The Primary Breaking Pattern of Main Roof Above the First Working Face Based on Main Bending Moment

Baogui Yang

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haigang yang (✉ haigangy@163.com)

China University of Mining and Technology(Beijing), Beijing 100083, China <https://orcid.org/0000-0001-7101-0765>

Xiaofeng Lu

CUMTB

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The primary breaking pattern of main roof above the first working face based on main bending moment

Yang Baogui, Yang Haigang*, Lu Xiaofeng

School of Energy and Mining Engineering, China University of Mining and Technology(Beijing), Beijing 100083, China

Abstract Scientific mining is based on breaking regularity of roof above underground working face in coal mine. In order to explore the primary breaking pattern of main roof above the first working face, on account of theory of thin elastic plate, development of the breaking in each region of main roof is analyzed and the breaking sequence of each region is explored in virtue of main bending moment taken as the breaking parameter. The results indicate that the first broken point of main roof is midpoint of the long side. The breaking, which occurs on the top surface of main roof, is caused by the second main bending moment. The fracture in long side region starts from midpoint of the long side and develops along the length direction of the working face. The fracture in middle region starts from the center of main roof and develops along the length direction of the working face. The fracture in short side region starts from midpoint of the short side and develops along advance direction of the working face. There always is an extreme value order of control moment in each region, $M_c > M_z > M_d$, when a single parameter is within a reasonable range. Due to this, the breaking sequence is the long side region, the middle region and the short side region although they end up with the same breaking pattern O-X. M_c , M_z and M_d depend on the advance distance of working face and increase linearly with transverse loading. Besides, the short side of main roof becomes stable with the increase of the length of working face. Revealing the primary breaking pattern of main roof above the first working face contributes to learning breaking behavior of main roof and providing theoretical support for design of the working face and roof management.

Key words main bending moment, the breaking pattern, the first working face, main roof, plate with four fixed sides

1 Introduction

Although exploitation of coal resources can bring valuable coal products for people, it may also raise some thorny issues in the mining operations. For example, strata movement not only pose a serious threat to the safety of mining production of the working face and adjacent stopes, but also can result in ground surface subsidence or even collapse. Revealing the laws of strata movement can contribute to addressing these problems and promote the development of mining technology. Because the movement of strata is closely related to the failure rule of the roof, it is crucial important to learn the failure pattern of the roof (Qian and Xu 2019; Zuo et al. 2019).

Several researchers have used the plate model to study the failure rule of the roof. For example, Zhao et al. (2018) have given analytic solution of their plate model, and presented the evolution of boundary condition of main roof on the base of calculating results of the bending moment. The model developed by Yu (2018) has shown that the midpoint of the long side in the thin plate with four simply clamped edges, and the midpoint of the clamped side in the thin plate with three simply clamped edges are more likely to break. Based on the stress and the bending moment in X direction and deflection of the roof, Xue et al. (2016) have investigated initial and periodic collapse behavior of the roof burdened with underground pressure. Yang et al. (2015)' results, which were based on the stress in Y direction of the thin plate have indicated that the centre and the midpoint of the long

side in the roof with four simply clamped edges are prone to break when initial collapse happens. Wang and Gao (2015) have presented inner failure mechanism of the roof according to calculated values of the bending moment and the stress in both X and Y direction, and shear stress of variable length of the working face. Liu and Li (2014)' theoretical analysis and numerical simulation results have given stress distribution of the island coal face and the evolution of the breaking roof with time. Pu et al. (2011) have analyzed the bending moment of the thin plate with four simply clamped edges, and they have obtained the collapsing, developing and transferring pattern of the roof. Zhang et al. (2010) have presented stress distribution of initial and periodic collapse obtained by using ANSYS, and revealed failure mechanism of the roof with highly inclined up-dip working face. Similarly, taking advantage of Mathcad software and then getting the contour line of the stress in both X and Y direction of the roof, Li et al. (2008) have showed the initial and periodic collapse pattern. Wang et al. (2008) have built the elastic plate model based on the roof supported by pillars, and showed the failure pattern in different stages in the light of the bending moment value. Wang et al. (2005) have calculated stress in the thin plates with four simply clamped edges and three simply clamped edges. They have had a good explanation of segmental, stage and migration pressure, which happens in hard strata. On the base of analyzing stress distribution of the roof in Bai Laping, a coal mine, Tang and Ye (2003) have drawn the conclusion that the first broken point of main roof is midpoint of the long clamped side.

Some studies (Zhao et al. 2018; Yu 2018; Xue et al. 2016; Yang et al. 2015; Wang and Gao 2015; Liu and Li 2014; Pu et al. 2011; Zhang et al. 2010; Li et al. 2008; Wang et al. 2008; Wang et al. 2005; Tang and Ye 2003) mentioned above were carried out under the assumption that normal stress reaching the critical values causes failure of the roof. It is not reasonable since the maximum value of normal stress is first principal stress, and sometimes stress in both X and Y direction are not the maximum value of normal stress. Similarly, the main moment is the true cause of failure of the roof when the bending moment is taken as the

failure criteria. Besides, some previous works (Zhao et al. 2018; Xue et al. 2016; Wang and Gao 2015; Zhang et al. 2010; Wang et al. 2008; Wang et al. 2005) are limited to broken points of the roof instead of the whole development process of the roof failure. In consideration of these limits, this study will be conducted. Firstly, the paper obtains distribution of the main bending moment and failure direction of broken points, and subsequently discusses the development of failure regions of main roof. Finally, parameter effect analysis is used to explore the breaking sequence of each region, and to get the primary breaking pattern of main roof above the first working face.

2 Development and analysis of the model

Beginning at open-off cut, the working face is advancing. As a result of it, stress applied on the immediate roof is increasing until stress reaches the maximum value, and then the immediate roof collapses. Similarly, after that, main roof also experiences the first collapse with the increasing exposure roof surface, and fitful collapse of the immediate roof. Several studies (Zhao et al. 2018; Yu 2018; Xue et al. 2016; Yang et al. 2015; Wang and Gao 2015; Liu and Li 2014; Pu et al. 2011; Zhang et al. 2010; Li et al. 2008; Wang et al. 2008; Wang et al. 2005; Tang and Ye 2003; He et al. 2017) show that mechanical behavior of the roof above underground working face can be studied by using the thin elastic plate theory.

2.1 Deflection surface equation

Before the first collapse, main roof can be simplified to a thin elastic plate, and its four sides are restricted by coal, the immediate roof, and overlying strata, which are regarded as fixed boundaries in the paper, and have no movement.

As showed in Fig.1, a thin elastic plate model with four fixed boundaries is built, and its x, y and z axis coincide with length, width and height direction of the working face, respectively. S denotes advanced distance of the working face, and t is the length. It is noted that $s < t$. F_1 , F_2 , G_1 and G_2 are midpoints of its corresponding side, and O is the central point of main

roof.

Fig.1 Mechanical model of rectangular thin elastic plate with four fixed boundaries

According to the thin elastic plate theory (Xu 2006; Timshenko and Goodier 1970; Timshenko and Woinowsky-krieger 1959), the fixed boundary condition is presented as follows:

$$\omega \Big|_{x=\pm \frac{s}{2}} = 0, \quad \frac{\partial \omega}{\partial x} \Big|_{x=\pm \frac{s}{2}} = 0 \quad (1)$$

$$\omega \Big|_{y=\pm \frac{t}{2}} = 0, \quad \frac{\partial \omega}{\partial y} \Big|_{y=\pm \frac{t}{2}} = 0 \quad (2)$$

Where ω is deflection of the thin plate.

The trial function of the above equation can be written as:

$$\omega = C \left(x^2 - \frac{s^2}{4} \right)^2 \left(y^2 - \frac{t^2}{4} \right)^2 \quad (3)$$

Where C is a parameter.

Since the equation of (3) satisfies displacement boundary conditions and inner force boundary conditions from (1) and (2), according to Galerkin method, there is:

$$C = \frac{49q}{87s^4 + 4s^2t^2 + 7t^4)D} \quad (4)$$

Where D is bending stiffness of the thin elastic plate.

Consequently, the deflection surface equation of the thin elastic fixed plate can be written as:

$$\omega = \frac{49q}{87s^4 + 4s^2t^2 + 7t^4)D} \left(x^2 - \frac{s^2}{4} \right)^2 \left(y^2 - \frac{t^2}{4} \right)^2 \quad (5)$$

2.2 Failure criteria

According to rock mechanical theory (Qian et al. 2010; Sun et al. 2009), when M_u is used as ultimate moment of main roof, the failure criteria is presented as follows:

$$\max \{ |M|, |M_2| \} = |M_l| \quad (6)$$

The equation of (6) shows that main roof collapses when main bending moment of a point in main roof reaches the maximum absolute value.

According to elastic thin plate theory (Xu 2006), plate stress can be expressed as function of ω and bending moment M_x and M_y , and torque M_{xy} can be calculated as:

$$M_x = -D \left(\frac{\partial^2 \omega}{\partial x^2} + \nu \frac{\partial^2 \omega}{\partial y^2} \right) \quad (7)$$

$$M_y = -D \left(\frac{\partial^2 \omega}{\partial y^2} + \nu \frac{\partial^2 \omega}{\partial x^2} \right) \quad (8)$$

$$M_{xy} = -D(1 - \nu) \frac{\partial^2 \omega}{\partial x \partial y} \quad (9)$$

In addition to main bending moment M_1 and M_2 , they can be expressed as:

$$M_1, M_2 = \frac{M_x + M_y}{2} \pm \sqrt{\left(\frac{M_x - M_y}{2} \right)^2 + M_{xy}^2}$$

(10)

Where $M_1 + M_2 = M_x + M_y$. Normal direction of

action surface of M_1 is vertical to that of M_2 , and the included angle (α) between the former one and x direction can be calculated as

$$\alpha = \arctan \frac{M_1 - M_x}{M_{xy}} \quad (11)$$

By substituting Eq. (7), (8) and (9) into Eq. (10), M_1 and M_2 can be determined as;

$$M_1 = -\frac{D(1+\nu)}{2} \left(\frac{\partial^2 \omega}{\partial x^2} + \frac{\partial^2 \omega}{\partial y^2} \right) + \frac{D(1-\nu)}{2} \sqrt{\left(\frac{\partial^2 \omega}{\partial y^2} - \frac{\partial^2 \omega}{\partial x^2} \right)^2 + 4 \left(\frac{\partial^2 \omega}{\partial x \partial y} \right)^2} \quad (12)$$

$$M_2 = -\frac{D(1+\nu)}{2} \left(\frac{\partial^2 \omega}{\partial x^2} + \frac{\partial^2 \omega}{\partial y^2} \right) - \frac{D(1-\nu)}{2} \sqrt{\left(\frac{\partial^2 \omega}{\partial y^2} - \frac{\partial^2 \omega}{\partial x^2} \right)^2 + 4 \left(\frac{\partial^2 \omega}{\partial x \partial y} \right)^2} \quad (13)$$

Since bending moment and torque are internal force applied on unit width, their dimension and unit are LMT^{-2} and MN , respectively, instead of L^2MT^{-2} and $\text{MN}\cdot\text{m}$ (Xu 2006).

2.3 Analysis of the model

To intuitively analyze failure behavior of main roof, some data from the KOU Zidong coal is used in this paper ($s=40$ m, $t=360$ m, $q=0.25$ MPa (Yu 2018; He et al. 2017), $E=30$ GPa, $\nu=0.2$ and $h=6$ m, where q , E , ν and h are lateral load, elastic modulus, Poisson's ratio and thickness of main roof, respectively).

Fig.2 is distribution of main bending moment. As showed in Fig.2, the maximum absolute value of the main bending moment (the second principal moment) happens in F_1 or F_2 , and is -43.44 MN. Substituting it into the function of first principal stress (Sun et al. 2009) yields tensile stress of main roof surface (i.e. 7.24 MPa). The value and the advanced distance (40m) equal approximately to the ultimate tensile stress and first collapse distance, respectively, which indicates reliability of the model and rationality of used parameters.

(a) The first principal bending moment

(b) The second principal bending moment

Fig.2 Distribution of main bending moment

From Fig.2 (a), it can be seen that maximum and minimum value of the first principal bending moment happens in points O (21.77 MN) and F_1 (or F_2 , -8.69 MN), respectively. Since the absolute value of 21.77 is greater than -8.69, according to Eq. (6), the point O is more likely to be the failure point of main roof. Similarly, F_1 (or F_2 , -43.43 MN) is the failure point of main roof in Fig.2 (b), which is caused by the second principal bending moment. By comparing the results from Fig.2 (a) and Fig.2 (b), it can be concluded that F_1 (or F_2 , -43.43 MN) is the failure point of main roof. Given that negative bending moment denotes main roof bending downward, there is tensile stress in the upper half of main roof, and compressive stress in the lower half in Fig.2. Collapse happens in the upper surface of the roof in this case while it happens in the lower surface if the first principal bending moment value of the point O reaches ultimate moment.

3 The development of failure of each region

From the discussion made above, five extreme points (F_1 , F_2 , O, G_1 and G_2) and F_1 (or F_2 , -43.43 MN), which is more likely to become failure, are obtained. In this section, failure patterns will be analyzed. To simplify the problem, main roof is divided into three parts, which are the short side region, the middle region and the long side region, as showed in Fig.3.

Fig.3 Region division of main roof

Since main roof collapses when main bending moment of a point in main roof reaches the maximum absolute value (M_k , the controlled bending moment) according to Eq. (6), and the sign of the bending moment

represents just bending direction, the focus of the paper is absolute value of main bending moment.

3.1 Failure of the long side region

Fig.4 (b) shows variation of M_k (the second principal moment) of some points. Their locations can be got through orient angle β (0° , 30° , 60° and 90°) and distance d (1, 2, 3, 4, 5 and 6 m) between the targeted point and F_2 , as presented in Fig.4 (a).

Fig.4 Variation of M_k of the long side region

From Fig.4 (b), it can be seen that when β keeps constant, M_k linearly decreases with the increase of distance d . M_k varies from 37.08, to 37.89, then to 40.22 and finally to 43.43 MN, if distance d keeps 1 m and β is 0° , 30° , 60° and 90° , respectively. M_k increment of these points, compared with the point F_2 , is 6.36, 5.55, 3.22 and 0.01 MN. M_k varies greatly along advanced direction of the working face while varying slightly along length direction of the working face.

When distance d is 6m, and β is 0 and 90° , M_k is approximately 10 and 43 MN, respectively, which indicates that after failure of F_2 , points along length direction of the working face are more likely to break. Due to the symmetry axis of x , there is similar distribution of main bending moment in the upper half of main roof.

Failure direction can be determined by calculating Eq. (11). For example, there are $\tan \alpha = \infty$ and

$\alpha = \pm 90^\circ$ about points on the long side of main roof,

which means that normal direction of action surface of M_1 is vertical to that of M_2 and x direction, which are parallel to each other. Failure of the points on the long side is caused by the second principal moment. In this way, there is tension damage along x direction in these points of main roof.

In fact, since M_{xy} of the points on the long side is 0 MN, and M_x and M_y are main bending moment according to the definition of main bending moment, normal direction of action surface is x direction and y direction. M_x is the second principal bending moment if the bigger one among M_x and M_y is M_y . Similarly, the failure situation along x direction of the points on the long side can also be obtained. Distribution of torque is shown in Fig.5.

Fig.5 Distribution of torque

From Fig.5, it can be draw that M_{xy} of points on the long side and the short side of main roof is 0 MN. The main bending moment of these points is corresponding M_x and M_y . The first and the second principal moment can be determined by value of M_x and M_y . While M_{xy} of points on main roof is not 0 MN, normal direction of action surface of main bending moment can be calculated by Eq. (11).

The obtained failure pattern above is that after failure of F_2 , points along length direction of the working face will successively break. Meanwhile, the same failure pattern will happen in the upper half of the main owing to the symmetry axis of x .

3.2 Failure of the middle region

Fig.6 (b) gives variation of M_k (the first principal moment) of some points. Their locations can be got through orient angle β ($0, 30, 60$ and 90°) and distance d (1, 2, 3, 4, 5 and 6 m) between the targeted point and reference point O , as presented in Fig.6 (a).

Fig.6 Variation of M_k of the middle region

Fig.6 (b) illustrates that when β is constant, there is remarkable decrease of M_k associated with the increase of distance d . M_k varies from 21.61, to 21.65, then to 21.73 and finally to 21.77 MN when distance d is 1 m and β is 0, 30, 60 and 90°, respectively. M_k increment of these points, compared with the point O, is 0.16, 0.12, 0.04 and 0.00 MN. M_k varies significantly along advanced direction of the working face while varying slightly along length direction of the working face. When distance d is 6 m, and β is 0 and 90°, M_k is approximately 16 and 21 MN, respectively, which suggests that after failure of O, points along length direction of the working face are more likely to break while points along advanced direction keeps stable. Owing to the symmetry distribution of M_k , main bending moment in other three quadrants of main roof has the same pattern. So, after failure of O, points on long symmetry axis of main roof will break.

From Fig 5, it can be found that M_{xy} of points on the long symmetry axis of main roof is null, and M_x is the first principal bending moment since the bigger one among M_x and M_y is M_x . The first principal bending moment causes failure of points on the long symmetry axis of main roof. So, tensile failure will happen in these points along x direction.

The obtained result above is that after failure of O, points along length direction of the working face will successively break.

3.3 Failure of the short side region

Fig.7 (b) presents variation of M_k (the second principal

moment) of some points. Their locations can be got through orient angle β (0, 30, 60 and 90°) and distance d (1, 2, 3, 4, 5 and 6 m) between the targeted point and reference point G_1 , as presented in Fig.7 (a). G_1 (or G_2) is more likely to break in the short side region.

Fig.7 Variation of M_k of the short side region

Fig.7 (b) indicates that if β is constant, there is linearity decrease of M_k associated with the increase of distance d . M_k varies from 0.54, to 0.52, then to 0.50 and finally to 0.49 MN if distance d is 1 m and β is 0, 30, 60 and 90°, respectively. M_k increment of these points, compared with the reference point, is 0.00, 0.02, 0.04 and 0.05 MN. M_k varies slightly along advanced direction of the working face while varying significantly along length direction of the working face. When distance d is 6m, and β is 0 and 90°, M_k is approximately 0.25 and 0.40 MN, respectively, which suggests that after failure of G_1 (or G_2), points along

advanced direction of the working face are more likely to break while points along length direction keeps stable. Owing to the symmetry distribution of M_k , main bending moment in the left side of main roof has the same pattern. So, after failure of G_1 (or G_2), points on the short side of main roof will break.

From Fig 5, it can be found that M_{xy} of points on the long symmetry axis of main roof is null, and M_y is the second principal bending moment since the bigger one among M_x and M_y is M_x . The second principal bending moment causes failure of points on the short symmetry axis of main roof. So, tensile failure will happen in these points along y direction.

The obtained result above is that after failure of G_1 , points along advanced direction of the working face

will successively break. Meanwhile, the same failure pattern will happen in the other side of the main owing to the symmetry axis.

4 Analysis of breaking sequence of each region

After getting the failure evolution of each region, breaking sequence will be discussed below. Since the points in which M_k reaches extremum is the breaking points, and their breaking sequence represents corresponding region', extremum of M_k of these points will be analyzed.

Substituting Eq. (5) into Eq. (12) and (13) yields

$$M_1 = \frac{49q(1+\nu)A - 49q(\nu-1)\sqrt{B^2 + 64x^2y^2(\frac{s^2}{4} - x^2)(\frac{t^2}{4} - y^2)^2}}{28s^4 + 16st^2 + 28t^4} \quad (14)$$

$$M_2 = \frac{49q(1+\nu)A + 49q(\nu-1)\sqrt{B^2 + 64x^2y^2(\frac{s^2}{4} - x^2)(\frac{t^2}{4} - y^2)^2}}{28s^4 + 16st^2 + 28t^4} \quad (15)$$

Where, $A = (\frac{s^2}{4} - x^2)(\frac{t^2}{4} - y^2)(\frac{s^2}{4} + \frac{t^2}{4} - x^2 - y^2) - 2y^2(\frac{s^2}{4} - x^2)^2 - 2x^2(\frac{t^2}{4} - y^2)^2$,

$$B = (\frac{s^2}{4} - x^2)(\frac{t^2}{4} - y^2)(\frac{s^2}{4} - \frac{t^2}{4} - x^2 + y^2) - 2y^2(\frac{s^2}{4} - x^2)^2 + 2x^2(\frac{t^2}{4} - y^2)^2$$

From Eq. (14) and Eq. (15), it can be seen that $M_1, M_2 = f(s, t, q, \nu, x, y)$, which shows that the first principal moment (M_1) and the first principal moment (M_2) is function of advanced distance of the working face, length of the working face, lateral load and Poisson's ratio. Extremum of M_k of the long side region, the middle region and the short side region is represented by M_c (the second principal bending moment, corresponding to the point of F_1 (or F_2)), M_z (the first principal bending moment, corresponding to the point of O) and M_d (the second principal bending moment, corresponding to the point of G_1 (or G_2)).

4.1 The effect of advanced distance of the working face

Before the first collapse, advanced distance of the

working face is equal to width of main roof. Affected by geological conditions and mining technology, main roof initially collapses when the advanced distance of the working face reaches 30 to 60 m. The effect of advanced distance of the working face on extremum of M_k of each region is presented in Fig.8.

Fig.8 The effect of s

Fig.8 indicates that with the increase of advanced distance of the working face, M_c , M_z and M_d increase too, and this trend becomes increasingly apparent, which suggests that advanced distance of the working face has a noticeable effect on M_c , M_z and M_d . When advanced distance of the working face keeps constant, there is $M_c > M_z > M_d$. It proves that failure of main roof begins at the point of F_1 (or F_2), develops at the point of O , and then at the point of G_1 (or G_2). The gap between the values of M_c when advanced distance of the working face is 10 (2.73 MN) and 60 m (96.83 MN), respectively, suggests that the main bending moment is governed by advanced distance of the working face. This is accordant with reality. The similar pattern can also be found when M_c is replaced by M_z and M_d .

4.2 The effect of length of the working face

Length of the working face is equal to length of main roof. Due to satisfactory performances in both economic and efficient terms, the longwall face has achieved breakthroughs in length for recent years. For example, Length of the working face in some mines with good geological conditions even reached 350 m, which is far greater than length that previous ones can have, such as 80 m. The evolution of M_k of each region with length of the working face is presented in Fig.9.

Fig.9 The effect of t

Fig.9 presents that with the increase of length of the working face, M_c and M_z increase while M_d decreases. But both these two trends become less apparent in the second half of the curves when length of the working face exceeds 240 m, which indicates that length of the working face exerts a marginal effect on M_c , M_z and M_d when it reaches a critical value. The decrease trend of M_d with the increase of length of the working face suggests that the point of G_1 (or G_2) is less likely to break. When length of the working face keeps constant, there is $M_c > M_z > M_d$. It shows that failure of main roof begins at the point of F_1 (or F_2), develops at the point of O , and then at the point of G_1 (or G_2). Besides, small increment of M_c and M_z with the increase of length of the working face partly explains continual breakthroughs in length of the working face these years.

4.3 The effect of lateral load

Before the first collapse of main roof, overlying strata is in a higher position owing to support from main roof. When the working face is advancing, load from overlying strata is small given that main roof bends, and abscission layer happens. Fig.10 gives the effect of lateral load (q) on M_c , M_d and M_z .

Fig.10 The effect of q

From Fig.10 it can be seen that with the increase of lateral load, there is linearly increasing M_c , M_d and M_z , and the increasing sensitivity of M_c , M_d and M_z successively reduces. Increment (0.05 MPa) of lateral load causes increase of M_c (8.68 MN), M_d (4.36 MN) and M_z (0.10 MN). When lateral load keeps constant, there also is $M_c > M_z > M_d$. It shows that failure of main roof begins at the point of F_1 (or F_2), develops at the point of O, and then at the point of G_1 (or G_2).

4.4 The effect of Poisson's ratio

Poisson's ratio has positive correlation with material strength. Poisson's ratio of main roof, overlying strata and coal successively increases, respectively. Fig.11 shows the effect of Poisson's ratio (ν) on M_c , M_d and M_z .

Fig.11 The effect of ν

From Fig.11 it can be obtained that in spite of the increase of Poisson's ratio, M_c (43.43 MN) and M_d (0.54 MN) keeps constant. This is mainly due to the fact that Poisson's ratio can be eliminated according to Eq. (15) and coordinate of F_1 (or F_2) and G_1 (or G_2). With the increase of Poisson's ratio, M_z also increases despite of small increment, which can nearly be seen as a constant. When Poisson's ratio keeps constant, there also is $M_c > M_z > M_d$. It indicates that failure of main roof begins at the point of F_1 (or F_2), develops at the point of O, and then at the point of G_1 (or G_2).

5 The breaking pattern of main roof

The working face is dynamic, and progressively approaches the main transportation road. The primary breaking pattern of main roof above the first working face shown in Fig.12 is obtained according to the development of failure of each region and breaking sequence of each region.

Fig.12 The primary breaking pattern of main roof above the first working face

Fig.12 shows that after failure of F_1 (or F_2), points along length direction of the working face will successively break. With the advancing working face, M_k of the point of O reaches ultimate moment, and then it collapses with the points along the long symmetry axis. After the similar failure happens in the point of G_1 (or G_2), there is formation of breaking pattern O-X (Zuo et al. 2019; Pu et al. 2011; Qian et al. 2010). Due to relative difference of M_k of each region of main roof, there is no probability that the long side firstly collapse, then the long symmetry axis, and finally the long symmetry axis.

6 Conclusions

(1) The first broken point of main roof is midpoint of the long side. The breaking, which occurs on the top surface of main roof, is caused by the second main bending moment.

(2) The failure in long side region starts from midpoint of the long side and develops along the length direction of the working face. The failure in middle region starts from the center of main roof and develops along the length direction of the working face. The failure in short side region starts from midpoint of the short side and develops along advance direction of the working face. The long side region firstly collapse, then the middle region, and finally the short side region. Together, there is formation of breaking pattern O-X.

(3) M_c , M_d and M_z are governed by advanced distance of the working face while length of the working face and Poisson's ratio have limited effect on M_c , M_d and M_z . The short side of main roof is less likely to failure with the increase of length of the working face. M_c , M_d and M_z linearly increase with the increase of lateral load.

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Figures

Figure 1

Mechanical model of rectangular thin elastic plate with four fixed boundaries

Figure 1

Mechanical model of rectangular thin elastic plate with four fixed boundaries

Figure 2

Mechanical model of rectangular thin elastic plate with four fixed boundaries

(a) The first principal bending moment

(b) The second principal bending moment

Figure 2

Distribution of main bending moment

(a) The first principal bending moment

(b) The second principal bending moment

Figure 2

Distribution of main bending moment

Figure 2

Mechanical model of rectangular thin elastic plate with four fixed boundaries

(a) The first principal bending moment

(b) The second principal bending moment

Figure 2

Distribution of main bending moment

Figure 3

Region division of main roof

(a) The first principal bending moment

(b) The second principal bending moment

Figure 3

Distribution of main bending moment

(a)

(b)

Figure 4

Variation of M_k of the long side region

Figure 4

Region division of main roof

Figure 5

Region division of main roof

Figure 5

Region division of main roof

(a)

(b)

Figure 6

Variation of M_k of the middle region

(a)

(b)

Figure 6

Variation of M_k of the long side region

Figure 7

Distribution of torque

Figure 7

Distribution of torque

Figure 7

Distribution of torque

(a)

(b)

Figure 8

Variation of M_k of the middle region

(a)

(b)

Figure 8

Variation of M_k of the middle region

Figure 9

The effect of t

Figure 9

The effect of t

(a)

(b)

Figure 9

Variation of M_k of the short side region

(a)

(b)

Figure 9

Variation of M_k of the short side region

Figure 9

Variation of M_k of the short side region

Figure 10

The effect of q

Figure 10

The effect of s

Figure 10

The effect of s

Figure 10

The effect of s

Figure 10

The effect of s

Figure 11

The effect of ν

Figure 11

The effect of t

Figure 11

The effect of ν

Figure 11

The effect of t

Figure 12

The effect of q

Figure 13

The effect of q

Figure 13

The effect of q

Figure 14

The primary breaking pattern of main roof above the first working face

Figure 14

The effect of ν

Figure 14

The effect of ν

Figure 14

The primary breaking pattern of main roof above the first working face

Figure 16

The primary breaking pattern of main roof above the first working face

Figure 16

The primary breaking pattern of main roof above the first working face