INTRODUCTION

Longwall mining has been widely applied in China in the recent decades. Safety hazards frequently happen at longwall mining working faces with hard roof conditions. This is one of the main challenges for underground mining, especially for most coal mines in Shanxi province in China.\(^1\) Hard roofs have characteristics of high tensile strength and large thickness. They normally have poor caveability and few existing rock joints.\(^2\) With the working face advancing, the hanging roof area increases gradually, resulting in the hanging roof of this opening room reaching area up to 8000 m\(^2\). The roof material is strong but brittle that causes it to cave suddenly once ground pressure reaches a threshold value. And this sudden failure causes the pressure to greatly exceed the capacity of the hydraulic roof supports. The sudden caving can cause spall of coal bodies,

#### Abstract

The hard roof leads to large deformation or failure of the entry and poses risks to mining safety. Shaped charge blasting is applied to directionally fracture the hard roof and release mining pressure in this paper. The stress condition around the blasting borehole required to induce fracture propagation is calculated by theoretical calculation and numerical simulation. Evolution of blasting-induced fractures between adjacent boreholes, main fracture in the shaped charge jet direction and secondary fractures in other directions is analyzed. The reliability of Livemore software of explicit dynamics analysis code (LS-DYNA) in simulating shaped charge blasting is validated by experimental results. A numerical model is established to reveal the formation processes of the shaped charge jet, disclose the evolution of the equivalent stress and understand the development of the main fractures and secondary fractures between adjacent boreholes. The failure type of the rock mass and the fracture development zone are identified. The results indicate that blasting-induced fractures mainly initiate and propagate in the shaped charge jet direction between adjacent boreholes. Shaped charge blasting leads to the directional propagation of fractures. The field monitoring results show that shaped charge blasting is able to realize the directional propagation of blasting-induced fractures and release mining pressure.

#### Keywords

directional propagation of blasting-induced fractures, hard roof, LS-DYNA3D, shaped charge blasting
root subsidence, instability of coal pillar, and even air blast accidents. All of the above pose serious risks to mining safety.3-6 This problem is currently encountered at Linzhida coal mine in Shanxi province, China. The roof rock in the 15# coal seam at Linzhida coal mine is limestone. The roof can hardly cave during the mining process, while forms a large suspended area and seriously influence mining safety.

Many efforts have been put on controlling the caving of hard roofs in previous studies. The existing techniques mainly include roof blasting, water injection, dense pressure-relief borehole drilling, gas fracturing, and hydraulic fracturing.7-13 These techniques induce the caving of hard roofs by changing the loading conditions of hard roofs, weakening hard roofs, or adding artificial fracture surfaces into hard roofs. Previous field applications suggest that blasting is an effective approach to improving caveability of hard roofs. This technique has been widely applied in the mining industry in China.14 Figure 1 shows the roof structures before and after blasting. The hard roof without roof blasting forms a suspended beam structure (Block B in Figure 1A) behind the working face (Figure 1A). This leads to obvious stress concentration in the surrounding rock masses of the entry (Range IV in Figure 1A). The hard roof fractures as the working face advances if roof blasting is properly used (Figure 1B). The surrounding rock masses of the entry in this case are in a low-stress area (Range III in Figure 1B), which improves the stability of the entry. The conventional blasting technique seriously damages the rock mass around the borehole. Quite much explosive energy is consumed in the damage process, leading to a relatively large damage area and a relatively small fracture area. The efficiency of blasting in this case is limited. Therefore, the shaped charge blasting technique was proposed by researchers to fill this gap. Shape charge blasting (SCB) uses an explosive charge that is shaped to focus the effect of the explosive’s energy. The shaped charge blasting technique forms the shaped charge jet after explosion through the explosive forming pellet. The shaped charge jet results in stress concentration in the rock mass along the specific direction and generates the initial directional fractures. The directional propagation of the initial fractures in the blasting process improves the blasting efficiency and enhances the fracture of the roof.15

Shape charge blasting directionally aggregates explosive energy and induces stress concentration that leads to directional propagation of fractures.16 This technique has been successfully applied in rock mass preconditioning, tunnel excavation, and coal seam gas extraction.17-19 The dynamic change of the stress distribution, the development of fractures, and the directional propagation of fractures have been investigated by many researchers based on theoretical analysis and laboratory experiments. Cho et al20 revealed the effect of the adjacent borehole (which is used to direct fracture propagation from the blasting borehole) on fracture propagation and described fracture propagation behavior from the aspect of stress concentration. He and Yang21 studied interaction between fractures generated from adjacent boreholes, using a high-speed camera and digital image processing. Ma and An22 investigated formation of fractures in the blasting process based on numerical simulation on evolution of stresses and fracture trajectories. Zhu et al23-25 disclosed the influence of the coefficient of decoupling charge on the stress distribution and the propagation of the main fractures in the rock mass. Wang26 studied fracture propagation between boreholes and the dynamic stress intensity factor at the fracture tip based on dynamic measurement methods and a dynamic digital laser experimental system. Zhu et al27 disclosed the influence of the coefficient of decoupling charge on the stress distribution and the propagation of the main fractures in the rock mass. Zhang et al28 analyzed the effects of the shape of the explosive forming pellet on the velocity of the shaped charge jet and the stress distribution. All of the above studies focus on the evolution of stresses in the blasting process and the effect of the borehole spacing on blasting efficiency. In addition, most previous studies put efforts on propagation trajectories of blast-induced fractures. Rare consideration is given to formation of the shaped charge jet and its effect on initiation and propagation of blast-induced fractures.

The stress condition around the borehole required to induce fracture propagation is calculated in this paper, using a numerical model validated by experimental results. The failure mechanism of the rock mass between adjacent boreholes, the evolution characteristics of the blast-induced fractures, and the evolution of the main fracture and the secondary fractures are studied. The effects of shaped charge blasting on fracture initiation and its directional propagation are revealed based on the analysis of the formation process of the shape charge jet. The dynamic evolution of the complex fracture network in the rock mass under the combined effect of shape charge jets and blasting is investigated based on comparison between the equivalent stress and rock strength. Finally, shaped charge blasting applied in 15210 head entry at Lingzhida coal mine, China. The field application indicates that shaped charge blasting is effective in decreasing the rib deformation, roof subsidence, and the caving interval by 35.8%, 62.4%, and 51.2%, respectively.

2  |  MECHANISM OF SHAPED CHARGE BLASTING AND FORMATION OF BLAST-INDUCED FRACTURES

2.1  |  Mechanism of shaped charge blasting

Yang et al29 utilized shaped charge blasting to directionally fracture the main roof and control the deformation of
the surrounding rock mass. This technique has been used to shape underground chambers and precondition hard roofs.\textsuperscript{16,30} Shaped charge blasting uses the explosive forming pellet to directionally accumulate explosive energy in order to improve blasting efficiency.\textsuperscript{31} The explosive forming pellet gradually forms the shaped charge jet (TSCJ) under the effect of the detonation wave after the detonation initiates. Figure 2 illustrates the formation process of the shaped charge jet. In the early state, large deformation commences in the explosive forming pellet due to the detonation wave (Figure 2A). The explosive forming pellet is compressed and deforms plastically. Its tips move symmetrically to the borehole axis. The wings of the explosive forming pellet approach toward their symmetry axis (Figure 2B, C). The explosive forming pellet is gradually compressed from a curved surface ($C_{11}A_2C_{12}$ in Figure 2D) to a curved surface ($D_{11}A_2D_{12}$ in Figure 2D) with the propagation of the detonation wave. Finally, the detonation waveforms two symmetric coin-shaped charge jets at the sides of the borehole, leading to stress concentration in the shaped charge jet directions. This induces fracture initiation in the shaped charge jet directions and directional propagation of fractures and contributes to wide ranges of fracture networks that stretch through adjacent boreholes.

2.2 Formation of blast-induced fractures

Two types of initial fractures are generated in the blasting process: (a) initial fractures induced by the shaped charge jets at the sides of the borehole; and (b) initial fractures around the borehole wall induced by the relatively uniform expansion of the detonation products (which is not along the shaped charge jet direction). The stress intensity factor at the fracture tip can be calculated by Equation (1):\textsuperscript{32}
where $K_I$ is the stress intensity factor, $P$ is the pressure applied to the fracture tip (induced by the shaped charge jet), $B$ is a correction coefficient, $r$ is the borehole radius, $L$ is the Instantaneous propagation length of radial fissures, $\sigma$ is tangential tensile stress induced by blasting.

The shaped charge jet formed by shaped charge blasting erodes and generates initial fractures in the rock mass around the borehole. When the erosion process terminates, the stress intensity factor at the fracture tip equals to rock toughness:

$$K_I = P B \sqrt{\pi (r + L)} + \sigma \sqrt{\pi L}$$

(1)

where $K_I$ is the stress intensity factor, $P$ is the pressure applied to the fracture tip (induced by the shaped charge jet), $B$ is a correction coefficient, $r$ is the borehole radius, $L$ is the Instantaneous propagation length of radial fissures, $\sigma$ is tangential tensile stress induced by blasting.

The shaped charge jet formed by shaped charge blasting erodes and generates initial fractures in the rock mass around the borehole. When the erosion process terminates, the stress intensity factor at the fracture tip equals to rock toughness:

$$K_I = P B \sqrt{\pi (r + L)} + \sigma \sqrt{\pi L}$$

(2)

where $P_0$ is the pressure applied to the fracture tip when the erosion process terminates.

Based on fracture mechanics, the fracture propagates if the stress intensity factor at the fracture tip is higher than the rock toughness as described in Equation (3):

$$K_I \geq K_{IC}$$

(3)

$$P_0 B \sqrt{\pi (r + L)} + \sigma \sqrt{\pi L} \geq K_{IC}$$

(4)

Initial fractures are generated in the rock mass around the borehole due to the erosion by the shaped charge jet. The detonation products enter these initial fractures and form a quasi-static stress field. The fracture propagates if Equation (5) is satisfied:

$$P \geq \frac{K_{IC} - (\sigma - \sigma_{\text{max}}) \sqrt{\pi L}}{B \sqrt{\pi (r + L)}}$$

(5)

where $\sigma_{\text{max}}$ is maximum tangential tensile stress.

At last, two main fractures form in the rock mass along the shaped charge directions, while few secondary fractures occur along other directions. The mechanism of shaped charge blasting is illustrated in Figure 3. Tensile stress perpendicular to the line connecting the two holes is generated by compression (due to the expansion within the boreholes); and the rock material in between will be fractured when the tensile stress exceeds the tensile strength of the rock.

3 | NUMERICAL SIMULATION ON SHAPED CHARGE BLASTING

3.1 | Model validation

The explicit dynamic numerical simulation software LS-DYNA is briefly introduced in this section. LS-DYNA is based on the Finite Element Method. It can solve
complicated nonlinear dynamic problems. Shaped charge blasting is simulated by the coupling of solid mechanics and fluid mechanics.

The ALE algorithm is used to accurately simulate the blasting process in order to avoid the existence of high stresses and large deformation in the elements (due to the impact force induced by blasting) in the elements of the LS-DYNA model. The JOHNSON_COOK model and the GRUNEISEN equation are used to predict the behavior of the explosive forming pellet.33

The JWL equation is adopted in LS-DYNA 3D to describe the relation between the pressure applied to the borehole wall by a unit detonation product and the volume of the detonation product (Equation 6):34

\[ P_1 = A \left( 1 - \frac{\omega}{R_1 V} \right) e^{-\nu R_1} + B \left( 1 - \frac{\omega}{R_1 V} \right) e^{-\nu R_2} + \frac{\omega E_0}{V} \] (6)

where \( P_1 \) is the pressure applied to the borehole wall by a unit detonation product, \( V \) is the relative volume of the detonation product, \( E_0 \) is the initial internal energy density of the detonation product, and \( A, B, R_1, R_2, \) and \( \omega \) are material constants determined by blasting experiments.35 The rocks near the blasting center are simulated by the plastic hardening material model due to their high strains in the blasting process. The MAT_ADD_EROSION damage criterion is used to determine the damage condition of each element in the simulation of fracture development.36 The dynamic plastic hardening model is used to simulate the other rock materials (except the rocks around the borehole). This model is related to the strain rate and considers the failure effect of the material (i.e., the failed material becomes anisotropy). The hardening coefficient in the dynamic plastic hardening model (\( \beta \)) can be adjusted to change the isotropy hardening quality and the dynamic hardening quality of the material (\( \beta = 0, 0 < \beta < 1, \) and \( \beta = 0 \) represent dynamic hardening, combined hardening, and isotropy hardening, respectively). Therefore, the influence of the strain rate on material strength can be analyzed by the Cowper–Symonds model. The relation between the yield stress and the strain rate is given in Equation (7):35

\[ \sigma_y = \left[ 1 + \left( \frac{\varepsilon}{e} \right)^{1/p} \right] \left( \sigma_0 + \beta E_p \varepsilon^{\text{eff}} \right) \] (7)

where \( \sigma_0 \) is the initial yield stress, \( e \) is the strain rate, \( c \) and \( p \) are the Cowper–Symonds strain rates, \( E_p \) is the effective plastic strain, \( E_p = E_y E_tan, E_y \) is the tangent modulus.

### 3.2 Application of LS-DYNA to blasting simulation

The reliability of LS-DYNA in simulating the blasting process is validated by comparing the simulation results with the previous experimental results.

#### 3.2.1 Wang’s experimental results

Wang26 studied fracture propagation trajectories in poly(methyl methacrylate) (PMMA). Many researchers37–39 mentioned that under dynamic conditions PMMA and rock show essentially similar fracture behavior. Hence, blasting experiments conducted in PMMA to investigate fracture initiation and propagation mechanisms in the near and far-field borehole zones can be considered analogous to those in rock. The PMMA sample has dimensions of 300 mm (in length) × 300 mm (in width) × 5 mm (in height). The PMMA sample has a longitudinal wave velocity of 2320 m/s and a transverse wave velocity of 1260 m/s. Its elastic modulus is 6.1 GPa. The dynamic fracture propagation rate is 0.31. The stress-optical constant of PMMA is 85 μm²/N. The borehole is at the center of the PMMA sample with a diameter of 8 cm. The roll has a diameter of 5 mm. The explosive

| Specimen | The length of main cracks | The length of secondary cracks | Notch | Angle |
|----------|--------------------------|-------------------------------|-------|-------|
| PMMA    | 49 cm                    | 8 cm                          | 15 mm | 4°    |
forming pellet is made by PMMA. Its thickness and intersection angle are 1 mm and 60°, respectively. The decoupling coefficient (in the radial direction) is 1.6. The explosive forming pellet and the explosive are bonded tightly by solid glue. This is to prevent the asymmetrical deformation of the explosive forming pellet. The experimental results are given in Table 1.

3.2.2 Comparison between simulation results and experimental results

The numerical simulation is based on PMMA properties and blasting parameters at Wang’s experimental. The simulation results are provided in Table 2. Figure 4 compares the simulation results and the experimental results. The propagation length of the main fracture and the length of the notch in the numerical simulation are 50 cm and 15 mm, respectively, which is consistent with the experimental results. Figure

| Specimen | The length of main cracks | The length of secondary cracks | Notch | Angle |
|----------|--------------------------|-------------------------------|-------|-------|
| PMMA    | 50 cm                    | 8 cm                         | 15 mm | 0°    |

**TABLE 2** Simulation results of specimen of fracture form and parameter

![Simulation](A) Simulation

Blasting borehole

Main cracks

Secondary cracks

![Experiment](C) Experiment

Blasting borehole

Main cracks

Secondary cracks

![Simulation](B) Simulation

Blasting borehole

Main cracks

Secondary cracks

![Experiment](D) Experiment

Blasting borehole

Main cracks

Secondary cracks

![Simulation](A) Simulation

Blasting borehole

Main cracks

Secondary cracks

**FIGURE 4** Comparison of the simulation results and experiment observations: (A) experiment results; (B) magnification of the borehole in experiment; (C) simulation results; (D) magnification of the borehole in simulation

**FIGURE 5** Shaped charge blasting model

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| $\rho_0$ (g cm$^{-3}$) | $D$ (m s$^{-1}$) | $A$ (GPa) | $B$ (GPa) | $R_1$ | $R_2$ | $\omega$ | $E_0$ (GPa) |
|------------------------|-----------------|------------|------------|-------|-------|---------|-------------|
| 1000                   | 3600            | 214.400    | 0.182      | 4.200 | 0.900 | 0.150   | 4.192       |

**TABLE 3** Properties of explosive and JWL state equation
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4A-D compares the sample damage in the experiment and the fracture development in the numerical simulation. The main fracture develops visibly in the shaped charge jet directions and is almost horizontal. The secondary fractures are relatively short and form symmetric cone-shaped notches (having lengths of 15 mm) in the shaped charge jet directions. Shaped charge blasting induces notches around the borehole in the radial direction, while results in the directional propagation of the blast-induced fractures. The simulation results by LS-DYNA coincide with the experimental results. It is concluded that LS-DYNA can effectively simulate fracture initiation and fracture propagation in the shaped charge blasting process.

3.3 Model establishment

The numerical model is established to study fracture propagation and stress evolution in shaped charge blasting. The model is based on the field conditions at Lingzhida coal mine, located in Changzhi City, Shanxi Province, China. The model has dimensions 300 cm (in length) × 150 cm (in width) × 180 cm (in height) (Figure 5). The material parameters in the numerical simulation are listed in Tables 3-6. The failure of the rock mass is mainly determined by the equivalent stress and the strain (Table 7). The blasting medium is air. The borehole spacing is 100 cm (Figure 6A). The borehole radius is 4.8 cm, and the roll diameter is 4.0 cm. The explosive forming pellet has thickness of 0.2 cm (Figure 6B). The detonation initiates at the center of the borehole. Nonreflecting boundary conditions are used in the simulation. This is to eliminate the blasting effect and the boundary effect on the simulation. The grids of each component in the simulation are meshed by the mapping method (Figure 7). The average grid sizes of the explosive and the explosive forming pellet are 0.18 mm and 0.1 mm, respectively. The maximum size and the minimum size of the air are 6.7 mm and 2.4 mm, respectively. The size ratio between adjacent elements is 1.15. The above arrangement leads to accurate simulation of the blasting process based on the comparison between the size of the rock element and the fracture width observed in the field condition.

3.4 Simulation results

3.4.1 Formation of shaped charge jet

The explosive forming pellet gradually forms the shaped charge jet (TSCJ) under the effect of the detonation wave after the detonation initiates. Figure 8 illustrates the formation of TSCJ. In the early state, large deformation commences in the explosive forming pellet due to the detonation wave (Figure 8A). The explosive forming pellet is compressed and deforms plastically. Its tips move symmetrically to the borehole axis. The wings of the explosive forming pellet approach toward their symmetry axis 4.8 μs after detonation (Figure 8B). The shaped charge metal jet has an approximately “V” shape. The explosive forming pellet is further compressed with the propagation of the detonation wave. A “Y”-shaped metal jet occurs 6.9 μs after detonation (Figure 8C). The velocity of TSCJ reaches the maximum in this stage, and the peak is at the tip of the jet. Finally, a long, thin linear shaped charge jet is formed 9.5 μs after detonation (Figure 8D).

3.4.2 Equivalent stress curves of rock elements

The changes of the equivalent stresses in different monitoring elements are presented in Figure 9. The equivalent stresses vary in similar tendencies against the detonation time. Nevertheless, the peaks of the equivalent stresses and the corresponding detonation time (ie, the detonation time used to reach the peak) are different. The “equivalent stress-detonation time” curve of each rock element can be divided into two stages: the propagation of the detonation wave (Stage I); and

| Table 4 | Mechanical parameters of rock in the model |
|---------|------------------------------------------|
| $\rho_0/(g \text{ cm}^{-3})$ | $E_y/(GPa)$ | $\mu$ | $\sigma_y/(MPa)$ | $E_{\text{冶}}/(GPa)$ | $\sigma_f/(MPa)$ | $\sigma_f/(MPa)$ | $c/s$ | $p$ |
| 2.50 | 28.70 | 0.25 | 35 | 30 | 33 | 3.30 | 2.50 | 4 |

| Table 5 | Mechanical parameters of air in the model |
|---------|------------------------------------------|
| $\rho_0/(g \text{ cm}^{-3})$ | $C_4$ | $C_5$ |
| 1.29e−03 | 0.04 | 0.04 |

| Table 6 | Mechanical parameter of the shaped charge cover |
|---------|------------------------------------------|
| $\rho_0/(g \text{ cm}^{-3})$ | $G_0/(GPa)$ | SIG0/(GPa) |
| 8.93 | 47.70 | 0.12 |

| Table 7 | MAT_ADD_EROSION parameters |
|---------|--------------------------------|
| $M_{\text{pres}}/(MPa)$ | $M_{\text{pres}}/(MPa)$ | $m_{\text{eps}}$ | $m_{\text{eps}}$ |
| 59.6 | −25.0 | 2.3e−03 | −8.1e−04 |

Note: $m_{\text{pres}}$: the maximum hydrostatic pressure should be taken as a positive value, representing pressure. The option is used for controlling the compression failure. $M_{\text{pres}}$: contrary to $m_{\text{pres}}$, it is used for controlling tensile failure, generally taking negative value. $m_{\text{eps}}$: the extreme value of principal strain is used for controlling compression failure, generally taking positive value. $m_{\text{eps}}$: contrary to $m_{\text{eps}}$, it should be taken as a negative value. This option is used for controlling tensile failure.
the erosion of the shaped charge jet (Stage II). The equivalent stress in Rock Element A reaches two separate peaks in these two stages, whereas the equivalent stresses in Rock Elements B and C only have peaks in Stage I. In the first state, the equivalent stress in each monitoring element reaches its peak about 3.5 μs after detonation. The peaks of the equivalent stresses are close to each other (about 25.1 MPa). Then, the equivalent stress fluctuates and declines after a sudden drop. Meanwhile, the damage area occurs in the surrounding rock mass around the borehole and initial fractures are induced. The curve steps into the second stage when the detonation time exceeds 7.5 μs. The equivalent stress in Rock Element A increases abruptly to another peak that is 35.4% higher than the first one. Then, the equivalent stress fluctuates and declines again after sharp decrease. The reason is that the shaped charge jet results in the increase of the equivalent stress in Rock Element A and also the further development of the fractures in the shaped charge jet directions. Finally, the main fractures initiating from adjacent boreholes interact and connect with each other. This is consistent with the fracture development illustrated in Figure 11. The equivalent stresses in Rock Elements B and C fluctuate and decline in the Stage II without any further substantial increase. The main fractures fail to connect with each other in this case, which coincides with the development of the secondary fractures in Figure 11. The results in Figure 9 suggest that shaped charge blasting alters the stress distribution in the rock mass and induces the directional propagation of the fractures.

3.4.3 | Evolution of equivalent stress

Figure 10A shows the damage area and the fracture area in the rock mass around the borehole. A “X”-shaped stress

![Figure 6](image-url)
concentration area occurs around the borehole due to the influence of the shaped charge structure on the propagation of the detonation wave in the early stage of the detonation. Part of the detonation wave reflects when it encounters the explosive forming pellet. Superimposition of the reflected detonation wave and the detonation wave propagating in the secondary shaped

FIGURE 7 Schematic diagram of model meshing: (A) air meshing; (B) rock meshing; (C) roll meshing; (D) TSCC meshing

FIGURE 8 Velocity distribution in liner during the formation of TSCJ: (A) initial of conical line; (B) initial of formation of jet; (C) intermediate formation of jet; (D) ultimate formation of jet before penetration
charge jet direction happens, leading to stress concentration in the rock mass around the borehole. In the main shaped charge jet direction, the explosive forming pellet absorbs the detonation energy once the detonation wave encounters the explosive forming pellet and transforms the detonation energy into the shaped charge jet that has highly concentrated energy. This results in the lag of the propagation of the detonation wave into the rock mass. Meanwhile, the stress wave propagates radially outwards from the borehole. The peak of the equivalent stress in the rock mass near the borehole reaches 46.0 MPa. Besides, the stress wave distributes in a triangular shape along between the boreholes. The reason is that the shaped charge jet leads to the abrupt increase of the stress in the erosion area and forms the stress concentration area in the shaped charge jet direction. The rock mass is fractured in the shaped charge jet direction, which contributes to the further directional propagation of the

**FIGURE 9** Evolution law of the rock element equivalent stress

**FIGURE 10** SCB effective stress distribution (Top view): (A) $t = 59.6 \mu s$; (B) $t = 98.3 \mu s$; (C) $t = 150.8 \mu s$; (D) $t = 274.1 \mu s$

**FIGURE 11** Evolution law of fracture field: (A) $t = 59.6 \mu s$; (B) $t = 98.3 \mu s$; (C) $t = 150.8 \mu s$; (D) $t = 274.1 \mu s$
fractures. The radial equivalent stress wave influences the area more 0.23 m away from the borehole after the detonation time exceeds 98.3 μs. Superimposition of the stress waves propagating from adjacent boreholes commences in the area between these boreholes, which induces the development and propagation of the fractures and weakens the rock mass strength (Figure 10B). When the detonation time reaches 274.1 μs, the propagation and superimposition of the detonation stress waves become more obvious, leading to the connection between the fractures in the roof (Figure 10D).

### 3.4.4 Propagation of blasting-induced fractures

Figure 11 illustrates the evolution of the fractures in the whole blasting process. A damage area with a radius of 0.1 m occurs around the borehole when the detonation time is 59.6 μs. The main fracture propagates toward the adjacent borehole with a length of 19.2 cm. Rare secondary fractures develop around the borehole (Figure 11A). When the detonation time reaches 98.3 μs, the secondary fractures form around the main fractures in a branch shape. The length of the main fracture increases to 23.1 cm. Few secondary fractures develop in the other directions (except the jet direction). This suggests that fractures are more likely to develop in the jet direction in shaped charge blasting. When the detonation time is 150.8 μs, the main fractures and the secondary fractures in the jet direction further propagate in a harpoon shape under the effect of the detonation wave and the shaped charge jet. The length of the main fracture reaches 39.1 cm. Again, rare fractures develop in the other directions (except the jet direction). Additionally, the superimposition of the detonation waves in the area between adjacent boreholes accelerates the development of the fractures. When the detonation time is 274.1 μs, the main fractures propagating from adjacent boreholes connect with each other in the shaped charge jet direction (Figure 11D). The hard roof is more likely to fracture in this case. Moreover, the secondary fractures around the main fractures propagate directionally in the horizontal direction. The reason might be that the development of the fractures in the middle of the borehole centers restrains the development of the secondary fractures.

The simulation results by LS-DYNA coincide with the simulation results22,40 indicate that shaped charge blasting directs the propagation and connection of the fractures in the jet direction. The evolution of the damage and failure processes of the roof as the detonation time increases is revealed.

### 4 CASE STUDY

#### 4.1 Geotechnical conditions

The fully mechanized mining method is applied at 15210 working face at Lingzhida coal mine. The strike length and the dip length of the working face are 1890 m and 200 m, respectively. The coal seam has an average thickness of 4.96 m, dipping at 3-6°. The mining depth is 260.4 m. The immediate roof (1.25 m), main roof (8.47 m), immediate floor (1.95 m), and main floor (4.51 m) rock mass are mudstones, limestones, carbon mudstones, and sandstones, respectively. Two thick, strong rock strata exist above the 15# coal seam with thicknesses of 8.49 m and 9.18 m, respectively. The stratum condition is detailed in Figure 12.

#### 4.2 Design of shaped charge blasting

Numerical simulation is conducted in this MS to determine the reasonable blasting parameters, and the results are applied at the mine site. Borehole monitoring is performed to investigate...
the fracture development in the blasting borehole. Besides, the deformation of the surrounding rocks is monitored to evaluate the efficiency of shaped charge blasting. In order to eliminate the influence of the blasting on the overly rock strata and the backfill wall, the blasting borehole is drilled 0.3 m away (toward the goaf) from the backfill wall at a dip angle of 75°.41 The borehole length is 10.5 m, which depends on the thickness of the hard roof.42,43 The borehole spacing is 1 m, which is based on the simulated main fracture length in Section 3. The borehole arrangement at 15210 working face is given in Figure 13.

Emulsion explosives (Level 2) are used. The dimensions of the roll are 32 mm (in diameter) × 200 mm (in length). The explosive forming pellets are installed at the sides of the explosive.

4.3 | Efficiency of shaped charge blasting

The fracture distributions around the borehole before and after SCB are observed by the borehole camera exploration device (YTJ20 type). The results are given in Figure 14. The rock mass around the borehole is relatively intact before blasting (Figure 14B). Visible damage is found after blasting due to the influence of the detonation wave (see the red circles in Figure 14C,D). In addition, obvious coin-shaped notches are observed in TSCJ directions with the maximum notch length being 15 mm. No notch and few fractures are found in other directions (except the jet directions) (see the yellow circle in Figure 14D). The
results indicate that SCB induces initial weaknesses (coin-shaped notches) around the borehole, which leads to the directional propagation of the fractures. This is consistent with the numerical simulation on the fracture development around the borehole in Figure 11A.

The rib deformation and the roof subsidence in the air-return entry (no blasting is used) and the head entry (blasting is used) are measured by the intersection point method. Figure 15 illustrates the evolution of the rib deformation and the roof subsidence when the deformation of the rock mass
at the P1 monitoring point reaches the maximum (“–” indicates that the monitoring point is behind the working face). Both the rib deformation and the roof subsidence reach the peaks (702 mm and 309 mm, respectively) at a distance 500 m behind the working face if no blasting is used. In the range 200-500 m behind the working face, the rib deformation and the roof subsidence decline gradually as the distance between the measured point and the working face decreases. The rib deformation and the roof subsidence decrease notably once shaped charge blasting is applied in the 15210 head entry. The rib deformation and the roof subsidence monitored 500 m behind the working face are 450 mm and 169 mm, respectively. Compared with the rib deformation and the roof subsidence monitored in the air-return entry (where shaped charge blasting is not applied), the rib deformation decreases 252 mm (by 35.8%) and the roof subsidence declines 281 mm (by 62.4%). Shaped charge blasting decreases entry deformation significantly, maintains the stability of the entry and ensures the safety of the working face.

The working resistance of the hydraulic supports in the 15210 head entry and the 15210 air-return entry is monitored (Figure 16). The first caving interval is 37.4 m, and the corresponding working resistance is 6.7 MPa (which is 0.5 MPa higher than the maximum working resistance of the hydraulic support) when shaped charge blasting is not applied. The rib deformation decreases 252 mm (by 35.8%) and the roof subsidence declines 281 mm (by 62.4%). Shaped charge blasting decreases entry deformation significantly, maintains the stability of the entry and ensures the safety of the working face.

The working resistance of the hydraulic supports in the 15210 head entry and the 15210 air-return entry is monitored (Figure 16). The first caving interval is 37.4 m, and the corresponding working resistance is 6.7 MPa (which is 0.5 MPa higher than the maximum working resistance of the hydraulic support) when shaped charge blasting is not applied. The hydraulic supports in the entries are clamped to the floor, which poses a risk to mining safety. Once shaped charge blasting is applied to the head entry, the first caving interval becomes much shorter and decreases by 52.1%. The working resistance of the hydraulic support is lower than its maximum working resistance, which meets the requirement for safe mining.

The field application results indicate that the entry remains stable and its deformation decreases notably once shaped charge blasting is applied. The working resistance of the hydraulic support is lower than its maximum working resistance, and the clamping of the hydraulic support to the floor is prevented. Therefore, shaped charge blasting can lead to the timely caving of the roof and highly improves the stability of the entry.

5 | CONCLUSIONS

Initiation and propagation of blasting-induced fractures in shaped charge blasting are studied by numerical simulation and the field application at Lingzhida Mine. Shaped charge blasting can improve blasting efficiency, optimize the roof structure, and ensure entry stability. The following conclusions can be drawn from the results.

1. The relationship between the stress intensity factor at the fracture tip and the fracture propagation length is determined by theoretical calculation. The explosive forming pellet deforms symmetrically to the borehole axis under the effect of the detonation wave. The shape of the explosive forming pellet changes from the V shape to the Y shape and finally becomes long, thin shaped charge jets with the fastest jet velocity. The peak of the velocity occurs at the tip of the jet.

2. A numerical model is established to simulate the stress evolution and fracture propagation in the SCB process. The reliability of the numerical model is validated by experimental results. The stress evolution in the roof strata and the initiation, propagation, and connection between fractures of adjacent boreholes are investigated. The stress disturbance zone (due to blasting) propagates outwards from the borehole center (radially) and forms a triangular stress concentration area between adjacent boreholes in the early stage of shaped charge blasting. Meanwhile, initial fractures are generated in the shaped charge jet.
direction. Based on the comparison between the development of the main fractures and the secondary fractures, it is concluded that shaped charge blasting obviously directs the propagation of the fractures between adjacent borehole. The simulation results are consistent with the field monitoring results of borehole inspection.

3. Shaped charge blasting is successfully applied in the 15210 working face at Lingzhida Mine. The deformation of the entry after shaped charge blasting decreases significantly. The rib deformation, roof subsidence, and the first caving interval decrease by 35.8%, 62.4%, and 51.2%, respectively, compared with that without shaped charge blasting. The working resistance of the hydraulic support is lower than its maximum working resistance. The results indicate that shaped charge blasting is able to weaken the hard roof, control entry deformation, and improve entry stability.

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CONFLICT OF INTEREST
The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS
MN involved in investigation; CY involved in data curation and paper writing; BJ involved in writing—original draft preparation; WX involved in writing—review and editing; WW involved in supervision; and WB involved in project administration. All authors contributed equally in this paper.

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REFERENCES
1. Zhang Z, Wang W, Li S, et al. An innovative approach for gob-side entry retaining with thick and hard roof: a case study. Tehnicki Vjesnik-Technical Gazette. 2018;25:1028-1036.
2. Xia B, Jia J, Yu B, Zhang X, Li X. Coupling effects of coal pillars of thick coal seams in large-scope stopes and hard stratum on mine pressure. Int J Min Sci Tech. 2017;27:965-972.
3. Zhang Z, Deng M, Bai J, Yu X, Wu Q, Jiang L. Strain energy evolution and conversion under triaxial unloading confining pressure tests due to gob-side entry retained. Inter J Rock Mech Min Sci. 2020;126:104184.
4. Zhang Z, Yu X, Wu H, Deng M. Stability control for gob-side entry retaining with supercritical retained entry width in thick coal seam longwall mining. Energies. 2019;12:1375.
5. He QY, Suorineni F, Oh J. Review of hydraulic fracturing for preconditioning in cave mining. Rock Mech Rock Eng. 2016;49:4893-4910.
25. Zhu ZM, Wang C, Kang JM, Li YX, Wang M. Study on the mechanism of zonal disintegration around an excavation. *Int J Rock Mech Min Sci.* 2014;67:88-95.

26. Wang YB. Study of the dynamic fracture effect using slotted cartridge decoupling charge blasting. *Int J Rock Mech Min Sci.* 2017;96:34-46.

27. Zhu ZM, Mohanty B, Xie HP. Numerical investigation of blasting-induced crack initiation and propagation in rocks. *Int J Rock Mech Min Sci.* 2007;44:412-424.

28. Zhang ZF, Wang LK, Silberschmidt VV. Damage response of steel plate to underwater explosion: effect of shaped charge liner. *Int J Impact Eng.* 2017;103:38-49.

29. Yang YQ, Jin QK, Yang RS. A new technology of directional fracture blasting in rock drift. *Eng Blasting.* 1995;81:8-10.

30. He QY, Xu JH, Joung OH. Application of dimensional analysis to project laboratory scale numerical modelling prescribed hydraulic fracturing results to field scales. *Energies.* 2018;11:1689-1715.

31. Duan BF, Zhou YC, Zheng SC. Blasting demolition of steel structure using linear cumulative cutting technology. *Adv Mech Eng.* 2017;9(11):168781401772908.

32. Wang Y. Analysis of dynamic characteristics of through-wall cracks between 2 boreholes in the directed fracture controlled blasting. *Fatigue Fract Eng Mater Stru.* 2018;41:273-286.

33. Zhang ZF, Wang LK, Silberschmidt VV, Wang SP. SPH-FEM simulation of shaped-charge jet penetration into double hull: a comparison study for steel and SPS. *Com Stru.* 2016;155:135-144.

34. Yang XJ, Liu CK, Ji YG, Zhang XY, Wang S. Research on roof cutting and pressure releasing technology of directional fracture blasting in dynamic pressure roadway. *Geo Geo Eng.* 2019;37:1555-1567.

35. Yang R, Bawden WF, Katsabanis PD. A new constitutive model for blast damage. *Int J Rock Mech Min Sci Geo Abstr.* 1996;33:245-254.

36. Livermore Software Technology Corporation. LS-DYNA Keyword User’s Manual. Livermore, CA: LSTC; 2003.

37. Nakagawa K, Sakamoto T, Yoshikai R. Model study of the guide hole effect on the smooth blasting. *Jpn Exp Soc.* 1982;43:75-82.

38. Kutter HK, Fairhurst C. On the fracture process in blasting. *Int J Rock Mech Min Sci.* 1971;8:181-202.

39. Rossmanith HP, Daehnke A, Knasmiller E, Kouzniak N, Ohtsu M, Uenishi K. Fracture mechanics applications to drilling and blasting. *Fatigue Fract Eng Mater Struct.* 1997;20:1617-1636.

40. Jayasinghe LB, Shang J, Zhao Z, Goh ATC. Numerical investigation into the blasting-induced damage characteristics of rocks considering the role of in-situ stresses and discontinuity persistence. *Comput Geotech.* 2019;116:103207.

41. Li HB, Xia XA, Li JC, Zhao J, Liu B, Liu YQ. Rock damage control in bedrock blasting excavation for a nuclear power plant. *Int J Rock Mech Min Sci.* 2011;48:210-218.

42. Chen BB, Liu CY, Yang JX. Design and application of blasting parameters for presplitting hard roof with the aid of empty-hole effect. *Shock Vibrat.* 2018;2018:1-16.

43. Wu WD, Bai JB, Wang XY, Yan S, Wu SX. Numerical study of failure mechanisms and control techniques for a gob-side yield pillar in the Sijiazhuang Coal Mine, China. *Rock Mech Rock Eng.* 2019;52:1231-1245.

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