NUMERICAL SIMULATION OF A FAILURE PATTERN OF THE ROOF IN COAL SEAM WORKING FACE

By

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This study adopts the cohesive element technology for the first time to analyze the dynamic evolution process of crack formation and propagation, and to clarify the mechanical mechanism of the "O-X" failure pattern in the roof. The mechanical behavior of cohesive failure inside the rock is simulated based on the maximum nominal stress criterion, and the Benzeggagh-Kenane (BK) fracture criterion is used to further describe the dependence of fracture energy on the combination of mixed tensile-shear mode. The results show that the "O"-shaped crack is formed on the top surface of the roof, and delamination occurs along the thickness direction, which coincides with the crack bifurcation position on the bottom surface of the roof. The "cross"-shaped crack forms on the center of the bottom surface of the roof, and extends towards the four corners at the bifurcation position to form a spatial "X"-shaped crack.

Key words: *roof, "O-X" failure pattern, cohesive element, BK fracture criterion*

Introduction

The fracture of the hard roof will lead to rockburst hazard, seriously endanger mine production safety. Therefore, studying the fracture pattern of hard roof is crucial for ensuring safe coal mining. Academician Chien Ming-Gao first proposed the theory of "voussoir beam", which has been applied to analyze the fracture pattern of the roof [1]. In addition to the formation of "voussoir beam" structure during the rupture of the roof, Wang and coauthors [2] reported that the fracture morphology of strata is a horizontal "O-X" type. Research by Dou and He [3] shows that the O-X fracture is the elemental structure of overlying strata. It was pointed out by Yu and coauthors [4] that the structure model for near field key stratum is "cantilever beam and voussoir beam" broken in the shape of "vertical O-X" while that of far field key stratum is "voussoir beam" broken in the shape of "horizontal O-X". Bai and coauthors [5] also reported that the vertical "O-X" type initial fracture, fracture adjustment and periodic fracture of the thick sandstone layer can easily induce strong mine earthquake events. However, the above studies have not quantitatively revealed the underlying mechanical

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mechanism of "O-X" fracture pattern, or have not fully simulated the generation process of O-X cracks. During to the fact that they have not been fully understood in theory and engineering, the mechanism of "O-X" fracture pattern needs to be further explored.

A theoretical model

Based on the extended Drucker-Prager (EDP) model, the plastic deformation of the matrix phase inside the rock is described, and the hyperbolic yield equation is written as [6, 7]:

$$F=\sqrt{l_0^2+q^2}-p\tan\beta-d^{'}=0,\quad d^{'}=\sqrt{l_0^2+\sigma_c^2}-\frac{\sigma_c}{3}\tan\beta \tag{1}$$

where F stands for the yield function, l_0 and $d^{'}$ are the model parameters, p, q and σ_c represent the hydrostatic pressure, Mises stress and uniaxial compressive strength respectively, and β is the friction angle of the Drucker-Prager (DP) model.

The yield stress σ_y describes the hardening law of the material. Here, σ_{y0} is the initial yield stress. Assuming that σ_y follows an exponential decay law, there is

$$\sigma_y(\bar{\varepsilon}^{pl})=A+Be^{-\zeta\bar{\varepsilon}^{pl}} \tag{2}$$

where ζ is the attenuation index, and A and B are the model parameters. Considering the residual equivalent yield stress and equivalent plastic strain as σ_{yR} and $\bar{\varepsilon}_R^{pl}$ respectively, there is

$$A=\sigma_{y0}-B;\quad B=\left(\sigma_{y0}-\sigma_{yR}\right)/\left(1-e^{-\zeta\bar{\varepsilon}_R^{pl}}\right) \tag{3}$$

The maximum nominal stress criterion of cohesive zone model (CZM) is used to represent the initial damage of the cohesive element, that is, when the maximum nominal strain ratio reaches 1.0, the damage is assumed to start [7]. G_n^C, G_s^C and G_t^C represent the critical fracture energy during pure deformation along the normal, first and second shear directions respectively. Assuming that $G_s^C=G_t^C$, the BK fracture criterion is used to describe the dependence of fracture energy on the combination of the mixed tensile-shear mode, given as [8]:

$$G_n^C+(G_s^C-G_n^C)\{\frac{\chi_s+\chi_t}{\chi_n+\chi_s+\chi_t}\}^{\eta}=G^C \tag{4}$$

where η is the material parameter, and χ_n, χ_s and χ_t represent the proportion of the work done by the tractions and their conjugate relative displacements in the normal, first, and second shear directions, respectively.

Finite element model

The finite element model is shown in Figure 1. The solid element type of the roof and coal is C3D8, and the material property is the hyperbolic Drucker-Prager elastoplastic material. Eq. (2) is used to simulate the softening behavior of the material. The failure criterion adopts the shear failure criterion. The mechanical parameters refer to Table 1 and Table 2, respectively. E is the elastic modulus and μ is the Poisson's ratio. The cohesive element type is COH3D8, and the material property is a linear elastic material with traction-separation behavior. The initial thickness of the cohesive layer is 1.0 mm by default. The damage initiation criterion is the maximum nominal stress criterion, and the damage evolution criterion adopts the energy-based linear softening BK fracture criterion. The relevant parameters are referred to Table 3. K_{nn}, K_{ss} and K_{tt} represent the tensile and two shear stiffness respectively. σ_{nn}, σ_{ss} and σ_{tt} represent the normal, first, and second shear nominal stresses respectively, and ρ is the density.

Boundary conditions: a uniform load of 10 MPa is applied to the top of the model, a uniform load of 10 MPa is applied to all sides, and a gravity load is applied in the vertical direction. The vertical displacement constraint is applied to the bottom of coal.

Table 1: Mechanical parameters of the roof and coal

Material	E	μ	ρ	β	ψ	φ
Roof	10.0	0.3	2.58	43.32	30	35
Coal	5.0	0.2	2.58	37.67	20	20

Table 2: Mechanical parameters of the Drucker-Prager model

Material	σ_t	σ_c	σ_{y0}	σ_{yR}	ζ	$\bar{\varepsilon}_R^{pl}$
Roof	8.0	60.0	49.41	5.0	50	1.0
Coal	4.3	30.0	22.42	2.6	10	1.0

Table 3: Mechanical parameters of the cohesive model

K_{nn}	K_{ss}	K_{tt}	ρ	σ_{nn}	σ_{ss}	σ_{tt}	G_n^C	G_s^C	G_t^C	η
12.0	2.4	2.4	2.58	8.0	12.0	12.0	0.12	0.4	0.4	2.0

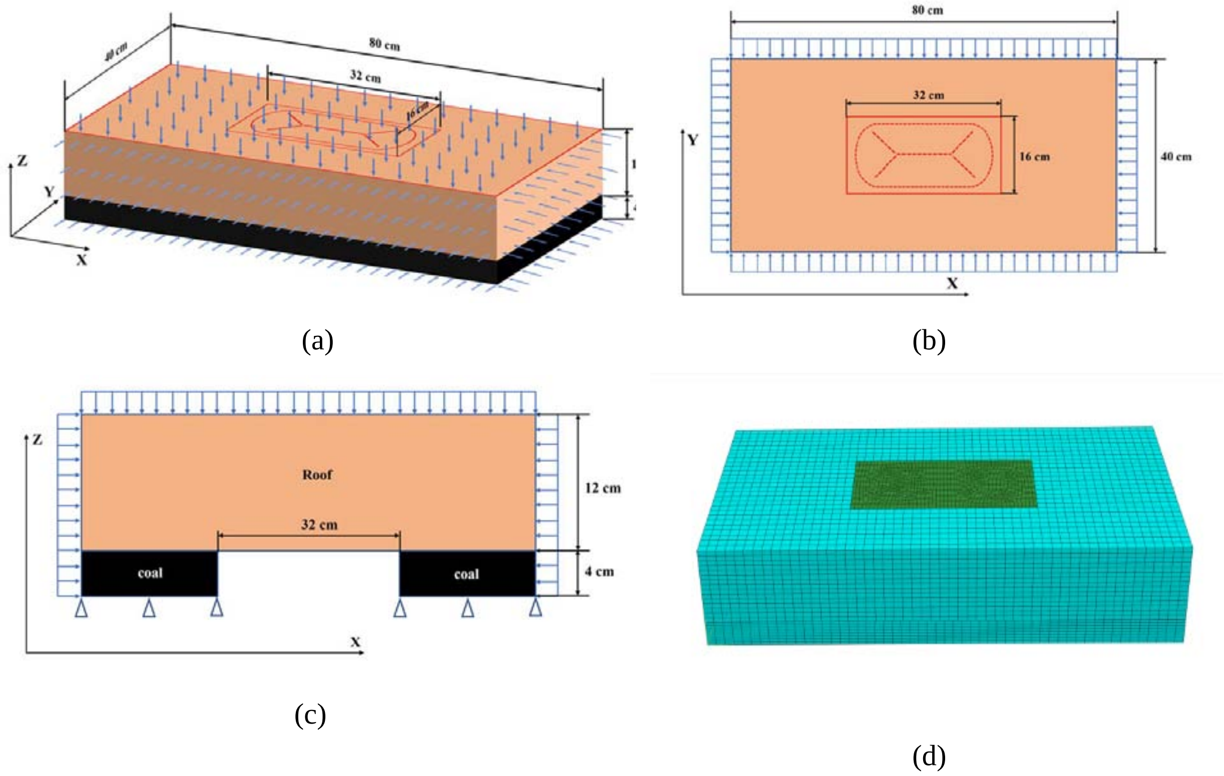
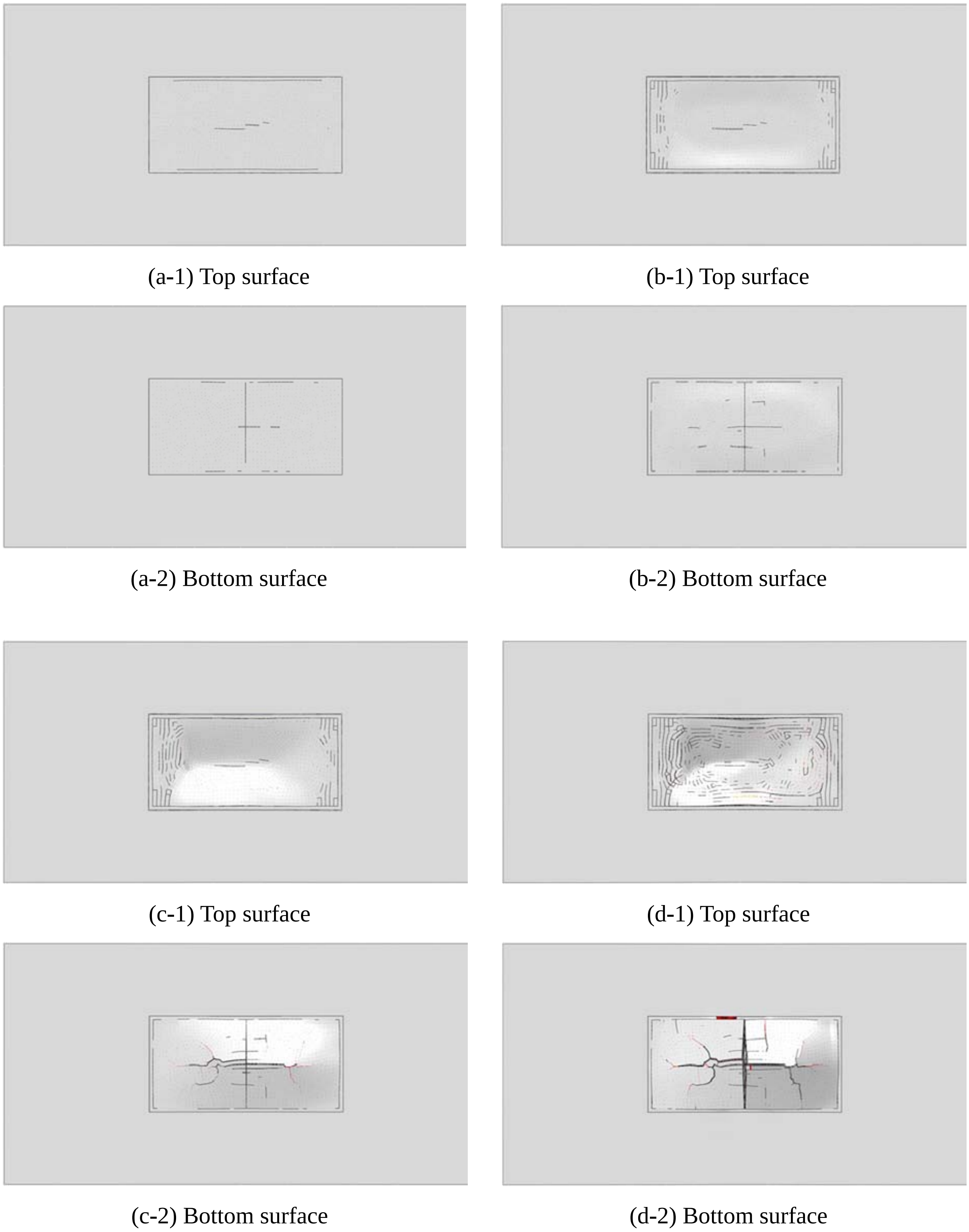


Fig.1 The finite element model of the roof and coal seam: (a) front view of the roof-coal system; (b) vertical view of the roof-coal system; (c) cross-sectional view of the roof-coal system after excavation; (d) schematic of the finite element mesh, cohesive elements are inserted in the excavation region

Simulation of the "O-X" fracture process of the roof

Analysis of the "O-X" fracture pattern

Figure 2 shows the distribution laws of cracks on the top and bottom surfaces of the roof at different time intervals. As shown in Figure 2, the "O"-shaped ring first appears on the top surface of the roof in the goaf region, while the "cross"-shaped crack first appears in the center of the bottom surface, and begins to branch along the long side to form an "X"-shaped crack. The bifurcation position roughly matches the inner boundary position of the "O"-shaped ring, and finally penetrates up and down to form a complete "O-X" spatial crack distribution pattern.



(a-1) Top surface (b-1) Top surface

(a-2) Bottom surface (b-2) Bottom surface

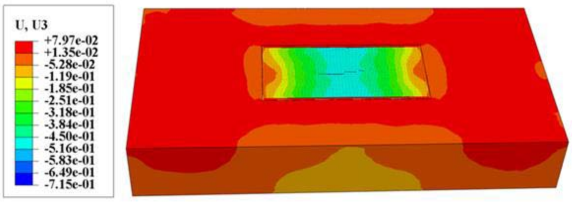
(c-1) Top surface (d-1) Top surface

(c-2) Bottom surface (d-2) Bottom surface

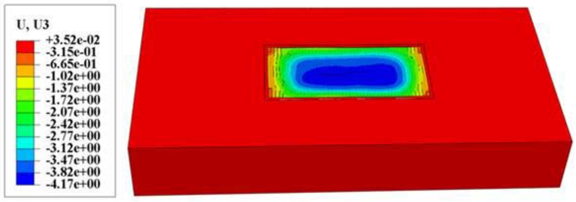
Fig.2 Distribution laws of cracks on the top and bottom surfaces of the roof at different time intervals: (a) time=360 s; (b) time=1260 s; (c) time=1980 s; (d) time=3600 s

Analysis of the settlement deformation

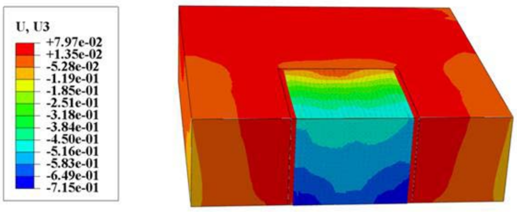
Figure 3 shows the front and cross-sectional views of the distribution laws of the settlement displacement in the roof at different time intervals. It can be seen that the cohesive elements of the roof in the goaf region are characterized by shear failure and then debonded from the surrounding rock mass, resulting in dislocation and slippage. The settlement displacement in the "O"-shaped ring shows a gradient distribution law, in an inverted "V" shape. With the appearance of "X"-shaped crack on the bottom surface and the penetration of "O"-shaped ring in the upper and lower directions, the characteristics of delamination appears in the thickness direction. Finally, the tensile fracture occurs on the bottom surface, the settlement displacement of the central position increases significantly, and the similar "voussoir beam" structure is completely formed.



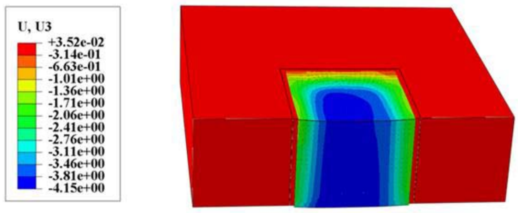
(a-1) Front view



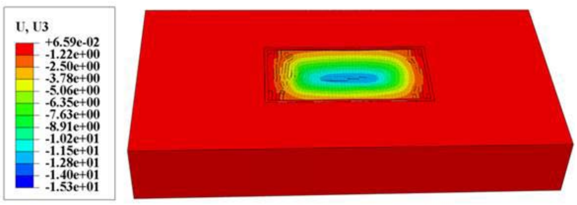
(b-1) Front view



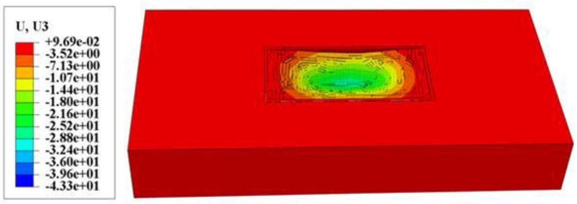
(a-2) Cross-sectional view



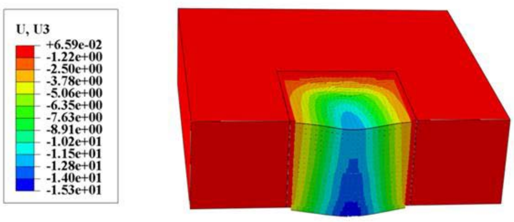
(b-2) Cross-sectional view



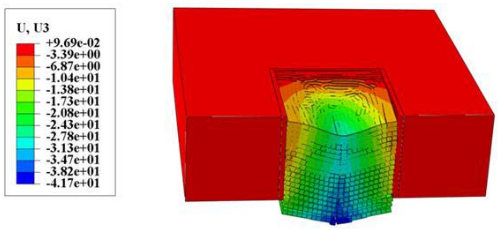
(c-1) Front view



(d-1) Front view



(c-2) Cross-sectional view



(d-2) Cross-sectional view

Fig.3 Distribution laws of the settlement displacement of the roof at different time intervals: (a) time=360 s; (b) time=1260 s; (c) time=1980 s; (d) time=3600 s

Conclusions

Based on the proposed theoretical method and finite element model, this paper carries out the mechanical analysis and numerical simulation of the "O-X" fracture process of hard roof. Firstly, a finite element model to simulate the "O-X" fracture pattern of the roof is developed based on the cohesive element analysis technology, which is used to predict the dynamic evolution process of the formation and propagation of fracture traces in the roof. Secondly, globally inserted cohesive elements are used to simulate the mechanical behavior of cohesive failure within the rock. Finally, a fracture criterion describing the mixed fracture mode of cohesive elements is given. The BK fracture criterion is used to describe the dependence of the fracture energy on the fracture mode during the "O-X" fracture process of the roof, and further study the mechanical behavior of the mixed tensile-shear fracture mode inside rock mass. By means of numerical simulation, the mechanism and basic reason of the formation of the "O-X" fracture in the roof are revealed, which lays a theoretical foundation for mine safety production.

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Nomenclature

F - yield function, [MPa]	$l_0, d^{'}$ - EDP model parameter, [MPa]
p - hydrostatic pressure, [MPa]	q - Mises stress, [MPa]
σ_c - compressive strength, [MPa]	σ_y - yield stress, [MPa]
φ - friction angle of MC model, [$°$]	β - friction angle of DP model, [MPa]
ψ - dilation angle of DP model, [$°$]	$\bar{\varepsilon}^{pl}$ - equivalent plastic strain, [1]
ζ - attenuation index, [1]	T - traction force, [N]
σ - nominal stress, [MPa]	ε - nominal strain, [1]
G^C - fracture energy, [$mJ \cdot mm^{-2}$]	χ - proportion of fracture mode, [1]
E - elastic modulus, [GPa]	μ - Poisson's ratio, [1]
K - stiffness, [GPa]	ρ - density, [$g \cdot cm^{-3}$]
t - time, [s]	U - displacement, [mm]

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