Numerical simulation of rock fractures induced by CO$_2$ blasting

B Wang$^{1,2}$ and H B Li$^{1,2}$.

$^1$State Key Laboratory of Geomechanics and Geotechnical Engineering, Institute of Rock and Soil Mechanics, Chinese Academy of Sciences, Wuhan 430071, China
$^2$University of Chinese Academy of Sciences, Beijing 100049, China

Abstract. As a safe and environment-friendly rock breaking technique, CO$_2$ blasting has been paid more and more attention. Most of previous researches estimate the radius of rock damage induced by CO$_2$ blasting according to explosive equivalent method, with less attention to the mechanism. In fact, compared with explosive blasting, the peak pressure and loading rate of CO$_2$ blasting are several orders of magnitude smaller. In order to further understand the mechanism, the commercial software LS-DYNA and Riedel-Hiermaier-Thoma material model have been used to simulate the rock fractures induced by CO$_2$ blasting. First of all, according to the previous researches, the ranges of the rise time and corresponding peak pressure of CO$_2$ blasting are estimated. Then, influences of the key parameters in blasting, viz., loading rate, in-situ stress and free face, on fracture patterns are explored. In the present study, the fracture patterns of CO$_2$ blasting are successfully simulated, and some of the well-known phenomena observed by other researchers can be reproduced. The numerical simulation in the present study has the potential to be applied in practical CO$_2$ blasting.

1. Introduction
As an economic and high-efficient rock breaking technique, explosive blasting is widely used in transportation, mining, hydropower and nuclear power engineering. However, owing to its side effects (e.g. blasting vibration, noxious gases, flames and flying rocks), explosive blasting may be restricted in some engineering, such as coal mine[1] and metro construction being adjacent to urban resident areas[2]. To meet the requirements of safe construction and environmental protection, more and more attention has been paid to non-explosive blasting techniques including CO$_2$ blasting. CO$_2$ blasting technique was first proposed by a British company called Cardox in the early 1950s, and the device and its application was introduced by Singh[3]. Figure 1 shows a schematic diagram of a non-disposable CO$_2$ blasting device, the main components of which include a heating rod, a liquid storage pipe with large rigidity and an energy release head. When the heating rod is ignited, the carbon dioxide in the liquid storage tube is rapidly heated from the liquid state to the supercritical state[4], and the pressure rises sharply, which finally causes the energy release plate to be sheared. Then, the CO$_2$ gasifies rapidly and ejects from the vent hole to impact the borehole wall, so as to fracture the rock. For the needs of different working conditions, a kind of disposable CO$_2$ blasting devices has also been proposed. In addition, Li et al. applied CO$_2$ blasting technique to the excavation of urban subway station, which showed that this technology achieved a good balance between efficiency and environmental protection[2].
It is of great significance to study the fracture patterns under different loading waveforms and boundary conditions for understanding the rock breaking mechanism of CO₂ blasting and popularizing the application of this technology. Bai et al. estimate the degree and scope of rock damage induced by CO₂ blasting according to TNT equivalence method, when designing blasting parameters[1]. This method does not consider the transition path and utilization ratio of energy, nor does it consider the difference between the rock breaking mechanism of CO₂ blasting and explosive blasting. In terms of the waveform of dynamic load, the peak value of CO₂ blasting is far lower than that of explosive blasting, and the rise time is significantly longer than that of explosive blasting (Table 1). Many studies have shown that the loading waveform has an important influence on the failure mode and fracture pattern of rock. Wang et al. studied the evolution law of the stress wave propagating from a borehole by analytical method[5]. It shows that the stress wave with long rise time tend to cause tension failure near the borehole, but the stress wave with short rise time tend to cause compression failure. Based on the particle discrete element method, literature[6] carried out numerical simulation to study the influence of the loading waveform on the propagation and the pattern of the cracks induced by blasting. Ma et al. introduced the JH model into LS-DYNA software and simulated the crack behaviour of rocks under different loading waveforms[7]. Although simulation results of [6] and [7] are consistent with the observations and theoretical expectations, but the applied loading waveforms are quite different from that of CO₂ blasting.

### Table 1. Pressure–time relationships for three typical fracturing techniques.

| Fracturing technique | Peak pressure (MPa) | Pressure increase duration (s) | Loading rate (GPa/s) |
|---------------------|---------------------|-------------------------------|---------------------|
| Explosive blasting  | 10⁴                 | 10⁻²                          | 10⁻³–10⁻¹           |
| CO₂ blasting        | 10²                 | 10⁻³                          | 10⁻¹–10⁻²           |
| Hydraulic fracturing| 10¹                 | 10²                           | 10⁻¹–10⁻²           |

The purpose of this paper is to study the crack propagation and fracture pattern in the rock under the action of dynamic load of CO₂ blasting, so as to improve the understanding of the rock breaking mechanism of CO₂ blasting. Therefore, LS-DYNA software is used to simulate rock fractures induced by CO₂ blasting, during which the RHT material model is used to simulate the rock, and a pressure-
time history function is used to consider the change of loading waveform applied on the borehole. At the same time, the influence of in-situ stress and free surface on fracture pattern is also studied.

2. Rock material model and parameters

The selection of rock material model is very important in the simulation of blasting. Blasting is a dynamic process, while rock is a typical brittle material with significant strain rate effect. TCK model, JH model, HJC model and RHT (Riedel-Hiermaier-Thoma) model are often used to simulate rock blasting because they can well describe the dynamic characteristics of rock. However, the TCK model just considers tension damage \[8\]. In contrast, JH model and HJC model consider compression damage but do not consider tension damage extensively\[9\]. Blast-induced damage is the result of the superposition of tension and compression damage. Therefore, the RHT model is employed in the present simulation for its extensive consideration of tension and compression damage. And it should be noted that the cracks are represented by the damage in the simulation, the same method has been used in \[10\].

The RHT material model contains three extreme surfaces that represent the strength of the material (Figure 2). The first surface is the yielding surface limited by a cap surface. Outside this surface, the material begins to plastically deform and there is a description of linear hardening. When the material reaches the failure surface, the damage of the material begins to progress until the damage equals 1. When the residual surface is reached, the material is considered completely damaged and the strength is determined by the residual surface. This model also includes the effects of strain rate.

The used values of parameters in the RHT model are shown in Table 2, which have been calibrated by\[10\].

| Parameter                      | Value  | Parameter                      | Value  |
|-------------------------------|--------|-------------------------------|--------|
| Density                       | 2660 kg/m³ | Reference compressive strain rate $E_{0c}$ | 3.0e-5 |
| Shear Modulus                 | 17 GPa | Reference tensile strain rate $E_{0t}$ | 3.0e-6 |
| Eroding plastic strain        | 2.0    | Break compressive strain rate $E_C$ | 3.0e25 |
| Parameter for polynomial EOS B<sub>0</sub> | 1.22 | Break tensile strain rate $E_T$ | 3.0e25 |
| Parameter for polynomial EOS B<sub>1</sub> | 1.22 | Compressive strain rate dependence exponent | 0.025 |
| Parameter for polynomial EOS T<sub>1</sub> | 43.87GPa | Tensile strain rate dependence exponent | 0.045 |
| Parameter for polynomial EOS T<sub>2</sub> | 49.40GPa | Pressure influence on plastic flow in tension | 0.001 |
| Hugoniot polynomial coefficient A<sub>1</sub> | 43.87GPa | Compressive yield surface parameter $G C^*$ | 0.85 |
| Hugoniot polynomial coefficient A<sub>2</sub> | 49.40GPa | Tensile yield surface parameter $G T^*$ | 0.4 |
| Hugoniot polynomial coefficient A<sub>3</sub> | 11.62GPa | Shear modulus reduction factor | 0.25 |
| Failure surface parameter $A$ | 2.50 | Damage parameter $D_1$ | 0.025 |
| Failure surface parameter $N$ | 0.85 | Damage parameter $D_2$ | 1.0 |
| Compressive strength          | 150MPa | Minimum damaged residual strain | 0.01 |
| Relative shear strength       | 0.07 | Residual surface parameter $A_f$ | 2.5 |
| Relative tensile strength     | 0.05 | Residual surface parameter $A_n$ | 0.85 |
| Lode angle dependence factor $Q_0$ | 0.72 | Grunnisen Gamma | 0 |
| Lode angle dependence factor $B$ | 0.01 | Crush pressure | 133MPa |
| Compaction pressure           | 6GPa  | Porosity exponent | 3 |
| Initial porosity              | 1.0   |                               |        |

**Figure 2.** Stress limit surfaces and loading scenario in the RHT model \[10\].
3. Dynamic loading produced by CO$_2$ blasting

In order to simulate rock fractures induced by CO$_2$ blasting, a pressure pulse can be applied to the bore-hole wall. It is crucial to determine the peak pressure and corresponding rise time of the applied pressure pulse for accurate simulation. As mentioned in the introduction, the pressure of CO$_2$ gasification is controlled by the thickness of the energy release plate, and its value varies from 100MPa to 300MPa. Considering the attenuation, we assume that the peak pressure is 100MPa. The rise time is highly related to the coupling relationship between rock and blasting tube, so it is difficult to determine. In this paper, we estimate it by referring to the research about high energy gas fracturing. Sandia National Laboratory of the United States has carried out many tests for high energy gas fracturing and concluded that the condition for producing multiple cracks is as follow[11]:

\[
\frac{\pi D}{C_p} < t_0 < \frac{16\pi D}{C_p}
\]

where $D$ is the diameter of the borehole; $C_p$ is the longitudinal wave velocity of the rock; $t_0$ is the rise time of the gas pressure. Assuming $C_p = 5000\text{m/s}$ and $D = 0.1\text{m}$, the range of the rise time is from 0.063ms to 1.0ms.

The following function proposed by [12] is used to describe the pressure-time relationship:

\[
P = P_0\xi \left[ \exp(-\alpha t) - \exp(-\beta t) \right]
\]

where $P$ is the pressure at time $t$, $P_0$ is the peak pressure. The relationship between $\alpha$, $\beta$, $\xi$ and the rise time $t_0$ is as follow:

\[
t_0 = \ln(\beta/\alpha)/(\beta - \alpha)
\]

\[
\xi = 1/\left[ \exp(-\alpha t_0) - \exp(-\beta t_0) \right]
\]

4. Numerical simulation

4.1. Effect of loading rate

The loading rate has a significant influence on the failure mode and fracture pattern of rock. Many researchers [7,12] have studied the influence of the loading waveform on the pattern of blast-induced fracture, which shows that high loading rate tend to produce a crushing area or many short cracks near the bore-hole, but the lower loading rate tend to produce less and longer radial cracks. It can be expected that the same regularity is adapted to CO$_2$ blasting. But there is still necessity to study the sensitivity of fracture pattern to loading rate for CO$_2$ blasting.

![Figure 3. Numerical model used to study the effect of loading rate.](image-url)
The simulation is simplified as a plane strain problem. The numerical model is established as shown in Figure 3, all the four edges of which are non-reflecting boundaries. Figure 4 shows the applied pressure-time curves of different loading rates. The peak pressure is kept at 100MPa, and the rise time varies between 0.075ms, 0.15ms, and 0.75ms. The final fracture patterns of the three cases are shown in the Figure 5. It can be found that 8 dominant radial cracks but no crush zone are produced in all the three cases, multiple fractures in CO$_2$ blasting are successfully simulated. The range of fracture zone increases with the decrease of loading rate, which agree well with previous researches[12].

4.2. Effect of in-situ stress
In underground excavation engineering, the influence of in-situ stress is inevitable. [13] studied the effect of in-situ stress on the fracturing of rock by explosive blasting based on LS-DYNA software. The results show that the blasting cracks tend to propagate along the direction of the maximum initial stress. Because the peak pressure and loading rate of CO$_2$ blasting are far smaller than that of explosive blasting, the effect of in-situ stress can be more significant.
Figure 6. Numerical model used to study the effect of in-situ stress.

The numerical model is established as shown in Figure 6, and the parameters for the dynamic load at the borehole surface are $P_0 = 100\text{MPa}$, $t_0 = 0.15\text{ms}$, $\beta/\alpha = 3$. Four cases are investigated as follow: (1) $P_1 = 0$, $P_2 = 0$; (2) $P_1 = 10\text{MPa}$, $P_2 = 0$; (3) $P_1 = 10\text{MPa}$, $P_2 = 10\text{MPa}$; (4) $P_1 = 20\text{MPa}$, $P_2 = 10\text{MPa}$. The in-situ stresses are loaded by dynamic relaxation technique in LS-DYNA software.

The final fracture patterns in four cases are shown in Figure 7. The results of Case (2) and Case (4) indicate that the cracks tend to develop along the direction of the maximum in-situ stress, because the static hoop tensile stress promotes the crack propagation. On the contrary, in the direction of the minimum in-situ stress, the crack propagation is suppressed by the static hoop compressive stress. The results of Case (3) indicates that isotropic in-situ stress can reduce the range of fracture zone. Due to the increase of in-situ stress, the crack lengths of case (4) are smaller than that of case (2), although the difference between two principal in-situ stresses is the same. By comparing Figure 7 (a) and (b), it can be seen that CO$_2$ blasting is more easy to be influenced by in-situ stress.

Figure 7. Simulation results of different in-situ stress conditions. (a) CO$_2$ blasting; (b) Explosive blasting[10].

4.3. Effect of a nearby free face
In bench blasting, the free face plays an important role in rock breaking. A numerical model is established as shown in Figure 8 to study the effect of the free face, and the parameters for the dynamic load at the borehole surface are $P_0 = 100$ MPa, $t_0 = 0.15$ ms, $\beta/\alpha = 3$. The simulated crack propagation process is shown in Figure 9. Before $t = 0.4$ ms, the radial cracks initiating from the borehole propagate without directional preference. After that, the propagation of cracks that are closer to the free face is extended because of the promotion of the reflected stress wave. No spalling happens in the process, for the reason that the ratio of $C_p t_0 \approx 0.75$m to the burden $w = 1$m is too large.

Figure 8. Numerical model used to study the effect of a nearby free face.

Figure 9. Simulation results of free face effect study. (a) CO$_2$ blasting; (b) Explosive blasting[12].

5. Discussion
Similar to explosive blasting, CO$_2$ blasting includes two phases of the dynamic action of stress wave and the quasi-static action of gas. The high pressure gas can penetrate into the cracks produced by stress wave, driving them to propagate further, which is called gas-wedge effect. Neglecting the gas-wedge effect is one of the limitations of this paper.

6. Conclusions
In this paper, the RHT model is employed to simulate rock fractures induced by CO$_2$ blasting based on LS-DYNA software. And the influences of loading rate, in-situ stress and free face on the fracture pattern are analysed. From the simulation results, the conclusions can be drawn as follows:
(1) When the loading rate changes in a certain range, the length of radial cracks increases with the decrease of loading rate, but the number does not change.

(2) The anisotropic in-situ stress makes the cracks tend to develop along the direction of the maximum in-situ stress, but the isotropic in-situ stress can only reduce the range of fracture zone.

(3) The nearby free face can extend the propagation of cracks that are closer to the free face is extended because of the reflected stress wave. No spalling happens, because the ratio of $C_{p0}$ to the burden $w$ is too large.

7. References
[1] Bai X, Zhang D, Zeng S, Zhang S, Wang D and Wang F 2020 An enhanced coalbed methane recovery technique based on CO2 phase transition jet coal-breaking behavior Fuel 265
[2] Li Q Y, Chen G, Luo D Y, Ma H P and Liu Y 2020 An experimental study of a novel liquid carbon dioxide rock-breaking technology Int. J. Rock Mech. Min. Sci.
[3] Singh S P 1998 Non-Explosive Applications of the PCF Concept for Underground Excavation Tunn. Undergr. Sp. Technol.
[4] Ke B, Zhou K, Xu C, Ren G and Jiang T 2019 Thermodynamic properties and explosion energy analysis of carbon dioxide blasting systems Min. Technol. Trans. Inst. Min. Metall.
[5] Wang J, Elsworth D, Cao Y and Liu S 2020 Reach and geometry of dynamic gas-driven fractures Int. J. Rock Mech. Min. Sci.
[6] Donzé F V., Bouchez J and Magnier S A 1997 Modeling fractures in rock blasting Int. J. Rock Mech. Min. Sci. 34 1153–63
[7] Ma G W and An X M 2008 Numerical simulation of blasting-induced rock fractures Int. J. Rock Mech. Min. Sci. 45 966–75
[8] Wang Z L, Li Y C and Shen R F 2007 Numerical simulation of tensile damage and blast crater in brittle rock due to underground explosion Int. J. Rock Mech. Min. Sci. 44 730–8
[9] Brannon R M, Leelavanichkul S, Jiang H and Zhao J 2009 Survey of Four Damage Models for Concrete Prod.sandia.gov
[10] Yi C, Johansson D and Greberg J 2018 Effects of in-situ stresses on the fracturing of rock by blasting Comput. Geotech.
[11] Cuderman J F 1986 High-energy gas fracturing in cased and perforated wellbores
[12] Cho S H and Kaneko K 2004 Influence of the applied pressure waveform on the dynamic fracture processes in rock Int. J. Rock Mech. Min. Sci. 41 771–84
[13] Jayasinghe L B, Shang J, Zhao Z and Goh A T C 2019 Numerical investigation into the blasting-induced damage characteristics of rocks considering the role of in-situ stresses and discontinuity persistence Comput. Geotech. 116