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Numerical simulation of blasting-induced fracture expansion in coal masses

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ABSTRACT

Bedding planes are common in coal seams, and have a significant influence on the crack expansion of coal masses. In this paper, the fracture patterns of coal masses during the blasting process are explored. Firstly, the damage zone at the tip of beddings is calculated based on the Kachanov equation, and crack connections among bedding planes are also discussed. Secondly, a constitutive model considering dynamic compressive and tensile failure is applied to analyze blasting-induced fracture propagation in coal masses using LS-DYNA software. The bedding plane, which is 0.2 m, 0.4 m and 0.6 m from the borehole respectively, is inserted into coal masses to explore its effects on the reflection and transmission of blasting stress waves. Parallel bedding planes and cross-joint planes are simulated to study fracture patterns during the blasting process. The results indicate that the transmission coefficient (T_{coe}) of stress waves at a bedding plane constantly decreases with increasing distance from the bedding to the borehole, and an increased number of beddings can result in decreased transmission at beddings. The effects of double-borehole blasting are also studied at 0 ms, 1 ms, 2 ms and 3 ms of delay time, respectively. The results indicate that crack initiation and propagation between two adjacent boreholes are closely related to detonation delay time, and fracture networks between two boreholes form when the delay time of adjacent boreholes is more than 3 ms.

1. Introduction

Hard seam weakening is often encountered in underground longwall coal mining. The pre-splitting blasting technique is usually used to generate fractures and control the effects of fragments in the coal seam[1,2]. The loosening of coal seams induced by blasting is considered as a damage process dominated by the combined contribution of the blasting stress wave and blasting-induced gas pressure, as shown in Fig. 1[3,4]. The stress waves determine the initial crack generation and the gas pressure controls the crack growth radially. There are many original cracks in rock masses. Some studies have shown that the internal pre-existing cracks within rock have a significant influence on blasting-induced stress wave propagation around the pre-existing cracks[5,6]. There are many parallel bedding planes in the coal mass, and the beddings may guide crack propagation in the blasting process. The blast stress wave is reflected and transmitted at the bedding planes. However, the effects of reflection and transmission stress waves on the fracture patterns of coal mass during blasting are not clearly understood. Therefore, it is important to investigate crack propagation around pre-existing cracks under blasting load.

Numerical simulation is an important method to study the blasting fracture mechanism and optimize blasting design. The blasting model plays an important role in the estimation of blasting fracture distribution. In the last three decades, many blasting models have been created to study the rock damage mechanism. Depending on the algorithm, these models can be divided into three groups: finite element models (FEMs), discrete element models (DEMs) and coupled finite-discrete element models (FEMDEMs).

FEMs mainly use a continuum damage approach to describe the rock mass fractures during the blasting process and some researchers divide the blasting process into two phases: the fracture generation phase with shock waves, and the fracture growth phase with elastic waves. Both rapid decay peak pressure and the quasi-static gas are considered in a numerical model using varying failure criteria[7–9]. Other researchers consider the blasting as an entire process, and the Jones-Wilkins-Lee (JWL) equation of state (EOS) is applied to simulate the effects of stress waves and gas pressure. Xie et al. developed a dynamic compression and tensile failure model to simulate rock mass failure in blasting models[10]. The stress distribution and damage of intact rock can be well described by FEM, which poorly demonstrates that of

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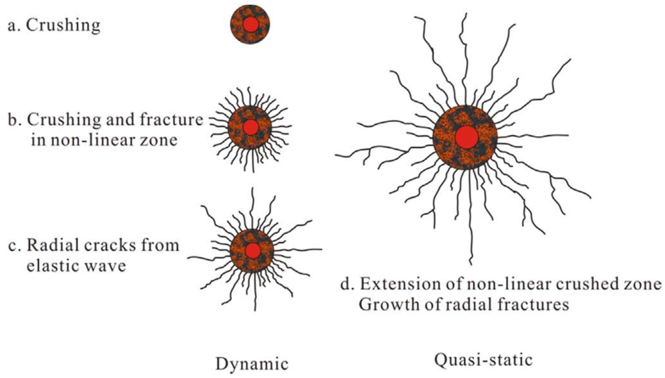

Fig. 1. Evolution of fracture patterns in consecutive stages in the fracture process of one-borehole blasting.

discontinuous rock mass during blasting. LS-DYNA provides a method to simulate jointed planes by contact interface. Ma and An developed the Johnson–Holmquist (J-H) material model in LS-DYNA to consider the failure of dynamic compression and tension, and the contact interface was used to study the effects of single joint planes. The results indicate that the reflected stress at the joint plane has a significant effect on fracture patterns[11]. Li et al. consider the fractures in rock as two non-welded surfaces and the thickness of the fractures can be ignored[12]. Zou et al. introduced the contact interfaces to simulate wave propagation across fractures in LS-DYNA. The contacts provide the medium for stress wave propagation, and the displacement discrete method is used to calculate the displacement of nodes at contact interfaces[13].

Many efforts have also been directed to the development of discontinuum numerical models[14]. The Universal Distinct Element Code (UDEC) and Particle Flow Code (PFC) have been used to explore the blast stress wave propagation in fractured rock masses[14,15], and it has been shown that multiple fractures have greater and faster absorbing the blast wave in the rock masses[16]. The effects of multiple parallel fractures on wave attenuation have also been studied using the displacement discontinuity model, which presents the relation between the dependence of the magnitude of the transmission coefficient and the ratio of fracture spacing to wavelength[17]. This is a very good method to study the effects of joint plane properties, spacing, and joint plane number. The DEM can estimate the direction of crack propagation in jointed rock mass. However, the stress wave can only be imported artificially in this method, which is not sufficient to build the relationship between explosive and blasting-induced cracks. It is also difficult for the DEM to consider the nonlinearity around the borehole.

Coupled methods, such as combining LS-DYNA and UDEC, can take advantage of FEM and DEM[18]. LS-DYNA can be used to model the blasting process of the explosive in a continuous medium. The explosion history can be measured on the wall of the borehole using the particle velocity or pressure; by importing the explosion history, UDEC modeling can simulate blast-wave propagation and fracture patterns in the jointed rock mass. There is another direct method by coupling the mesh of FEM and DEM. Paluszny and colleagues simulate discrete fracture growth by creating a new mesh at each step to confirm the new fracture geometry leading to the formation of primary fragmentation[19]. Yang and colleagues propose a gas-solid interaction model, which couples a finite element viscous-fluid model and a combined finite-discrete element solid model, to simulate the entire blasting process[20,21]. The viscous-fluid model is used to describe the effect of explosive gas, and the finite-discrete element is used to simulate the fracture model. The gas-solid interaction is achieved by converting discontinuous meshes to continuous meshes. In this method, the stress is calculated by the FEM before fracture initiation. After the stress exceeds the failure strength of the rock mass, the discontinuous cracks generated by the DEM are used to compute the interaction between cracks.

To understand the reflection and transmission of stress waves around bedding planes during blasting, based on the above analysis, a constitutive model considering dynamic and tensile failure was applied in LS-DYNA to simulate fracture patterns during blasting. The contact interfaces were inserted in numerical models to simulate the bedding planes in several models, which were used to study the fracture patterns and stress wave propagation around bedding planes. The element removal method is used to describe the crack generation and growth during blasting. The crack initiation and connections in coal mass were studied, and the effects of parallel beddings, cross-joints and double borehole on crack growth are presented in this paper.

2. Numerical simulation method

2.1. Failure criterion of coal mass in models

After detonation, a cavity is formed around the blasting hole. In this zone, the compressive stress of material exceeds the dynamic compressive strength, and the strain on the material is very large. Many studies have indicated that the mechanical properties of rock mass represent a close relationship with the strain rate of materials under the action of dynamic loads, and these results provide parameters for simulating rock mass blasting[22,23]. Therefore, the strain rate effect should be considered near the blasting borehole, which can accurately describe the material failure characteristics around the blast hole. The yield function can be expressed as:

$$\varphi = J_2 - \frac{\sigma_y^2}{3} = \begin{cases} \le 0 \text{ for elastic load} \\ >0 \text{ for plastic harding} \end{cases} \qquad (1)$$

where J_2 is equal to $\frac{1}{2}S_{ij}S_{ij}$, that is the second deviator stress tensor, and σ_y is the yield stress, given by

$$\sigma_y = \sigma_0 + \beta E_p \varepsilon_{eff}^p \qquad (2)$$

where $\varepsilon_{eff}^p = \int_0^t d\varepsilon_{eff}^p = \int_0^t \sqrt{\frac{2}{3}d\varepsilon_{ij}^p d\varepsilon_{ij}^p}$

The plastic strain rate (ε_{ij}^p) is the difference between the total (ε_{ij}) and elastic (ε_{ij}^e) strain rates: $\varepsilon_{ij}^p = \varepsilon_{ij} - \varepsilon_{ij}^e$, E_p is plastic hardening modulus, which is equal to $\frac{E_y E_{\tan}}{E_y - E_{\tan}}$, Ey is the Young's modulus, $E_{\tan}$ is the tangent modulus, σ_0 is the initial yield stress, and β is the hardening parameter. The hardening parameter (β) is used to describe the degree of hardening, and $\beta = 0$ means kinematic hardening, $\beta = 1$ means isotropic hardening, and $0 < \beta < 1$ means mixed hardening, In this simulation, the β is set to 1.

The Cowper-Symonds model[24] is applied to describe the effect of strain rate. Substituting Eq. (2) into the Cowper-Symonds model, and the relationship between yield stress and strain rate is obtained from[25]:

$$\sigma_y = \left[1 + \left(\frac{\dot{\varepsilon}}{c}\right)^{\frac{1}{\lambda}}\right](\sigma_0 + \beta E_p \varepsilon_{\mathrm{eff}}^p) \qquad (3)$$

where $\dot{\varepsilon}$ is the strain rate of material, c, and λ is the parameter of the Cowper-Symonds model.

The dynamic compressive failure criterion of material can be obtained from

$$\sigma_{cd} > \sigma_y \qquad (4)$$

or,

$$\varepsilon_{eff}^p > \varepsilon_{\max}^p \qquad (5)$$

where $\varepsilon_{\max}^p$ is determined by the material property. In this paper, Eq. (4) is adopted as the dynamic compressive failure criterion of the coal mass.

For the tensile failure of material at positions far away from the blasting borehole, referring to the results of[22,26], the dynamic tensile strength has a relationship with strain rate which can be written as:

$$\sigma_{td} = A_t \dot{\varepsilon}^m \qquad (6)$$