Stress distribution and rockburst characteristics of roadway group under the influence of fault and fold structures: a case study

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ABSTRACT
Dynamic disasters such as rockbursts have different characteristics with different geological structures. The rockburst mechanism and the influencing factors of a typical composite fault-fold structure were explored by theoretical analysis and numerical simulation. The results showed that: (1) the influence of the composite fault-fold structure on the roadway group rockburst was mainly caused by tectonic stress disturbance; (2) the stress peak value and the influence range of the hanging wall of the fault were larger than those in the footwall, and the stress of the syncline axis was larger than that of the anticline axis; (3) the tectonic stress of the composite fault-fold structure was the highest, the stress value reached to the peak when the fault dip angle was 65°, and the tectonic stress was directly proportional to the elastic modulus of coal and first increased and then decreased with the increase in coal seam thickness; and (4) before rockburst, seismic activities concentrated within 200 m from the footwall and 0–250 m in the hanging wall of the fault, mainly concentrated in 0–20 and 0–40 m, respectively. The spatial distribution coincided with the high static stress area.

HIGHLIGHTS
1. The asymmetry of stress and microseismic events of composite fault-fold structure reveals the asymmetry of rockburst potential. The rockburst potential of the hanging wall of the fault is greater than that of the footwall, and the rockburst potential of the syncline is greater than that of the anticline
2. Based on the analysis of stress characteristics and fault activation, it is revealed that the rockburst of roadway group is mainly affected by the static tectonic stress of composite fault-fold structure.
3. Four influencing factors: structure type, fault dip angle, coal seam thickness, and coal elastic modulus are analysed, and the causes of stress concentration of composite fault-fold structure are revealed.
Introduction

The mining depth of coal mines in central and western China often exceeds 600 m. Rockburst, as a typical dynamic disaster, restricts the safe and efficient production of coal mines under high in situ stress and complex geological conditions (He et al. 2017; Zhang et al. 2021). The occurrence of a rockburst is closely related to fault and fold geological structure: significant roadway stress concentration can be present under the influence of tectonic stress, and when the fault and fold structure are close to each other to form a composite fault-fold structure, the further increase in coal stress after the superposition of structural stress may induce hazardous dynamic failure (Li et al. 2014; Michael and Thomas 2018). For example, on 3 November 2011, a rockburst occurred near a large reverse F16 fault during the mining of 21,221 working face in Qianqiu Coal Mine, resulting in 10 deaths and 75 trapped cases (Cai et al. 2015). On 1 April 2012, a rockburst occurred at the intersection of fault F3110-1 and fault F3109-1 during the mining of 3110 island working face in Chaoyang Coal Mine, resulting in 1 death and 16 injuries (Wang et al. 2012); On 2 August 2019, the f5010 and f5009 roadways of Tangshan mine located at the axis of Fv fault and syncline structure suffered a rockburst, resulting in seven deaths and five injuries, with a direct economic loss of 6.14024 million yuan (China Hebei Coal Mine Safety Supervision Bureau 2019).

Some scholars studied the influence of geological structure on the static stress and rockbursts of the roadway (Bruce et al., 2017; Wang et al. 2017a, 2017b). He et al. (2017) found that the static tectonic stress concentration and the dynamic stress release of fault activation were important influencing factors of roadway rockbursts. Shen et al. (2020) revealed through the measured data that the closer the working face to the geological structure, the more significant change of stress states and geotechnical conditions. Cao et al. (2001) found that dynamic disasters such as rockbursts and gas outbursts always occurred at the footwall of the reverse fault through the statistics of the structural characteristics of the four mines. Jiang et al. (2020) found that the change in fault friction angle had a significant impact on tectonic stress and roadway rockburst. Wang et al. (2018a) analysed the stress distribution characteristics of fault structure under the condition of thick and hard rocks by numerical simulation. Based on the analysis of the rockburst case of Xing’an Coal Mine, Wang et al. (2018b) found an abnormal concentration of stress, energy, and microseismic signals around the syncline structure, and the rockburst potential of the syncline axis was the highest. Cao et al. (2018) revealed the correlation between fold structural characteristics (maximum curvature, amplitude, etc.), coal seam thickness, and in situ stress. The aforementioned research results showed that various factors controlled the occurrence of rockbursts in the zones with geological structures such as faults and folds, such as fault characteristics, fault friction angle, rock stratum characteristics, fold type, and fold amplitude. The occurrence mechanism and characteristics of rockbursts varied with different structural characteristics, which brought difficulties to the monitoring and prevention of roadway rockbursts.

At the same time, some scholars studied the rockburst in the compound structural area composed of different geological structures (Cao et al. 2003; Zhao et al. 2018a). Through statistics, Zhao et al. (2018b) found two or more influencing factors for
most rockburst accidents in the Muchengjian coal mine, and the existence of a composite structure made the rockburst more intense. Through the dynamic disaster assessment of the 4 coal seam structural areas and the Pingdingshan mining area in China, Cao et al. (2020) and Zhang et al. (2019a) found that when the mine structure type was a composite structure, the more dense the composite structure was, the more prone it was to dynamic disasters such as rockbursts. Zhao et al. (2019) studied the rockburst accident in the Shuangyashan coalfield and concluded that the tectonic stress was the dominating factor of roadway rockbursts in the compound structural area.

Mengcun coal mine (hereafter referred to as MC), as a representative strong rockburst mine in the Binchang mining area of Shaanxi Province, has a buried depth of more than 600 m, composite fault-fold structure, and high in situ stress. According to statistics, from 31 August 2015, to 24 May 2020, during the driving and use of the main roadway group in the MC coal mine, multiple rockburst accidents of varying degrees caused by the composite structure occurred. A similar rockburst occurred in the Hujiahe coal mine in the Binchang mining area and the Huating coal mine in the Huating mining area. Therefore, it is of great significance to study the mechanism and characteristics of rockbursts in the roadway group under the ‘fold-fault’ composite structure for the prevention and control of rockburst in the Binchang and Huating mining areas.

Existing studies showed that the static stress of geological structure and dynamic stress of fault activation were the main causes of roadway group rockbursts induced by the composite structure. However, in combination with the specific characteristics of the composite fault-fold structure, few reports are available on the stress distribution and fault activation discrimination of the composite structure. Based on the MC coal mine roadway group, this study discussed the rockburst mechanism of the roadway group in the composite fault-fold structure area. The evolution characteristics of tectonic stress under different geological factors were analysed. The outcomes of the study might provide a reference for the prevention and control of similar rockbursts with a composite structure.

Site overview

Geological conditions

As the first strong rockburst mine in the Binchang mining area, the MC coal mine mainly mines 4 coal seam, with buried depth of 620–750 m, thickness of 3.70–26.02 m, and average thickness of 16.25 m. Through laboratory identification, 4 coal seam were found to have strong bursting liability. The MC coal mine is equipped with five main roadways in 4 coal seam, including main air-return roadway, main transportation roadway, belt conveyor roadway, secondary transportation roadway, and secondary air-return roadway, and the width of the coal pillar between roadways is 35 m, as shown in Figure 1.

The MC minefield area comprises three folds, of which Yuankouzi syncline and Xiejiazui anticline intersect with five main roadways, the fold axis direction is northeast, and Xiejiazui anticline extends westward in the east-west direction. Meanwhile,
the DF29 fault is located between the Yuankouzi syncline and the Xiejiazui anticline. The fault strike is parallel to the axial strike of the two folds, the fault throw is 18 m, and the fault dip angle is 60°–65°. The nearest distance between fold and fault structures is 40 m, and the tectonic stress interacts with each other to form a composite fault-fold structure. The structural parameters of fold and fault are shown in Tables 1 and 2.

As shown in Figure 2, the lithology of the roof above 4 coal seam was mainly coarse sandstone and medium sandstone. According to the key layer theory (Liang et al. 2017), it is judged that No. 21 fine sandstone and No. 9 coarse sandstone are sub-key layers, and No. 7 and No. 8 coarse sandstone are combined main key layers.

**Roadway group rockburst**

The MC coal mine adopts a microseismic monitoring system called SOS, manufactured by the Central Mining Institute of Poland, to monitor microseismic (MS) events in the whole mine in real time. A total of 13 underground MS detectors are arranged around the main roadway area, as shown in Figure 1. During the driving and use of the main roadway group, rockbursts to varying degrees occurred many times and caused support damage and floor heave to the roadway, as shown in Figure 3. The occurrence time, location, failure form, and distance from the structure of three representative roadway rockbursts were determined, as shown in Table 3 and Figure 4.

At 4:31 am on 31 August 2015, a $1.00 \times 10^5$ J rockburst occurred during the driving of the main transportation roadway and appeared 0–30 m behind the face. The
maximum bulge of the roadway pillar side (right side) was 1 m, the shoulder deformation was relatively large, more than 10 large pieces of concrete attached to the roadway roof collapsed, 2 metal net were torn, and several bolt plate were fractured. The site damage and the position of the rockburst are shown in Figures 3 and 4(a).

At 1:18am on 7 March 2019, a $1.21 \times 10^5$ J rockburst occurred at 1600–1635 m of the main transportation roadway, resulting in an average floor heave of about 0.5 m within 35 m of the roadway, pieces of concrete attached to the roadway roof fell off, and the belt support was damaged for 6 m. The site damage and the position of the rockburst are shown in Figures 3 and 4(b).

At 0:08am on 24 May 2020, a $2.37 \times 10^5$ J rockburst occurred near the DF29 fault, which resulted in a local floor heave of 1.5 m in the secondary transportation roadway.
and the belt conveyor roadway, the belt conveyor turned over, and three roadway repairers were injured to varying degrees.

The statistics of the location, lithology of surroundings, and distance from the structures of the three rockbursts are shown in Table 3. The three rockbursts are located in the roadway group of the composite fault-fold structure, 130–160 m away from the structures.

**Table 3. Statistical data of the rockburst of the MC main roadway group.**

| No | Rockburst | Lithology | Damage roadway | Damage range (m) | Distance from structures (m) |
|----|-----------|-----------|----------------|-----------------|------------------------------|
|    |           |           |                |                 | DF29 | Yuankouzi syncline | Xiejiazui anticline |
| 1  | 2015.8.31 | Coal      | Main transportation roadway | 30 | 30 | 45 | 160 |
| 2  | 2019.3.7  | Coal      | Main transportation roadway | 35 | 0 | 80 | 130 |
| 3  | 2020.5.24 | Coal      | Secondary transportation roadway | 78 | 0 | 50 | 160 |

**Figure 3.** A rockburst on-site appearance in the roadway group.

**Figure 4.** Location of microseismic events before a rockburst of the central roadway.
from the Xiejiazui anticline, 0–30 m away from the DF29 fault, and 45–80 m away from the Yuankouzi syncline. From the perspective of spatial location, the composite fault-fold structure was the main cause of the roadway group rockburst.

**Rockburst mechanism of roadway group under the composite fault-fold structure**

**Tectonic stress analysis of the composite fault-fold structure**

The distribution of fault tectonic stress is affected by factors such as fault length, fault dip angle, and \textit{in situ} stress. The DF29 fault along the dip section was simplified into an elliptical stratum fracture with a length of $2q$, and the complex coordinate system was established based on the long and short axes of the ellipse: $z = x + iy$. The area on the $z$ plane is transformed into the area on the $\zeta$ plane. In $\zeta$ plane, $\zeta = \rho (\cos \varphi + i \sin \varphi) = \rho e^{i \varphi}$ can be obtained, where $\rho$ is the length of a point in the coordinate
system and the centre of the ellipse, m; \( \varphi \) is the included angle between the connecting line between a point in the coordinate system and the centre of the ellipse and the long axis of the ellipse, \( ^\circ \); \( \rho \) and \( \varphi \) form a polar coordinate system (Liu et al. 2016; Zhang et al. 2020), as shown in Figure 5.

The complex variable function was obtained

\[
z = x + iy = \omega(\zeta) = \frac{q}{2} (1/\zeta + \zeta)
\]

(1)

where \( \omega(\zeta) \) is the variation function.

Then, the complex function of the stress component and its boundary conditions were as follows.

\[
\sigma_x + \sigma_y = 4\text{Re}\varphi'(z)
\]

(2)

\[
\sigma_y - \sigma_x + 2i\tau_{xy} = 2[\bar{z}\varphi''(z) + \psi'(z)]
\]

(3)

\[
\varphi'(z) + z\varphi'(z) + \psi'(z) = i \int \left( \bar{f}_x + i\bar{f}_y \right) ds
\]

(4)

where \( \sigma_x \) is the tectonic stress in \( x \) direction, \( \sigma_y \) is the tectonic stress in \( y \) direction, \( \tau_{xy} \) is shear stress, \( \varphi(z) \) and \( \psi(z) \) are the complex potential functions; and \( \bar{f}_x + i\bar{f}_y \) is the complex function of boundary surface forces.

According to the relationship between stress component and complex potential function in a curvilinear coordinate system and boundary conditions, the following was obtained

\[
\sigma_\varphi + \sigma_\rho = 4\text{Re}\Phi(\zeta)
\]

(5)

\[
\sigma_\varphi - \sigma_\rho + 2i\tau_{\rho\varphi} = \frac{2\zeta^2}{\rho^2\omega'(\zeta)} \left[ \bar{\varphi}(\zeta)\Phi'(\zeta) + \omega'(\zeta)\Psi(\zeta) \right]
\]

(6)

\[
i \int \left( \bar{f}_x + i\bar{f}_y \right) ds = \Phi(\zeta) + \omega(\zeta)/\left[ \omega'(\zeta)\Phi'(\zeta) + \Psi(\zeta) \right]
\]

(7)

where \( \sigma_\varphi \) is the circumferential stress, \( \sigma_\rho \) is radial stress, and \( \tau_{\rho\varphi} \) is the shear stress, at the same time \( \varphi'(\zeta) = \varphi(z) \), \( \varphi'(\zeta) = \varphi'(z)/\omega'(\zeta) = \Phi(\zeta) \); then \( \psi'(\zeta) = \psi(z) \), \( \psi'(z) = \psi'(\zeta)/\omega'(\zeta) = \Psi(\zeta) \).

Under the condition of finite stress, the complex functions \( \Phi(\zeta) \) and \( \Psi(\zeta) \) were as follows:

\[
\Phi(\zeta) = \frac{1 + \nu}{8\pi} \left( \bar{F}_x + i\bar{F}_y \right) \ln \zeta + U\omega(\zeta) + \varphi_0(\zeta)
\]

(8)
\[ \Psi(\zeta) = -\frac{3 - \nu}{8\pi} (F_x - i F_y) \ln \zeta + (U' + i V') \omega(\zeta) + \psi_0(\zeta) \tag{9} \]

\[ \varphi_0(\zeta) = \sum_{n=1}^{\infty} u_n \zeta^n; \psi_0(\zeta) = \sum_{n=1}^{\infty} v_n \zeta^n \tag{10} \]

Combining the in situ stress field and boundary conditions as shown in Figure 5, the equilibrium equation was given:

\[ U = (\sigma_v' + \sigma_h')/4; U' = (\sigma_v' - \sigma_h')/2 \tag{11} \]

\[ V' = 0; \left( \int_{-s}^{+s} F_x + i F_y \right) ds = 0 \tag{12} \]

\[ F_x = F_y = 0 \tag{13} \]

Combined with formula \((8)-(18)\), the following formula could be obtained:

\[ \varphi'(z) = \frac{\sigma_v'}{2} \left( \frac{z}{\sqrt{z^2 - q^2}} \right) + \frac{\sigma_h'}{4} - \frac{\sigma_v'}{4} \tag{14} \]

\[ \psi'(z) = -\frac{\sigma_v' + \sigma_h'}{2} \tag{15} \]

where \(a, a_1, a_2\) and \(\gamma, \gamma_1, \gamma_2\) are the distance and included angle from point \(D\) to the left end, middle point, and right end of the fault, respectively. Then, combined with Equation \((3)\), the tectonic stress increment of point \(D\) is:

\[ \Delta \sigma_x = -\sigma_v'(D - E - 1) \tag{16} \]

\[ \Delta \sigma_y = -\sigma_v'(1 - D - E) \tag{17} \]

\[ \Delta \tau_{xy} = -\sigma_v'F \tag{18} \]

where \(D = (a_1/\sqrt{aa_1}) \cos [\gamma_1 - (\gamma + \gamma_2)/2], E = \left[ q^2 a_1/\sqrt{(aa_2)^3} \right] \sin \alpha \sin [3(\gamma + \gamma_2)/2], \)

\[ F = -\left[ q^2 a_1/\sqrt{(aa_2)^3} \right] \sin \alpha \cos [3(\gamma + \gamma_2)/2]. \]

The stresses \(\sigma_v'\) and \(\sigma_h'\) as defined in previous Equations \((16)\) and \((17)\) are transformed in a coordinate system aligned with the fault according to the fault dip angle \(\delta:\)

\[ \sigma_v' = \frac{\sigma_h + \sigma_v}{2} - \frac{\sigma_h - \sigma_v}{2} \cos 2\delta - \tau_{vh} \sin 2\delta \tag{19} \]
The measured horizontal principal stress direction of in situ stress in the MC coal mine was perpendicular to DF29 fault, and $\sigma_h = 31.46\text{MPa}$, $\sigma_v = 22.60\text{MPa}$. After substituting the length of 240 m and dip angle of $65^\circ$ of the DF29 fault into formula (16)–(20), combined with the stress transformation formula, the horizontal stress increment of the fault was obtained, as shown in Figure 6. Due to the influence of in situ stress and fault dip angle, the distribution range of horizontal stress increment in the hanging wall of the fault was larger than that in the footwall, showing an asymmetric distribution, and the maximum horizontal stress increment was about 16.4 MPa.

4 coal seam stress monitoring lines around the fault in Figure 6 were set to obtain the horizontal stress increment curve, as shown in Figure 7. The horizontal stress increment of the hanging wall of the fault was significantly higher than that of the footwall, which was 16.41 MPa and 14.52 MPa, respectively, and the distance between the stress peak point and the fault plane was 46 m and 43 m, respectively.

The composite fault-fold structure tectonic stress was mainly composed of fault stress increment and fold tectonic stress. A FLAC 3D numerical simulation model was established based on the fold curvature and amplitude determined by the contour line of the floor of 4 coal seam to explore the x-x horizontal stress distribution at different distances from the roadway to the anticline and syncline axes. The length, width, and height of the model were 800, 320, and 200 m, respectively. Five coal main roadways were modelled in the centre of the model, bounded by 80-m coal pillars on both sides. The width of the coal pillar between roadways was 34 m; the width and height of roadways were 4 and 4 m, respectively; and thickness of the floor coal was 2 m. When the roadways tunnelled to positions I (60 m behind the syncline axis), II (synclinal axis), III (60 m in front of the syncline axis), IV (anticline axis), V (52 m in front of the anticline axis), VI (120 m in front of the anticline axis), and VII
(192 m in front of the anticline axis), the plan view of the roadway group is shown in Figure 8.

The plan view revealed the stress concentration around the roadway during driving, and the degree of stress concentration varied at different distances from the fold axis. Therefore, the x-x horizontal stress in roadway roof behind the face was extracted, as shown in Figure 9. The stress curves of the five main roadways showed that the highest vertical stress was mainly located around the lateral roadway, up to about 36 ~ 39 MPa. With further driving of roadways, the maximum stress around the belt conveyor roadway presented a ‘rise-drop’ trend. The maximum peak stresses were located on the syncline axes, and the stress was 39.13 MPa. At the same time, the peak stress curves of five main roadways located on the syncline axis showed that the horizontal stress of the central main roadway was higher than that of the lateral roadways under the influence of the superposition of the roadway abutment stress. In conclusion, a higher stress concentration would be formed in the fold axis and the central roadway, and the rockburst potential would be improved due to the fold structures and the layout of roadway groups.

The stress distribution of coal seams in the composite structural area could be obtained by the superposition of fault stress increment and fold tectonic stress, as shown in Figure 10. The stress of the coal seams in the hanging wall and footwall of the composite structure was asymmetrically distributed. The peak stress of the hanging wall was 52.83 MPa, which was higher than 45.74 MPa of the footwall. The influence range of the tectonic stress of the hanging wall was about 230 m, which was larger than 120 m of the footwall. The peak stress and distribution range indicated that the rockburst potential of the hanging wall of the composite structure was significantly higher than that of the footwall.

**Rockburst mechanism of the roadway group in the composite fault-fold structure**

Under static and dynamic stress disturbance, a rockburst was induced when the coal stress exceeded the critical value (He et al. 2017; Cao et al. 2019). According to the
static tectonic stress field distribution of the composite fault-fold structure mentioned earlier, combined with the fault slip formula, whether DF29 is activated or not was assessed using Equation (21) defined as follows (Cai et al. 2019):

\[
\left( \sum \sigma_v - \sum \sigma_h \right)_{slip} = \frac{2(c + \sum \sigma_h \tan \varphi_f)}{(1 - \tan \varphi_f \cot \theta) \sin 2\theta}
\]  

(21)

where \( \sum \sigma_v \) and \( \sum \sigma_h \) are the vertical and horizontal stress components at the fault plane after the superposition of in situ stress and composite tectonic stress increment, expressed as \( \sum \sigma_v = \int (\sigma_v + \Delta \sigma_v) \), \( \sum \sigma_h = \int (\sigma_h + \Delta \sigma_h) \). \( \varphi_f \) is the fault friction angle, taken as 30°; \( c \) is the cohesion of fault plane, taking 2 MPa with reference to the mechanical properties of coal and rock in the MC coal mine. The minimum principal stress (33.1 MPa) of the DF29 fault calculated using Equation (21) was less than the activation critical value (77.59 MPa), and it was judged that the DF29 fault was not activated.

Therefore, it was comprehensively determined that the main disturbance of the composite fault-fold structure to the roadway group under the condition of nonactivation of the DF29 fault in the MC coal mine was tectonic stress, as shown in Figure 11. The static stress of coal and rock mass around the roadway group in the composite structural area was affected by roadway abutment stress and tectonic stress (Cheng and Zhang 2018). The static stress of coal of the lateral roadway in single structural area was \( \sigma_s + \sigma_{g1} \), of which \( \sigma_s \) was the roadway abutment stress, \( \sigma_{g1} \) is the static stress increment caused by structure 1. The static stress of the coal of central roadway
in the composite structural area was 
\[ \sigma_s + \sigma_{g1} + \sigma_{g2} + \Delta \sigma_s, \] of which \( \Delta \sigma_s \) was the superimposed abutment stress increment, and \( \sigma_{g1} + \sigma_{g2} \) was the static stress increment caused by the composite structure formed by structure 1 and structure 2.

Compared with no structural and single structural area, the rockburst core area around the roadway group (where the coal stress exceeded the critical stress \( \sigma_{B\text{min}} \)) was larger after the superposition of static stress increment caused by composite structure and abutment stress. The nonlinear release of cumulative elastic energy in this area induced a roadway group rockburst. In addition, if mining dynamic stress \( \sigma_d \) disturbance was present, not only the peak value of superimposed stress of coal was higher (the roadway was more prone to the rockburst), but also the rock burst core area was larger, and more coal bodies participated in the rockburst; the higher the elastic energy released, the more severe the rockburst.

**Figure 9.** Horizontal stress of the roadway group in the fold structure.

**Figure 10.** Horizontal stress of coal seam in the fold structure and composite structure.
Numerical simulation of influencing factors of the composite fault-fold structure tectonic stress

As shown in Figures 1 and 11, the rockburst of the roadway group of the MC coal mine occurred in the composite fault-fold structure area. Compared with other non-rockburst roadway areas, the structural area was obviously affected by tectonic stress. Four tectonic stress influencing factors, including structure type (Cai 2015), fault dip angle (Yang et al. 2018; Li et al. 2021), coal seam thickness (Guo et al. 2018; Zhang et al. 2019b), and coal elastic modulus (Zhao et al. 2014), were selected for numerical simulation analysis. In this study, the finite element numerical simulation software FLAC 3D was used to analyse the influence of the aforementioned factors on composite fault-fold structure tectonic stress.

Simulation scheme of influencing factors

Simulation model

The simulation model of the composite fault-fold structure was established in combination with the site conditions, and the roadway was vertically arranged with the composite fault-fold structure after simplifying the azimuth, as shown in Figure 12. The footwall of the DF29 fault and Xiejiazui anticline were located on the left side of the model, and the right side of the composite structure included the hanging wall of the fault and Yuankouzi syncline. The dip angle of the DF29 fault was preliminarily set at 65°, and the distance from the fault plane to the syncline and anticline axes was 40 and 150 m, respectively. Five coal mine roadways driving in the centre of the model, bounded by 80-m coal pillars on both sides. The width of the coal pillar between roadways was 34 m, the width and height of roadways were 4 and 4 m, respectively, and the floor coal thickness was 2 m. At the same time, x-x horizontal stress monitoring lines (x-x horizontal stress was monitored because its direction was the same as the maximum horizontal in-situ stress of MC coal mine) were arranged in the middle of the coal seams in the hanging wall and footwall of the composite structure.

The nonsimulated strata overlying the coal seam were replaced by uniform stress 19 MPa, the fixed boundary was adopted at the bottom of the model, and the other
surfaces except the top were the rolling support boundary. According to the in situ stress test results of the MC coal mine, the initial stress in x and y directions of the model was 34 and 22.6 MPa, respectively. Based on the Mohr-Coulomb strength criterion (Zhao et al. 2013; Małkowski et al. 2017), combined with the rock mechanics test results of MC coal mine and adjacent mines, the physical and mechanical parameters of coal and rock are shown in Table 4.

The shear modulus of rock mass near the fault was about one fifth of the mechanical parameters (Ivins and Lyzenga 1986). Therefore, the normal stiffness (KN) and tangential stiffness (KS) of the interface of the simulated fault were set as 3.1 and 1.29 GPa, respectively, about one third and one sixth of the four coal mechanical parameters. The friction angle of the interface was set as 30°, and the cohesion was 2 MPa (Barton and Choubey 1977; Zhu et al. 2016)

**Numerical simulation scheme**

The evolution of coal seam tectonic stress was studied according to four influencing factors: structure type, fault dip angle, coal seam thickness, and coal elastic modulus. The simulation scheme was as follows.

- Structure type: Four numerical models of no structure, single fault, single fold, and composite fault-fold structure are established.
- Fault dip angle: Taking the junction point between the hanging wall of the fault and the middle line of the coal seam as the centre to rotate the fault plane, eight composite structure numerical models with fault dip angles of 30°, 40°, 45°, 50°, 60°, 70°, 80°, and 90° were established.
- Coal seam thickness: Seven numerical models of composite structures with coal seam thicknesses of 2, 4, 8, 12, 16, 24, and 32 m, were established.
- Coal elastic modulus: A total of 6 numerical models of composite structures with different coal elastic moduli of 0.5, 1.0, 1.5, … and 3.0 GPa were established.
Analysis of stress evolution of composite structure

Tectonic stress evolution of structure type

Figure 13 shows the x-x horizontal stress distributions of coal seams of four structural types: no structure, single fault, single fold, and composite fault-fold structure. The x-x horizontal stress (original in situ stress) of no structure coal seam was 34.0 MPa, and the stress curve was a straight line. For the model of single fault, the stress concentration in the hanging wall and footwall near fault plane was observed, and the maximum horizontal stress in the hanging wall was significantly higher than that in the footwall, which were 43.9 and 37.5 MPa, respectively; the stress increment was 9.9 and 3.5 MPa, respectively, compared with the original in situ stress. The horizontal stress concentration of the hanging wall 0–31 m away from the fault plane was obvious, and it decreased at 31–167 m. The horizontal stress concentration of the footwall 0–15 m away from the fault plane was obvious, and it was slightly lower than the original in situ stress at 15–135 m. For the single fold model, the coal seam stress reached the highest at the syncline and anticline axes, which were 35.5 and 34.1 MPa, respectively, which increased by 1.5 and 0.1 MPa, respectively, compared with the in situ rock stress. As shown in Table 5, for the composite fault-fold structure model, the hanging wall horizontal stress reached the maximum at the fault and syncline axis, which were 45.2 and 35.6 MPa, respectively, increasing by 1.3 and 0.1 MPa compared with single fault and single fold structure, respectively. The horizontal stress concentration of the hanging wall 0–40 m away from the fault plane was obvious; it decreased slightly at 40–260 m, which was 9 and 84 m larger than the single fault structure. The horizontal stress of the footwall reached the maximum at the fault, which was 38.4 MPa, larger than the single fault structure, and the minimum stress was 33.5 MPa at the anticline axis. The stress concentration and reduction ranges were 20 and 190 m, respectively, which increased by 5 and 70 m compared with the single fault structure.

The results of tectonic stress simulation of different structural models of the MC coal mine showed that faults had more obvious influence on tectonic stress compared with folds. When the faults and folds were superimposed into a composite structure, the syncline axis was located in the stress concentration area of the hanging wall of the fault, the folds and fault tectonic stress were superimposed, and the stress at the hanging wall of the fault and syncline axis increased by 1.3 and 1.1 MPa, respectively, compared with the single fault structure. At the same time, the stress concentration area in the hanging wall increased to 260 m, which was consistent with the theoretical

| Lithology             | Bulk modulus (GPa) | Shear modulus (GPa) | Cohesion (MPa) | Tensile strength (MPa) | Friction angle (°) |
|-----------------------|--------------------|---------------------|----------------|------------------------|--------------------|
| Coarse sandstone      | 2.80               | 2.00                | 2.30           | 2.30                   | 34                 |
| Fine sandstone        | 5.35               | 4.17                | 2.50           | 2.00                   | 35                 |
| Sandy mudstone        | 2.68               | 1.84                | 2.00           | 2.00                   | 32                 |
| 4 coal                | 1.19               | 0.37                | 0.50           | 0.80                   | 23                 |
| Mudstone              | 3.03               | 1.56                | 1.00           | 1.20                   | 27                 |
| Aluminous mudstone    | 3.03               | 1.56                | 1.00           | 1.20                   | 27                 |
analysis. The obvious stress concentration area increased to 40 m, which was consistent with the roadway group rockburst area.

**Tectonic stress evolution of fault dip angle**

According to the stress analysis of the structural type, the horizontal stress of the composite fault-fold structure is mainly concentrated in the fault area, and the stress increment in the hanging wall and footwall of the fault is much higher than that in the fold axis. Therefore, the later analysis of the horizontal stress mainly focuses on the area of the fault. Figure 14 shows the horizontal stress evolution of the composite fault-fold structure under different fault dip angles. The maximum horizontal stress of the footwall was 34.7–37.0 MPa at 30–40 m away from the fault plane. The horizontal stress of the hanging wall reached the maximum at 0–20 m away from the fault plane, which were 37.9–45.2 MPa.

The horizontal stress around the fault plane of the composite structure was significantly higher than that of the fold axis. When the dip angle of the fault was 30°–65°, the horizontal stress of the hanging wall increased with the increase in the dip angle and reached the peak at 65°, which was 45.2 MPa. When the dip angle of the fault was 65°–90°, the horizontal stress of the hanging wall decreased with the increase in the dip angle, and the decline rate was higher than the rise rate. The horizontal stress of footwall decreased with the increase in the fault dip angle, with a small variation range of 2.3 MPa.

The simulation results showed that the fault dip angle had an obvious influence on the hanging wall than footwall. The horizontal stress of hanging wall first increased
and then decreased with increases in the dip angle and reached the maximum at 65°. The DF29 fault dip angle of the MC coal mine was 65°, and the simulated horizontal stress concentration factor of hanging wall and footwall was 1.33 and 1.13, respectively, much higher than in-situ stress. Therefore, it was concluded that the dip angle 65° of the DF29 fault was an important factor causing the stress concentration of the composite fault-fold structure.

Tectonic stress evolution of coal seam thickness

Figure 15 shows the horizontal stress evolution of the composite fault-fold structure under different coal seam thicknesses. The maximum horizontal stress of the footwall was 30.4–44.8 MPa at 0–20 m away from the fault plane, and the horizontal stress of the hanging wall reached the maximum at 0–30 m away from the fault plane, which was 36.9–45.7 MPa. The horizontal stress around the hanging wall of the composite structure was basically higher than that of the footwall. When the coal seam thickness was 2–24 m, the horizontal stress of the hanging wall increased with the increase in the coal seam thickness and reached the peak at 24 m, which was 45.7 MPa. When the coal seam thickness was 24–32 m, the horizontal stress of the hanging wall decreased with the increase in the coal seam thickness. The horizontal stress of footwall increased with the increase in coal seam thickness, and the variation range was 14.4 MPa.

The simulation results showed that the composite fault-fold structure was obviously affected by the coal seam thickness. The maximum horizontal stress concentration factor of the hanging wall of the fault was 1.34 when the coal thickness was 424 m, and that of the footwall was 1.32 when the coal thickness was 32 m. The 4-coal seam thickness in the MC coal mine was 16 m, corresponding to the horizontal stress concentration factors of the hanging wall and footwall were 1.33 and 1.13, respectively, which were at a high level. Therefore, it was concluded that the 4-coal seam thickness of 16 m was an important factor causing the stress concentration of the composite fault-fold structure.

Tectonic stress evolution of the coal elastic modulus

Figure 16 shows the horizontal stress evolution of the composite fault-fold structure under different coal elastic moduli. The peak value of horizontal stress of the footwall of the fault was 30.6–39.4 MPa, and that of hanging wall was 33.8–46.6 MPa.
With the increase in the elastic modulus of coal, the horizontal stress of the composite fault-fold structure changed sharply. The horizontal stress of the hanging wall and footwall of the fault positively correlated with the elastic modulus of the coal. When the elastic modulus was 0.5 GPa, the horizontal stress around the fault was about 0.2–2.4 MPa lower than the in situ stress. When the elastic modulus was 1 GPa, the horizontal stress concentration factor around the fault was 1.01–1.1, which was close to the in situ stress. When the elastic modulus was higher than 1 GPa, the coal stress around the fault continued to increase and exceed the in situ stress.

The simulation results showed that the composite fault-fold structure was affected by the coal elastic modulus. When the coal elastic modulus exceeded 1 GPa, the horizontal stress around the fault exceeded the in situ stress (34 MPa); while the elastic modulus of 4 coal seam in the MC coal mine was 2.6 GPa, the horizontal stress concentration factor of 4 coal seam was 1.33, which was at a high level. Therefore, it was concluded that the elastic modulus of 2.6 GPa of 4 coal seam was an important factor causing the stress concentration of the composite fault-fold structure.

The tectonic stress simulation results of the influencing factors of the composite fault-fold structure were as follows: (1) among the four structural types, the tectonic stress of the composite fault-fold structure reached the maximum, which was 45.2 MPa; (2) the dip angle of the DF29 fault was 65°, and the horizontal stress of coal seam reaches the peak value; (3) the tectonic stress first increased and then decreased with the increase in the coal seam thickness, and the horizontal stress of 4 coal seam of 16 m was at a high level; (4) the elastic modulus of 4 coal seam was 2.6 GPa, higher than 1 GPa, and the horizontal stress around the fault exceeded the in situ stress. Therefore, it was comprehensively judged that the horizontal stress concentration in the composite structural area of the MC coal mine was caused by the superposition of the ‘fault-fold’ structural type; the dip angle DF29 fault was 65°, 4 coal seam thickness was 16 m, and the coal elastic modulus was 2.6 GPa.

Seismic characteristics and prevention of the roadway group rockburst under the composite fault-fold structure

Temporal and spatial distributions of MS under the composite fault-fold structure

The MS events before three rockbursts of the roadway group in the composite fault-fold structure were counted, and the MS events with energy $E > 10^4$ J and $E \leq 10^8$ J
were defined as high-energy and low-energy events, respectively, as shown in Table 6. On 31 August 2015, when the main transportation roadway was driving to the DF29 fault, the high static stress coal in the composite structural area was affected by the driving dynamic stress, and 405 MS events occurred in a week. The daily frequency of MS events was 50.63/d, and the frequency of high-energy MS events was high, accounting for 16.3%. During the use of the roadway group, ‘3.7’ and ‘5.24’ rockbursts occurred, no mining activity was performed around the main roadways, and the static stress of coal was affected by the tectonic stress of the composite structure. Therefore, the frequency of MS events decreased significantly; 120 days before the two rockbursts, the MS frequency decreased to 40 and 19, respectively. Compared with the ‘8.31’ rockburst, the daily frequency of MS decreased to 0.33/d and 0.01/d, respectively, decreased by 99.35% and 99.98%. The ratio of high-energy MS also decreased significantly, which was 7.5% and 10.5%, respectively.

Combined with simulation results of the influencing factors of the composite structure tectonic stress and the statistics of MS frequency and energy, the causes of ‘3.7’ and ‘5.24’ rockbursts during the roadway group use were determined: without mining dynamic stress disturbance, the structural type, fault dip angle, coal seam thickness, and elastic modulus of the composite fault-fold structure caused the stress concentration in the structural area. Therefore, under the superposition of the abutment stress of the roadway group and tectonic stress, the static stress of coal around the roadway exceeded its critical stress, and the nonlinear release of elastic energy stored in coal induced the roadway rockburst. The cause of ‘8.31’ rockburst during roadway driving: the coal around the roadway was affected by the superposition of the driving dynamic stress, abutment stress, and tectonic stress, and the coal stress exceeded the critical stress to induce the rockburst.

The spatial distribution of MS events was affected by the coal stress level and dynamic stress disturbance (Lu et al. 2012; Shi et al. 2019). According to the simulation results in Figure 13, the stress concentration degree of coal at different positions of the composite fault-fold structure was different.

Therefore, the statistical area of MS aggregation was divided with the DF29 fault plane as the centre. Areas a and b of the footwall were 20–210 m and 0–20 m away from the fault plane, and areas c and d of the hanging wall were 0–40 m and 40–260 m away from the fault plane, respectively. Therefore, the MS spatial aggregation (MS frequency/statistical range) before three rockbursts is shown in Table 6 and Figure 17. Comparing ‘8.31’ rockburst with ‘3.7’ and ‘5.24’ rockbursts, the maximum MS aggregation of the
Table 6. Statistics of MS events in three rockburst cases.

| No | Rockburst | Statistics date       | State  | Number of MS | Daily frequency of MS | Energy level | Frequency | Ratio | Area | Frequency | Ratio | Aggregation/m |
|----|-----------|-----------------------|--------|--------------|-----------------------|--------------|-----------|-------|------|-----------|-------|--------------|
| 1  | 8.31      | 2015.8.24–2015.8.31   | Driving| 405          | 50.63                 | High         | 66        | 16.3% | a    | 83        | 20.5% | 0.44         |
|    |           |                       |        |              |                       | Low          | 339       | 83.7% | b    | 71        | 17.5% | 3.55         |
|    |           |                       |        |              |                       | High         | 3         | 7.5%  | c    | 148       | 36.5% | 3.70         |
|    |           |                       |        |              |                       | Low          | 103       | 25.4% | d    | 103       | 25.4% | 0.47         |
| 2  | 3.7       | 2018.11.7–2019.3.7    | Use    | 40           | 0.33                  | High         | 3         | 7.5%  | a    | 16        | 40.0% | 0.08         |
|    |           |                       |        |              |                       | Low          | 8         | 20.0% | b    | 8         | 20.0% | 0.40         |
|    |           |                       |        |              |                       | High         | 10        | 25.0% | c    | 10        | 25.0% | 0.25         |
|    |           |                       |        |              |                       | Low          | 6         | 15.0% | d    | 6         | 15.0% | 0.03         |
| 3  | 5.24      | 2020.1.24–2020.5.24   | Use    | 19           | 0.01                  | High         | 2         | 10.5% | a    | 3         | 15.7% | 0.02         |
|    |           |                       |        |              |                       | Low          | 2         | 10.5% | b    | 2         | 10.5% | 0.10         |
|    |           |                       |        |              |                       | High         | 8         | 42.1% | c    | 8         | 42.1% | 0.20         |
|    |           |                       |        |              |                       | Low          | 6         | 31.6% | d    | 6         | 31.6% | 0.03         |
roadway under driving dynamic stress disturbance was 3.70, which was 925.0% of that without dynamic stress disturbance. Compared with static stress, the superimposed stress of coal under dynamic stress disturbance was much higher than the critical stress; the coal was more prone to rockburst. At this time, the rockburst core area was larger, more coal participated in the rockburst, and the MS activities were more intense. The spatial distribution of MS before three rockbursts was basically concentrated in the range of 0–200 m away from the hanging wall and 0–250 m away from the footwall of the fault, which was consistent with the theoretical analysis and simulation results. In addition to the MS data error caused by the maintenance of some road areas in the ‘3.7’ rockburst, the MS spatial aggregation of different areas of the ‘8.31’ and ‘5.24’ rockburst events was as follows: area c > area b > area d > area a, which was consistent with the simulation results of the composite structure tectonic stress.

**Prevention and control of rockburst in the roadway group with the composite fault-fold structure**

The rockburst mechanism of the roadway group in the composite fault-fold structure area was that the high static stress formed by tectonic stress and abutment pressure exceeded the critical stress $\sigma_{B_{\text{min}}}$ of surrounding coal, and the nonlinear release of elastic energy stored in coal induced the roadway group rockburst. The superimposed stress of coal under static stress and dynamic stress disturbance was much higher than the critical stress, and the coal was more prone to the rockburst. The larger the rockburst core area was, the more the coal participating in the rockburst; also, the MS activities are more intense. At the same time, the roadway group rockbursts and MS events were concentrated in high static stress area of the composite structure. Therefore, the prevention and control of the roadway group rockburst in the composite fault-fold structure area included three aspects: (1) the coal seam roadway should be changed to the rock seam roadway to improve the critical stress $\sigma_{B_{\text{min}}}$ of surrounding rock and coal, and the rockburst core area of the roadway was reduced or even eliminated under the same superimposed stress; (2) in the stress construction
area of the composite structure, the static stress of coal was reduced, the integrity of surrounding coal was damaged, and the critical stress $\sigma_{Bmin}$ was improved through stress relief measures such as coal large-diameter drilling and coal blasting; and (3) dynamic stress disturbance on roadways should be reduced or avoided in the structural area, such as increasing the width of the safety coal pillar to isolate the working face from the main roadway group, which can prolong the propagation path of the disturbed stress wave.

**Conclusions**

1. The composite fault-fold structure tectonic stress in the MC coal mine had obvious asymmetric distribution, and the stress peak value and influence range of the hanging wall of the structure were 52.83 MPa and 230 m, respectively, which were higher than those of the footwall. Also, the rockburst hazard potential of the hanging wall was high.

2. According to the fault slip criterion, the DF29 fault was judged to be inactive, indicating that the influence of the composite fault-fold structure on the roadway group was mainly static tectonic stress. Therefore, the rockburst mechanism of the roadway group in the composite fault-fold structure area was that the high static stress formed by tectonic stress and abutment pressure exceeded the critical stress of surrounding coal, and the nonlinear release of elastic energy stored in the coal induced roadway rockburst.

3. The tectonic stress simulation results of the influencing factors of the composite fault-fold structure showed that the tectonic stress reached the maximum when the structural type was composite and the fault dip angle was 65°; the tectonic stress first increased and then decreased with the increase in coal seam thickness and increased with the increase in coal elastic modulus. It was comprehensively concluded that the stress concentration of the composite fault-fold structure was caused by the structure type, fault dip angle of 65°, 4 coal seam thickness of 16 m, and coal elastic modulus of 2.6 GPa.

4. MS events before the rockburst were distributed at 0–200 and 0–250 m away from the footwall and hanging wall of the fault plane, respectively, and concentrated at 0–20 and 0–40 m, which were consistent with the simulation results of the stress concentration area. Under the influence of driving dynamic stress disturbance, the energy of MS events in the roadway group in the composite structural area was high, and its aggregation reached 3.70, which was 925.0% of that without dynamic stress disturbance, indicating that the MS activities were more intense and the rockburst damage was more severe when the roadway was disturbed by dynamic stress, which was consistent with the theoretical analysis result.

**Disclosure statement**

The authors declared that they have no conflicts of interest to this work.
Funding

This research is supported by National Natural Science Foundation of China under Grant Nos. 51734009, and Major Science and Technology Innovation Program of Shandong Province under Grant Nos. 2019SDZY02.

Data availability statement

The data used to support the findings of this study are available from the corresponding author upon request.

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