PAPER

Simulation of crack growth for metal plates with holes based on cohesive zone model

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Abstract
Hole defects are very common in metal plates. The propagation of cracks in engineering structural members will be affected by the holes of the members, which will not only change the propagation direction of cracks, but also have the ability to limit the growth of cracks. Therefore, the study of material fracture crack propagation caused by the distribution of holes and other factors under loading conditions has become a problem that needs to be considered in structural design. The cohesive zone model (CZM) can effectively avoid the singularity problem of crack tip stress when simulating crack growth, and at the same time can clearly show the crack growth path. Based on exponential CZM, the finite element analysis of tensile test for metallic materials with hole defects was carried out. The crack propagation law under constant load was obtained. It was proved that CZM could simulate the crack propagation in metallic materials with holes more accurately. The influence of the pore size, shape, distribution on the crack propagation is discussed. The results show that the smaller the distance difference between holes, the greater the supporting reaction force. The smaller the radius of the hole, the higher the fracture toughness and the maximum supporting reaction force of the metal plate. And it also can be seen that as the number of holes increases, the maximum supporting reaction force and fracture toughness of the metal plate decrease. The use of staggered holes distribution has greater supporting force and better toughness. The research results of this paper provide a theoretical basis and reference for investigating the propagation and propagation of cracks in the process of damage and failure of materials and for structural design and performance evaluation of engineering materials.

1. Introduction

Metal plates are widely used in various fields of society, such as home appliances manufacturing field, automotive manufacturing field, aviation field and precision instrument production field [1–4]. There are many defects in the rolling process of metal plate due to various reasons, and the hole defects are one of the most common [5]. The existence of holes and cracks directly affects the strength of the metal plate and causes hidden dangers. The hole defects cannot be avoided in actual structures. It is found that the existence of hole defects in metal plates will affect the crack propagation and change the crack propagation path. Proper hole size and hole location can also limit the development of cracks in the metal plates, which is beneficial to engineering components [6].

Based on existing numerical simulation software, geometric modeling and calculation methods, many academics have studied the evolution mechanism of plastic damage of metallic materials with hole defects [7, 8]. Bambang et al. [9] examined the effect of pore diameter on the strength of glass Sbraided/epoxy composites. They found that as the hole diameter grew, the tensile strength of the specimen declined. The previous studies by
Jiang et al [10] showed that different shapes of foam holes would have an impact on the compression performance of foamed aluminum plates. Nieh et al [11] made similar observations. They studied the effect of hole shape on tensile strength of open aluminum plate. The results show that the shape of the hole does affect the tensile strength of the foamed aluminum sheet at a certain porosity. Wang et al [12] conducted static compression experiments on copper plates with different porosity. Their analysis showed that the energy absorption rate of copper plate increased with the increase of porosity. After the porosity reaches 60%, the energy absorption rate decreases. Zhao et al [13] simulated the crack propagation in a plate with holes using extended finite element method. The results showed that the crack propagation path will shift towards the hole. And the closer the hole is to the crack, the larger the deflection angle is.

Damage and fracture mechanics are usually used to assess the damage evolution of structural components that contain crack-like flaws. Barenblat et al [14] proposed a cohesive zone model (CZM). The CZM as a typical damage model is based on an assumption that the material damage is restrained within the cohesive zone near the crack tip. Cohesive models have two regimes: a reversible state from which no damage accumulates, and a softening state from which the resilience of the local material is reduced. In recent two decades, the studies of CZM have attracted lots of interest. Dunbar et al [15] used CZM to simulate the process of crack propagation for high toughness steel materials commonly used in modern natural gas pipelines. The results showed that CZM can be successfully used to simulate ductile crack propagation. Xue et al [16] studied the effect of holes of different shapes and sizes on 7050 high-strength aluminum alloy by using FE method. They found that the fracture toughness of the specimen decreased with the increase of the hole size. Zhao et al [17] simulated the tensile fracture process of steel plates using five different models. The five models are bilinear, polynomial, trapezoidal, exponential, and Park–Paulino–Roesler models. Their findings indicated that the five models tend to mimic the same effect. Kumar et al [18] studied the influence of holes on crack propagation path by using virtual node extended finite element method (VNXFEM), and compared the method with extended finite element method (XFEM). The results shows that the crack can be deflected by the stress attraction near the hole. The results of this method are very close to those of XFEM. Cheng [19] studied the influence of hole size on mechanical properties of aluminum plate with holes. The results show that under the condition of the same porosity, the hole size has no significant effect on the compression performance of aluminum plate.

In the studies mentioned above, most scholars only studied the influence of single parameter change of hole on material tensile strength. The effect of holes on crack propagation path and fracture toughness of metal plates has not been systematically investigated. This article builds a two-dimensional finite element model of metallic materials with holes, and uses CZM to simulate the crack propagation path of the process of tensile test. The exponential cohesive force model in this paper uses the maximum nominal stress criterion to predict crack propagation path. This finite analysis method displays accurately the whole progress of tensile test in the macro and micro aspects. Based on the simulation results, the effects of hole spacing, hole size, hole number and hole distribution on crack propagation path and fracture toughness were systematically analyzed. The result revealed the fracture process of plate and the mechanical deformation mechanism. It provides theoretical and technical support for the evaluation of mechanical property and structural integrity of the metal plates under different working conditions and conditions.

2. Modeling aspects

2.1. Basic principles of CZM

CZM was originally proposed as a phenomenological model of brittle fracture by assigning a degradation-versus-separation law to a zone along the crack front. And now it has formed a systematic and complete effective fracture model. The CZM is established on the basis of elastic-plastic fracture mechanics. The ductile fracture of metal plate with holes occurs during the process of hole initiation, growth and coalescence. This ductile fracture process can be modelled by assigning a cohesive to a layer of cohesive elements and performing a virtual node extended finite element method (VNXFEM).

\[ \sigma = f(\delta) \]

Meanwhile, the energy generated in the process of material interface separation is defined as Fracture Energy $\phi$. 

\[ \phi = \int_{a}^{b} \sigma \cdot dA \]
When the CZM is used to calculate the fracture damage of materials, the key problem is the convergence of the calculation results in the calculation iteration, which affects the simulation results to a certain extent. For example, when simulating crack propagation, especially when the cohesion interface reaches the peak of cohesive strength, there will be difficulties in calculating convergence. Some non-convergence situations can be solved by adding incremental steps and reducing loads, but most of them are difficult to solve. There are four models in the literature: bilinear, linear parabola, exponential and trapezoidal laws [21]. Considering the convergence of the calculated results, in this work, the exponential cohesion zone model is adopted. The stress-displacement relationship of the exponential cohesive force model is sketched in figure 2. At the beginning, the tensile strength of the material increases linearly with the increase of displacement. Then, the tension increases to the maximum value, the material is damaged and cracks occur. As the crack increases, the strength of the material decreases, resulting in the decrease of the tension. When the stress is zero, the material cracks and fails, forming a complete crack [22].

\[
\varphi = \int \sigma d\delta = \int f(\delta) d\delta
\]

Figure 1. Schematic diagram of crack growth.

Figure 2. The stress-displacement curve.
For an ideal elastic interface, the relationship is defined by an elastic potential function \( \phi \) such that [23]:

\[
\phi(\Delta) = \phi_n + \phi_n \exp\left(-\frac{\Delta_n}{\delta_n^0}\right) 
\times \left\{ \left[ 1 - r + \frac{\Delta_n}{\delta_n^0} \right] \frac{1 - q}{r - 1} - \left[ q + \frac{r - q}{r - 1} \frac{\Delta_n}{\delta_n^0} \exp\left(-\frac{\Delta_n^2}{\delta_n^2}\right) \right] \right\}
\]

where, \( \phi_n, \delta_n, \delta_n^0, q, \) and \( r \) are constitutive parameters, \( q = \phi_n/\delta_n \), \( r = \Delta_n^0/\delta_n^0 \). \( \delta_n \) is the normal displacement and \( \delta_n^0 \) is the tangential displacement. \( \phi_n \) and \( \phi_n^0 \) are the fracture energy of the cohesive force unit under pure normal cracking and pure tangential cracking respectively. \( \delta_n^0 \) is the cracking displacement corresponding to the maximum normal strength, and \( \delta_n^0 \) is the cracking displacement corresponding to the maximum shear strength.

Partial derivative of the above formula can be obtained:

\[
\sigma_n = -\frac{\varphi_n}{\delta_n^0} \exp\left(-\frac{\Delta_n}{\delta_n^0}\right) \left\{ \frac{\Delta_n}{\delta_n^0} \exp\left(-\frac{\Delta_n^2}{\delta_n^2}\right) + \frac{1 - q}{r - 1} \left[ 1 - \exp\left(-\frac{\Delta_n^2}{\delta_n^2}\right) \right] \right\}
\]

\[
\sigma_r = -\frac{\varphi_r}{\delta_n^0} \frac{\Delta_n^0}{\delta_n^0} \left\{ \frac{\Delta_n}{\delta_n^0} \exp\left(-\frac{\Delta_n^2}{\delta_n^2}\right) \right\}
\]

The parameter relation of exponential cohesive force model can be obtained:

\[
\varphi_n = e \cdot \sigma_{\text{max}} \cdot \delta_n^0
\]

\[
\varphi_r = \sqrt{\frac{e}{2}} \cdot \tau_{\text{max}} \cdot \delta_r^0
\]

where \( e = \exp(1) \), and \( \sigma_{\text{max}} \) and \( \tau_{\text{max}} \) are the cohesive surface normal strength and tangential strength, respectively, and \( \delta_n \) and \( \delta_r \) are corresponding characteristic lengths.

The anisotropic bond strength of element interface can be derived from the maximum normal bond strength \( \sigma_{\text{max}} \):

\[
\sigma_n = \sigma_{\text{max}} \exp\left(1 - \frac{\Delta_n}{\delta_n^0}\right) \left\{ \frac{\Delta_n}{\delta_n^0} \exp\left(-\frac{\Delta_n^2}{\delta_n^2}\right) \right\} + \frac{1 - q}{r - 1}
\]

\[
\times \left[ 1 - \exp\left(-\frac{\Delta_n^2}{\delta_n^2}\right) \right] \left[ \frac{\Delta_n}{\delta_n^0} \exp\left(-\frac{\Delta_n^2}{\delta_n^2}\right) \right] + \xi_n \frac{dt}{dt} \left( \frac{\Delta_n}{\delta_n^0} \right)
\]

\[
\sigma_r = 2\sigma_{\text{max}} \frac{\delta_n^0}{\delta_r^0} \left( \frac{\delta_n^0}{\delta_r^0} \right) \left\{ \frac{\Delta_n}{\delta_n^0} \exp\left(-\frac{\Delta_n^2}{\delta_n^2}\right) \right\}
\]

\[
\times \left[ 1 - \exp\left(-\frac{\Delta_n^2}{\delta_n^2}\right) \right] \left[ \frac{\Delta_n}{\delta_n^0} \exp\left(-\frac{\Delta_n^2}{\delta_n^2}\right) \right] + \xi_r \frac{dt}{dt} \left( \frac{\Delta_n}{\delta_r^0} \right)
\]

where \( \xi_n \) and \( \xi_r \) are viscosity-like parameters. The viscosity isn’t meant to represent a physical energy dissipation process, but to control instabilities that tend to occur when a crack initiates at a weak plane.

In this paper, the Maxs Damage criterion is used to predict crack propagation [22]. The thickness of cohesion unit used is 0.01 mm. The cohesion element stiffness \( E \) formula is as follows:

\[
E_n = \frac{\sigma_{\text{max}}}{\delta_n^0} T_0
\]

\[
E_r = \frac{\tau_{\text{max}}}{\delta_r^0} T_0
\]

2.2. Material parameters

This section provides information on the materials used for the FE analysis carried out in this study. The material of the sheet used in the present simulation is steel S355J2 + N. The steel S355J2 + N is widely used in shipping, rail and other transportation industries. Figure 3 shows the geometric dimensions of the model. In this paper, the steel plate models were provided in a rectangle shape (dimension: 80 × 150 mm). All the holes are in the same horizontal line. A notch is prefabricated in the center of the left edge which is 10 mm in size. Refer to
The mechanical properties of steel S355J2+N are shown in Table 1 and the cohesion unit parameters are listed in Table 2.

This paper uses a custom subroutine to insert the cohesion unit. The thickness of the cohesion unit used is 0.01 mm. Figure 4 shows the meshing diagram of a rectangular notched plate.

According to the literature [24], the ultimate yield strength of the steel is 527 MPa, and the strain at this time is about 5%. Considering the influence of metal ideal plasticity on the tensile test results, the formula can be obtained:

\[ \varepsilon_p = \frac{\sigma - 425.7}{2025.1} - \frac{\sigma}{E} \]  

(12)

where, \( \varepsilon_p \) is the plastic strain, and \( \sigma \) is the yield strength entering the yield stage. Table 3 shows the approximate curve at the yield stage.

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**Table 1. Metal mechanical property parameters.**

| Material | Elastic modulus E (MPa) | Poisson’s ratio \( \mu \) | Yield strength \( \sigma \) (MPa) |
|----------|-------------------------|---------------------------|----------------------------------|
| Steel    | 205000                  | 0.3                       | 430                              |

**Table 2. CZM parameters.**

| Maximum normal Cohesive strength \( \sigma_{\text{max}} \) (MPa) | Maximum tangential cohesion strength \( \tau_{\text{max}} \) (MPa) | Separation displacement \( \delta_0 \) (mm) | Fracture energy \( \Phi \) (MPa-mm) |
|---------------------------------------------------------------|---------------------------------------------------------------|------------------------------------------|---------------------------------|
| 430                                                          | 1001.9                                                       | 0.008                                    | 30.1                            |

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Figure 3. Geometric diagram of rectangular notched plate.

Figure 4. Meshing diagram of rectangular notched plate.
3. Experimental simulation

3.1. Influence of different horizontal distance of holes on crack propagation path

In this section, the effect of the horizontal distance between the center of the hole on the toughness of the model is discussed. Four groups of different data were selected for simulation. The geometric dimensions of the model are shown in figure 1. The geometry and boundary conditions of the models are consistent. The radius of holes radius is 7.5 mm. The distances between the circular holes (referring to the distances between the centers of the circles) were listed in table 4.

Figure 5 shows the cloud diagram of crack propagation in the fracture process of the four models. Judging from the crack growth cloud image of figure 5, the whole process of metal plate failure can be divided into four stages: stress increase, crack generation, crack growth and complete fracture. Firstly, stress increases around the holes. Then the crack appears at the tip of the notch and runs through all holes on the same horizontal line successively. Finally lead to the plate fracture failure. As shown in table 6, the total length of holes of model A, B and C are 100, 87.5 and 112.5 mm, respectively. And the distance differences between the corresponding centers of the circles are 5 mm, 2.5 mm, and 7.5 mm respectively.

And as can be seen from figure 6 and figure 7, this effect of horizontal spacing between holes on fracture toughness of metal plate is equally significant compared with the hole distribution. Figure 6 shows force-displacement curves of four types. The area formed between the curve and the horizontal axis can be indirectly regarded as the fracture toughness of the plate. It was found that the curves of models A, B, C and D have the similar trends. The maximum supporting reaction force of models A and B are 486 and 814 N, respectively, as shown in figure 7. It is obvious that the maximum supporting reaction force of model B is 67.8% higher than that of model A. And the model B has the largest fracture toughness of the four models. This shows that the horizontal distance of holes has an important effect on the fracture toughness of metal plates. This phenomenon is due to the smaller horizontal distance of the holes in Model B. Model B has a smaller horizontal hole, so its sixth hole is further to the right of the plate. Therefore, after the crack passes through the plate, model B will obtain the maximum supporting reaction force. Meanwhile, the fracture toughness of sheet metal varies greatly. This can be verified by model C. The maximum supporting reaction force of model C is 406 N. The sixth hole of

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Table 3. Yield strength and plastic strain.

| Yield strength $\sigma$ (Mpa) | 430 | 450 | 470 | 490 | 510 | 527 |
|-------------------------------|-----|-----|-----|-----|-----|-----|
| plastic strain $\varepsilon_p$ | 0   | 0.0098 | 0.0196 | 0.0294 | 0.0391 | 0.0474 |

Table 4. The distance between the centers of different models.

| Model | $L_1$ (mm) | $L_2$ (mm) | $L_3$ (mm) | $L_4$ (mm) | $L_5$ (mm) | L (mm) |
|-------|-------------|-------------|-------------|-------------|-------------|-------|
| A     | 20          | 20          | 20          | 20          | 20          | 100   |
| B     | 17.5        | 17.5        | 17.5        | 17.5        | 17.5        | 87.5  |
| C     | 22.5        | 22.5        | 22.5        | 22.5        | 22.5        | 112.5 |
| D     | 18          | 19          | 20          | 21          | 22          | 100   |
Model C is closer to the right edge of the metal plate than Model A. So, the maximum supporting reaction force of Model C is 16.2% less than Model A. When the length of L is the same (such as A and D), changing the distance difference between the center of the holes. The distance difference between the centers of round holes in model D gradually increases and the distance between the center of the circular hole in Model A is maintained at 20 mm. The maximum supporting reaction force of model A and D is 486 and 362 N, respectively. It is changed by 33.9%. This is consistent with the above. This change indicates that the increase of the horizontal distance of the hole will lead to the decrease of the maximum branch reaction force and fracture toughness of the metal plate under the same total length L.

3.2. Influence of porosity on crack propagation path
Porosity is influenced by the hole radius and the number of holes. Therefore, this section is divided into two parts: the hole radius and the number of holes.

3.2.1. Influence of hole radius on crack propagation path
This section discusses the influence of the change of hole radius on the fracture toughness of metal plate at a certain horizontal distance. Five groups of different data were selected for simulation. The geometric dimensions of the model are shown in figure 1. The geometry and boundary conditions of the models are consistent. The different holes radius of five models were listed in table 5.

Figure 8 shows the cloud diagram of crack propagation in the fracture process of the five models. It can be seen that the force-displacement curves of the five metal plate models with holes also conform to the four failure processes: stress increase, crack generation, crack growth and complete fracture. As shown in table 5, the radius of holes of model E, F, A, G and H are 2.5, 5, 7.5, 8.5 and 9.5 mm, respectively. As can be seen from figure 9 and
Figure 10, the maximum supporting reaction force of models E, F, A, G and H are 721, 707, 486, 467 and 394 N, respectively. The area formed between the curve and the horizontal axis can be indirectly regarded as the fracture toughness of the plate. It is obvious that the fracture toughness and the maximum supporting reaction force of model E are the maximum, and those of model H is the minimum. And the maximum supporting reaction force of model E is 83% more than Model H. This shows that the hole radius has an important effect on the fracture toughness of metal plates. It can be found that the maximum supporting reaction force and fracture toughness of the metal plate with holes decrease gradually with the increase of the hole radius. This phenomenon is due to the fact that smaller the aperture, the longer the total distance of the crack’s path through the metallic plate.

3.2.2. Influence of different number of holes on crack propagation path

This section discusses the influence of the change of hole radius on the fracture toughness of metal plate at a certain horizontal distance. Five groups of different data were selected for simulation. The geometry and

| Model | E | F | A | G | H |
|-------|---|---|---|---|---|
| holes diameter mm | 2.5 | 5 | 7.5 | 8.5 | 9.5 |

Figure 8. The crack propagation cloud image of different holes radius of five models.

Figure 9. Force-displacement curves of plates with different hole radius.

Table 5. Different holes radius of five models.
boundary conditions of the models are consistent. Figure 11 shows the cloud diagram of crack propagation in the fracture process of the five models. It can be seen that the force-displacement curves of the five metal plate models with holes also conform to the four failure processes: stress increase, crack generation, crack growth and complete fracture.

The force-displacement curves of five models are acquired and the experimental results are shown in figure 12. It is obvious that the fracture toughness and the maximum supporting reaction force of model I are the maximum. Figure 13 shows the maximum supporting reaction force of models I, G, A, K and L are 698, 606, 486, 273 and 277 N, respectively. Model I has the maximum supporting reaction force and fracture toughness. It can be seen that as the number of holes increases, the maximum supporting reaction force and fracture toughness of the metal plate decrease. The result shows that the hole numbers have an important effect on the fracture toughness of metal plates.

3.3 Influence of hole distribution on crack propagation path

In this section, four kinds of pore models with the same porosity but different distribution patterns were established (figure 14). The geometry and boundary conditions of the four models are consistent. The vertical distance of holes in model A, M, N and O are 0, 10, 20 and 30 mm. The crack growth process of the four models is shown in figure 15. Judging from the crack growth cloud image of model A, M, N and O, it also can be observed that the force-displacement curves of the four metal plate models with holes also accord with the four failure processes: stress increase, crack generation, crack growth and complete fracture. With the increase of external load, the crack begins to expand from the notch tip to the first hole, and then slowly passes through the surrounding holes, finally forming a complete crack. It can also be seen from the figure that the propagation path of the crack can change with the position of the hole.
Through the tensile experiment tests of the metal plate with holes, the force-displacement curves for four metal plates with holes have been acquired from the tensile tests. The experimental results are shown in figure 16. Each curve fully characterizes the variation in tensile strength during the specimen damage process. It can be observed that the force-displacement curves of the four metal plate models with holes models have similar tendency. The experimental results exhibit good repeatability of the force-deformation curves. At the start, all curves describe a linear rising tendency. Nevertheless, with the displacement increasing, the tendency towards
curves of models is obviously different. This illustrates that the hole distribution has a significant influence on the fracture toughness of the metal plate with holes. The metal plate with interlaced holes of 10 mm has higher mechanical properties indicating that the staggered distribution of holes can enhance the properties of materials. The staggered distribution of holes can prolong the crack propagation path and improve the fracture toughness of the metal plate. The maximum supporting reaction force of model A, M, N and O are 486, 543, 767 and 455 N, respectively, as shown in figure 17. It can be seen that the strength of model N is 58% higher than that of model A. The results show that it is very important to choose the reasonable hole distribution.

When the distribution of holes is reasonable, the crack will pass through the holes in sequence. It will prolong the crack propagation path and increase the fracture toughness of the metal plate. In order to explore the appropriately hole distribution models, parameters are set up every 5 mm between the M and O models, as shown in table 6. The geometry and boundary conditions of the models are consistent.

The crack deflection angle $\alpha$ was expressed to quantify the strength of the attraction effect of different vertical distances on the crack growth path. It is important to note that the crack deflection angle $\alpha$ represents only a simple trend. It is a simple quantification of the strength of the stress attraction on the crack propagation path at the edge of the hole.

Figure 18 shows the force-displacement curves of plates with different hole distribution. The area formed between the curve and the horizontal axis can be indirectly regarded as the fracture toughness of the plate. It can be seen that the change of the hole distribution will have an impact on the fracture toughness of the plate. Figure 19 shows the maximum supporting reaction force of plates with different hole distribution. As far as the results are concerned, model N has the highest fracture toughness and maximum reaction force among all models.
Figure 17. The maximum supporting reaction force of four models with different hole distribution.

Figure 18. Force-displacement curves of plates with different hole distribution.

Figure 19. The maximum supporting reaction force of plates with different hole distribution.

Table 6. Different hole distribution of five holes.

| Hole dislocation distance (mm) | M  | P  | N  | Q  | O  |
|-------------------------------|----|----|----|----|----|
| 10                            | 10 | 15 | 20 | 25 | 30 |
Table 7 shows the crack deflection angle $\alpha$ of models. Compare with model M to model N, when the vertical distance of the hole is 20 mm (model N), the crack deflection angle $\alpha$ is the largest, and the stress at the edge of the hole has the strongest attraction to crack propagation. The deflection angle of the crack propagation path is also the largest. Although the crack deflection angle $\alpha$ of model Q and model O is also relatively large, the crack do not pass through the holes in sequence. It can also be observed that the deflection angle of the crack propagation path increases first and then decreases with the increase of the vertical distance of the hole. And the fracture toughness of the metal plate also increases first and then decreases. Before reaching the maximum supporting reaction force, the curves of several cases are the same, and the maximum supporting reaction force is almost the same. The different hole distribution leads to different trends in the second half of the curve. This phenomenon is caused by the hole can prolong the propagation distance of the crack. The stress at the hole edge affects the crack propagation path from the initial stage of crack propagation. The propagation path of the crack will approach the hole direction under the attraction of the hole. Because of the presence of holes, the cracks do not run through the plate in a straight direction as they did before. The longer the path of crack propagation through the hole, the better the fracture toughness of the metal plate. However, too long vertical distance of holes does not cause crack propagation. Instead, the cracks go straight through the metal plate without passing through holes. With the increase of the vertical distance between the crack and the hole, the effect of the hole on the crack is gradually weakened. This is also consistent with the previous conclusion that it is very important to choose the appropriate hole distribution.

In order to verify the above conclusions, the following three models are used in this paper for comparison, and the finite element simulation cloud map is obtained, as shown in figure 20. Figure 21 shows the force-displacement curves of metal plates. It can be observed that the staggered distribution of holes can prolong the propagation distance of cracks. Therefore, the fracture toughness of model M is larger than that of model R. This result confirms the above conclusion.

|     | M | P | N | Q | O |
|-----|---|---|---|---|---|
| crack deflection angle $\alpha$ | 28 | 20 | 29 | 38 | 26 |

Figure 20. The crack propagation paths of three models.

Figure 21. The force-displacement curves of metal plates.
4. Conclusions

In this work, a custom subroutine is used to insert the cohesion unit. The process of tensile fracture of metal plates with holes is simulated by using the cohesive force model. The relationships among hole distribution, hole spacing, aperture size and are investigated in detail. Main conclusions are summarized as follow:

(1) Based on CZM, the influence of holes on crack growth path in tensile fracture of metal plate with holes is systematically studied. This method can well simulate the process of metal plate fracture failure.

(2) The whole process of metal plate with holes failure can be divided into four stages: stress increase, crack generation, crack growth and complete fracture. With the increase of the external load, the stress around the hole gradually increases, and then the crack appears, and then the crack gradually expands between the holes, finally forming a complete crack leading to the fracture of the metal plate.

(3) The horizontal distance of holes has an important effect on the fracture toughness of metal plates. When the distance differences between the corresponding centers of the circles are 2.5 mm, the maximum supporting reaction and fracture toughness are the largest.

(4) The porosity has an important effect on the fracture toughness of metal plates. The smaller the radius of the hole, the higher the fracture toughness and the maximum supporting reaction force of the metal plate. And it also can be seen that as the number of holes increases, the maximum supporting reaction force and fracture toughness of the metal plate decrease.

(5) The hole distribution has a significant influence on the fracture toughness of the metal plate with holes. Compared with the linear arrangement of holes, the staggered distribution of holes can enhance the properties of materials. The crack deflection angle $\alpha$ is introduced to represent the strength of the attraction effect of holes on crack growth path. The results show that, within a certain range, the larger the fracture toughness, the larger the crack deflection angle $\alpha$.

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Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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