining is characterized by high ground stress compared with shallow mining. Therefore, construction methods such as drilling and blasting should take into account the high-stress characteristics of deep mining, so that relevant technological innovation can be applied to achieve efficient resource development.

Drilling and blasting is a traditional and effective construction method, widely used in deep roadway excavation and rock breakage. During blasting excavation operations for an underground hydropower station, Lu et al. (2012) found that high ground stress was one of the main factors affecting the propagation of blasting-induced cracks. They concluded that when the ground stress exceeded 10–12 MPa, it was unreasonable to carry out the blasting plan in deep rock mass based entirely on blasting plans designed for shallow rock mass. Under blasting loading, crack propagation parallel to the maximum principal stress direction was significantly enhanced by high ground stress (Donzé et al., 2008; Ma and An, 2008; Xie et al., 2017; Yang et al., 2014). Bai et al. (2013) believed that in the blasting plan of deep rock mass, appropriate increase of the hole spacing in the direction of maximum principal stress can improve the blasting quality and reduce the number of explosives needed. Nevertheless, in most blasting plans of deep rock mass, the high ground stress is not taken into account, resulting in incorrect use of the explosive energy and poor blasting results.

Natural rock mass contains a large number of defects such as joints, holes, and cracks; such defects have an important impact on the damage to jointed rock mass (Rossmanith, 1998; Chen and Zhao, 1998). Wang et al. (2009) and Wang and Konietzky (2009) combined a finite element method (LS-DYNA) and a discrete element method (UDEC) to analyze the dynamic fracture of jointed rock mass under blasting loading. The effects of the bedding angle, stiffness and bedding surface friction coefficient on the failure of the rock mass were also studied. Zhu et al. (2007) adopted the AUTODYN-2D software to simulate the effects of the joint location, width and filling material on the blasting failure of rock mass. They also simulated the failure of defective rock under blasting loading by using the contact blasting model (Zhu et al., 2011). Li and Ma (2010) presented a comprehensive study of the reflection and transmission of a blasting stress wave at a rock joint through theoretical analysis; they developed a wave equation which can be directly used to calculate the reflection and transmission of various incident stress waves at the joint. Yang et al. (2008, 2016) used laboratory experiments to study the obstructive effects of joints on crack propagation, and obtained the evolution trend of the dynamic stress intensity factor and the propagation velocity of cracks which formed at the joint under blasting stress.

There has been growing interest by researchers and engineers in the influence of high ground stress on the blasting fragmentation of deep rock mass. The interaction between the blasting stress wave and joints

* Corresponding author.
E-mail address: dingcx91@sina.com (C. Ding).

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Nomenclature

a	distance from blasting source to joint endpoint
c	optical stress constant
D_{max}, D_{min}	characteristic size of caustics
d_{eff}	effective thickness
E	elastic modulus
$F(v)$	correction factor
g	numerical factor
K_I, K_{II}	mode-I and mode II stress intensity factor
l_x, l_y	horizontal and vertical displacement
PMMA	polymethyl methacrylate
S	strain energy density factor
t	time
v_x, v_y	horizontal and vertical crack propagation velocity
W	strain energy density
z_0	reference distance
α	angle between blasting source and joint
β	deflection angle of incident light
ΔD_{max}, Δd_{eff}	error of D_{max} and d_{eff}
Δz_0, $\Delta\mu$	error of z_0 and μ
Δl_x, Δl_y	horizontal and vertical displacement difference
Δt	time interval
δ_I, δ_{II}	calculation error of K_I and K_{II}
θ	crack initiation angle
μ	ratio coefficient
σ	static stress
σ_x, σ_y, τ_{xy}	stress component of micro-unit
υ	Poisson's ratio

in a normal stress state has been studied extensively. However, the effects of high ground stress during blasting on the dynamic behavior of jointed rock mass are rarely reported, especially the results of experimental studies. An underground blast (under high-stress conditions) was simulated in a faulted rock mass by Aliabadian et al. (2014); their results showed that both the fault and the high-stress conditions in the deep rock mass restricted the propagation of the dynamic fracture and limited the rock mass breakage to an area around the blast hole and the immediate vicinity of the fault. Additionally, numerical simulations conducted by Wei et al. (2016) indicated that high-stress conditions would prevent the formation and propagation of blasting-induced cracks, while existing joints would enhance crack extension as well as guide crack propagation along the joint direction.

In this study, specimens were preloaded in the laboratory to simulate the high-stress state of deep rock mass and to study the dynamic behavior of joint initiation and propagation under blasting stress. The results are helpful to understanding blasting theory and for engineering applications related to deep rock mass.

2. Materials and methods

2.1. Experimental principle

As an experimental method of optical measurement mechanics, the caustics method (Hao et al., 2014; Xing et al., 2017) is widely applied in studies of the crack-tip stress field. Materials deform when subjected to stress, becoming thinner under tensile stress and thicker under compressive stress. For transparent materials without external stress, vertical incident light is transmitted directly, leading to a uniform bright area on the reference plane. Running cracks occur in structures under certain loading conditions. Under these conditions, the optical properties of the stressed area at the crack tip change, causing vertical incident light to refract. The corresponding area on the reference plane therefore becomes a shaded area. This is the basic principle of optical caustics formation. The shaded area on the reference plane is called the caustic spot, and the boundary of the caustic spot represents the caustics. Fig. 1 shows the caustics morphologies at the crack tip with different ratio coefficients μ ($\mu = K_{II}/K_I$). When $\mu = 0$, the crack is classified as a mode-I crack (Fig. 1a); when $\mu > 0$, it is a mixed mode I-II crack (Fig. 1b), where D_{max} and D_{min} are two characteristic sizes of the mixed mode I-II crack caustics. As μ increases, the caustics morphology tends to resemble mode II. Fig. 2 shows the relationship between D_{max}, D_{min} and μ.

Using the relationship shown in Fig. 2, the stress intensity factor at the crack tip can be calculated from Eqs. (1) and (2) (Rosakis, 1980; Papadopoulo, 1992).

$$K_I = \frac{2\sqrt{2\pi}F(v)}{3z_0 d_{eff} c g^{5/2}} D_{max}^{5/2} \tag{1}$$

$$K_{II} = \mu K_I \tag{2}$$

Here, K_I is the mode-I stress intensity factor; K_{II} is the mode-II stress intensity factor; $F(v)$ is the correction factor associated with the running crack velocity and the surface-wave velocity, in practice, $F(v) \approx 1$; d_{eff}, c and g are the effective thickness, optical stress constant and numerical factor of the experimental material, respectively; z_0 is the reference distance for a particular experiment. In this experiment, polymethyl methacrylate (PMMA) is used as the experimental material; the numerical factor g (Sih, 1981) for PMMA is = 3.02, d_{eff} = 6 mm, c = 85 μm^2/N, and z_0 = 900 mm.

2.2. Experimental system

A digital laser dynamic caustics experimental system was used in this paper (Fig. 3). The main components of the system are the laser device (DWGD; 300–1500-mW; Beijing Laserwave Optoelectronics Technology Co., Ltd.), beam expander, field lenses (1200-mm focal length; 300-mm radius), self-designed high-stress loading device, high-speed camera (FASTCAM-SA5), and computer.

Our experiments needed to be performed in a parallel light field, which was obtained by the following steps: the laser device emits a

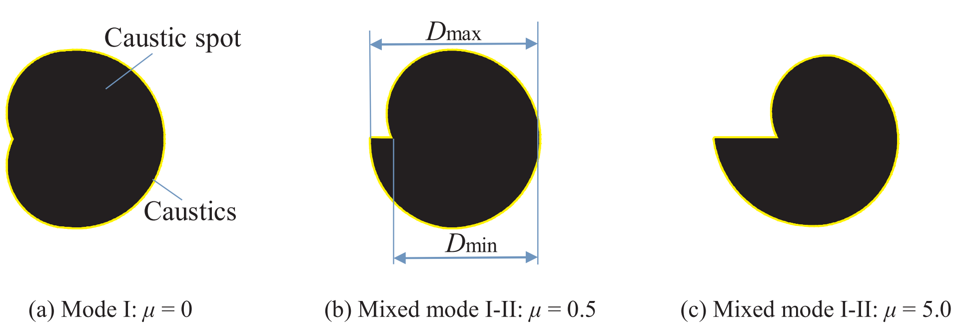

Fig. 1. Caustics morphologies with different ratio coefficient μ.