Numerical Simulation Analysis of Rock Fracture Propagation Based on VUMAT

Mingtao Hu[1, a, #], Zihan Li[2, b, #], Zhongjue Wang[3, *, #]

[1]Xi 'an University of Technology State Key Laboratory of Eco-hydraulics in Northwest Arid Region of China

[2]School of Civil Engineering Xi 'an University of Architecture and Technology Xi 'an, Shaanxi

[3]School of Water conservancy Yunnan Agricultural University Kunming, Yunnan

* Corresponding Author Email: 1127169893@qq.com, [a]hu17354620703@163.com, [b]lizihan0518@163.com

[#]These authors contributed equally.

Abstract. The study of crack propagation in rock is of great significance to the stability of structural engineering. In this paper, through ABAQUS software, a simulation method of rock fracture propagation law is proposed. The D-P criterion of shear effect (Drucker Prager criterion) is embedded into the VUMAT subroutine in ABAQUS software, and the rule of rock fracture propagation is analyzed by using the element deletion method. The results show that: (1) stress concentration occurs first at the tip of the prefabricated crack, and then fracture occurs; (2) The fracture pattern is perpendicular to the crack, develops symmetrically, and produces secondary horizontal cracks; (3) The crack develops and forms an anti-wing crack, which continues to expand with the secondary horizontal crack, and finally the rock is destroyed. (4) Compared with the test results, the model can better reflect the law of rock crack propagation.

Keywords: ABAQUS, D-P criterion, VUMAT subroutine, Element deletion method, Rock crack propagation.

1. Introduction

Fissure is a very common geological structure. In practical projects, the unstable development of joints, cracks, holes and other defects in the rock will lead to geological disasters such as cave collapse and slope instability. Therefore, it is of great significance to study the law of rock fracture propagation.

There are many methods to study rock crack propagation and fracture failure. The model test can better observe the change of fracture development, but the model test is generally time-consuming and costly. At present, computer simulation technology is widely used to analyze the law of rock fracture propagation.

ABAQUS software can simulate many problems in the engineering field [1]. The elastic-plastic model of complex high-rise building structure is established by Wang et al. [2] using ABAQUS software, and according to the deformation and stress characteristics in the earthquake time history, the stress strain time history and plastic strain time history of structural member section are obtained. Yi et al. [3] used ABAQUS to carry out secondary development, and verified the effectiveness of the subprogram through an example of uniaxial tension. The concrete damage model established by Wang et al. [4] and Bai et al. [5] takes uniaxial tension and compression as the failure mode, uses VUMAT subroutine to realize secondary development, and obtains the uniaxial tension and compression process of concrete test block through numerical simulation. Li et al. [6] established the damage constitutive model of rock, and took Mohr Coulomb criterion as the condition for failure judgment to obtain the stress-strain relationship of rock. Wang et al. [7] used the proposed model to conduct numerical simulation of rock failure process with maximum tensile stress criterion, maximum compressive stress criterion and Mohr Coulomb criterion respectively, and obtained the process of crack tip from initiation, expansion, penetration to formation of macro crack model failure. The finite element numerical model of rock specimen was established by Wang et al. [8] to study the initiation and propagation of marble cracks with prefabricated cracks at different angles.

It can be seen from the above documents that the rock fracture propagation simulation system still needs to be further improved. Based on D-P criterion and ABAQUS subroutine VUMAT as a platform, this paper proposes a method to simulate the process of crack propagation in rock model. Compared with the test results, the model can better reflect the law of rock crack growth, and the simulation method is practical and reliable.

2. Establishment of rock failure model under uniaxial compression

2.1. Model establishment

Using Python language programming, through the secondary development of ABAQUS subroutine VUMAT, a rock fracture model based on uniaxial compression is established. In ABAQUS software platform, build a model component (Fig. 1).

Set the performance parameters of the model materials. Assume that the model materials meet the elastic, isotropic and other conditions within the calculation range. See Table 1 for the mechanical parameters of the simulation values [9].

Dynamic analysis step is adopted for engineering simulation to control state variables and set loads. The normal constraint is applied at the bottom of the model, and the top of the model is compressed by displacement controlled loading. The loading displacement is set to 15mm, the loading rate is 0.0005mm/step, and the proposed amplitude curve is set. The edges of the model components are seeded, and the model mesh is set to triangle. In order to reduce the workload and facilitate the analysis of fracture results, 15 species are distributed on the short side, 30 species are distributed on the long side, 20 species are distributed on the upper and lower surfaces of the model, and 40 species are distributed on the left and right surfaces of the model in the fracture area with obvious fracture, and the grid is divided (Fig. 2).

Table 1. Rock mass mechanical parameters of rock materials used in the model

	Density	*E*	μ	*C*	ϕ
Sandstone	2.6kg/m^3	2930MPa	0.38	3.11MPa	40.90

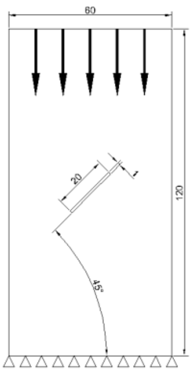


Figure 1. Calculation Model (mm)

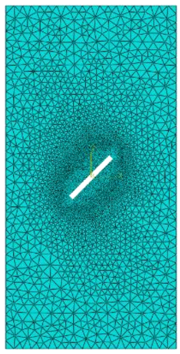


Figure 2. Mesh Model

2.2. D-P failure criterion

Under uniaxial compression, the failure of rock model mainly includes weak plane shear failure, brittle failure and plastic failure, which are important characteristics of rock model. On this basis, the fracture of the rock model is simulated, and D-P criterion is used as the condition for failure judgment.

In ABAQUS software, the D-P criterion of shear effect is embedded into the VUMAT subroutine, and the failure element deletion algorithm is introduced, and the deformation and failure of the rock model under uniaxial compression are simulated [10].

D-P criterion is based on Mohr-Coulomb criterion, and VONMISE yield criterion is modified. D-P criterion assumes that the material is an ideal elastoplastic body, so no strengthening criterion is set to simplify the calculation process. The yield failure surface of the object will not change with the yield of the material, but the yield strength will increase with the increase of the pressure.

D-P criterion [11]:

$$f = \sqrt{J_2} + \alpha I_1 - K = 0 \tag{1}$$

$$J_2 = [(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2]/6 \tag{2}$$

$$I_1 = \sigma_1 + \sigma_2 + \sigma_3 \tag{3}$$

$$\alpha = \frac{2 \sin \varphi}{\sqrt{3}(3 - \sin \varphi)} \tag{4}$$

$$K = \frac{6C \cos \varphi}{\sqrt{3}(3 - \sin \varphi)} \tag{5}$$

Where, J_2 is the second invariant of the deviatoric stress tensor; I_1 is the first invariant of the stress tensor; α、K is the material parameter of rock. σ_1、σ_2、σ_3 is the first principal stress, the second principal stress and the third principal stress of the element respectively; C、φ refers to the cohesion and internal friction angle of rock respectively.

Generally, the principle of failure is based on the Eq. (1) reached by any basic unit first, and the principle of failure is based on the failure criterion. The D-P criterion is embedded in the VUMAT subroutine to simulate the fracture process of the rock model under uniaxial compression.

2.3. Principle of element deletion method

The element deletion method is a method that can solve the shortcomings in the finite element analysis software. The precondition of the finite element analysis should consider the objects that meet the continuum hypothesis. It not only considers that the substance is a continuum composed of multiple particles without gaps, but also considers that various physical quantities of the substance will change continuously. Therefore, the element deletion method overcomes this assumption.

Under the assumption of continuous medium, after the object is divided into several units, it is considered that the units will not disappear. However, in the project, there will be some cases of damage caused by fracture, compression, etc. which make some units disappear or lose efficacy due to the existence of yield fracture. The function of unit disappearance or failure is applied to ABAQUS software to simulate the development of rock fracture propagation.

In the subroutine VUMAT, a certain state variable is assigned according to the selected D-P criterion, which is used to characterize whether the material fails. 0 is invalid, 1 is normal. During the calculation, it is necessary to select the state variable in the field output manager and add the user's subprogram file. The change of rock fracture can be clearly observed by using the element deletion method.

Under the action of uniaxial compression load, when the stress state of a certain element is satisfied, the model element is regarded as damaged and deleted by the principle of element deletion. Through repeated iterative calculation, the stress and strain results of the model element are output (Fig. 3).

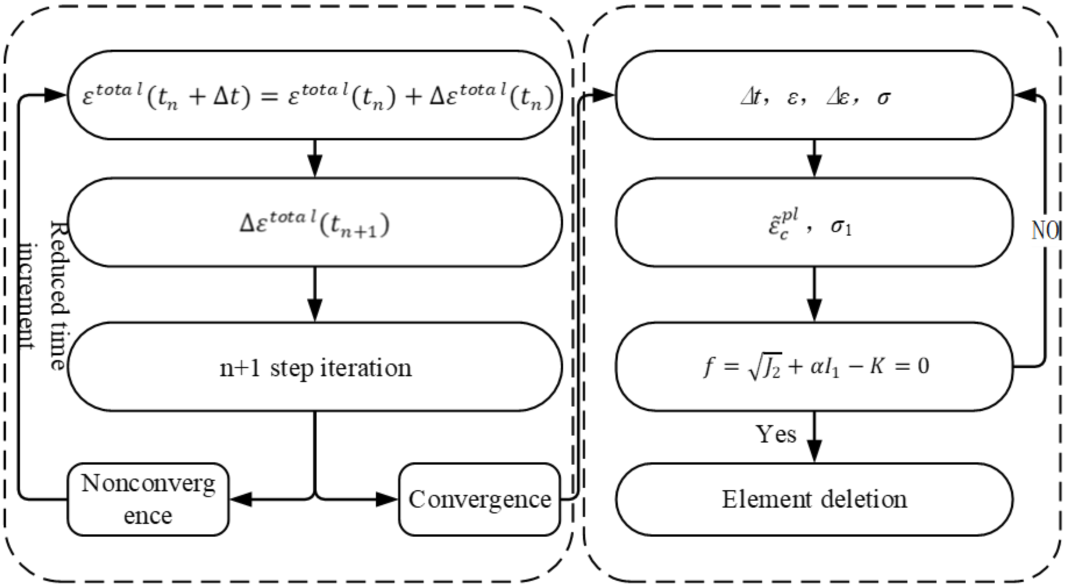
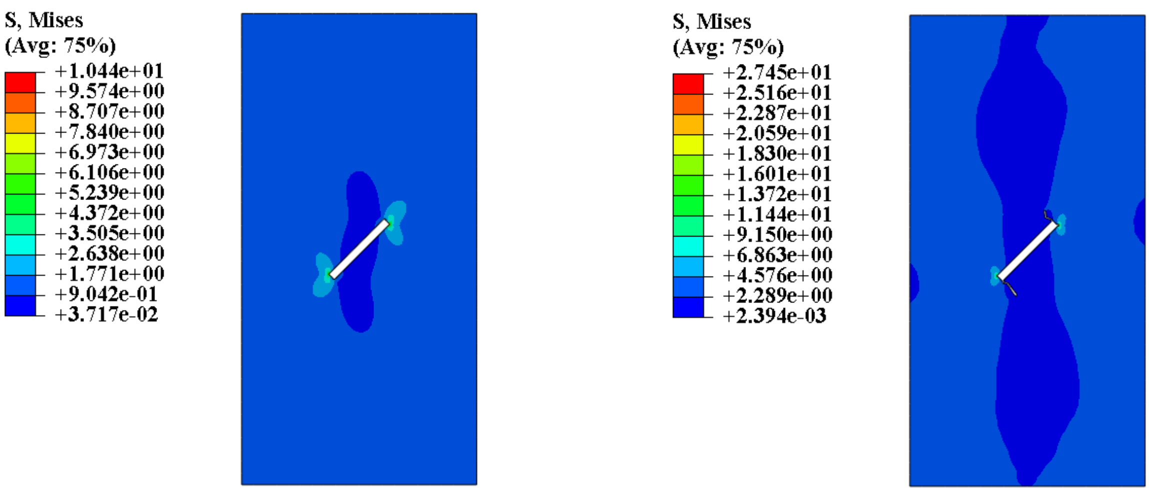


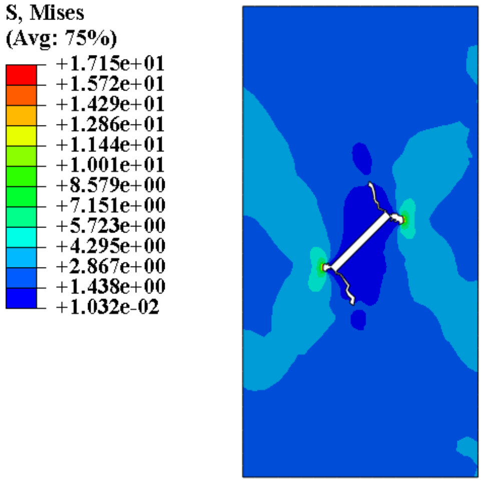
Figure 3. Simulation Flow Chart

2.4. Result analysis

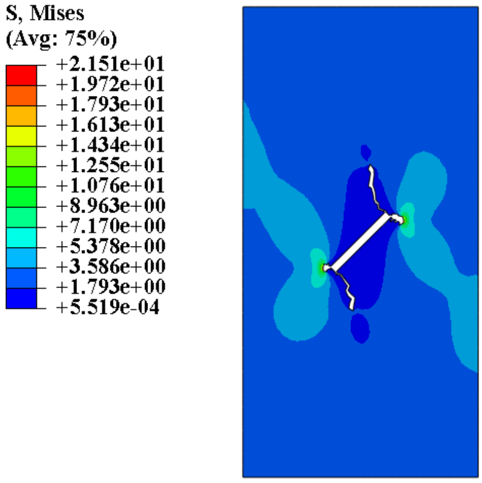
As shown in Fig. 4. It can be found that the stress at the tip of the prefabricated crack of the model increases gradually under the action of uniaxial compression load, and there is an obvious stress concentration phenomenon. With the increasing load, when the element around the stress concentration area at the tip of the prefabricated crack meets the failure conditions of D-P criterion, the model member will be crushed in a small range ($U=7.475\times10^{-2}$mm), the fracture pattern is perpendicular to the crack and continues to develop along the vertical direction ($U=1.112\times10^{-1}$mm), and the crack lines at the upper and lower parts of the prefabricated cracks are relatively consistent. The number of failure elements increases with the increase of load, and secondary horizontal cracks ($U=1.990\times10^{-1}$mm)) occur at the other corner of the short side of the crack area, continuously extending along the horizontal direction of the crack tip (U=1.778mm). Then the crack changed direction and developed to the right surface of the model, forming an anti-wing crack (U=1.944mm), and the secondary horizontal crack continued to expand. Finally, cracks develop into macro cracks and rock is destroyed.



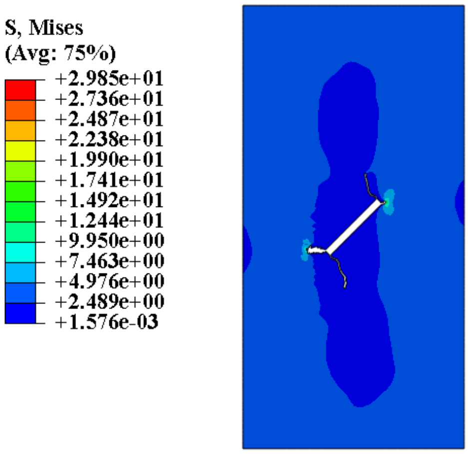
$U=6.724\times10^{-2}$mm $U=7.475\times10^{-2}$mm



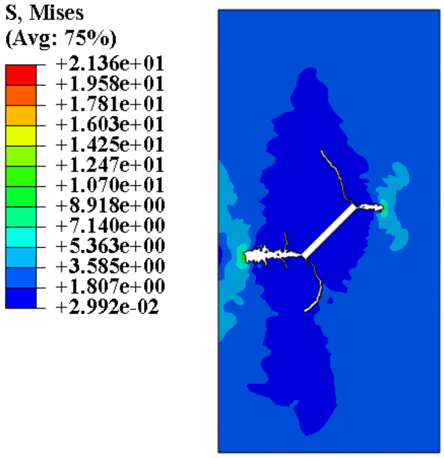
U=1.112×10^{-1}mm



U=1.990×10^{-1}mm



U=1.778mm



U=1.944mm

Figure 4. Rock Failure Process (Unit: MPa)

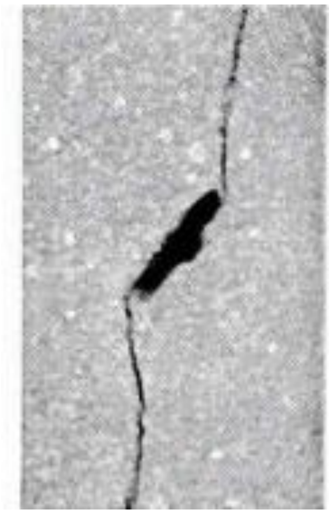


Figure 5 (a) Test results [12]

Figure 5 (b) Simulation results

Figure 5. Comparison Chart

Fig. 5 shows that the simulation results are basically consistent with the test results [12]. This simulation method provides theoretical support for further research on the expansion of rock fractures.

3. Summary

(1) Stress concentration occurs at the tip of the prefabricated crack, and then fracture occurs.

(2) The crack pattern is perpendicular to the crack, developing symmetrically from top to bottom, and producing secondary horizontal cracks.

(3) The crack pattern develops to form an anti-wing crack, which continues to expand with the secondary horizontal crack, and finally the rock is damaged.

(4) The simulation results are consistent with the test results, and the simulation method is reliable.

Acknowledgment

Project No.51909214

References

[1] S.T. Zhang. On the Development and Application of Computer Aided Engineering (CAE) [J]. Science and Technology Communication, 2010, 16:232-233.

[2] D.S. Wang, Z.S. Li, C.M. Li, W.W. Jiang, G.J. Wang, Y. Liao. Implementation of elasto-plastic time history analysis of complex structures in ABAQUS software [J]. Architectural Structure, 2007 (05): 92-95+12.

[3] L. Yi, Y. Peng. Secondary development of constitutive model of solid propellant materials based on VUMAT [J]. Mechanical Strength, 2013, 35 (03): 391-394.

[4] W.L. Wang. Secondary development and application of concrete damage constitutive model based on ABAQUS [D]. North China University of Water Resources and Hydropower, 2021.

[5] W.F. Bai, S.J. Zhang, J.F. Guan, J.Y. Chen. Research on statistical damage constitutive model of orthotropic concrete [J]. Journal of Water Resources, 2014, 45 (05): 607-618.

[6] T. Li, S. Zhang. Development and application of a statistical constitutive model of damaged rock affected by the load-bearing capacity of damaged elements [J]. ZhejiangUniv.Sci. A16,644–655(2015).

[7] H. Wang, H. Zhou , S. Shang. Development and Application of Rock Fracture Propagation Numerical Simulation System. Geotech Geol Eng 40, 3075–3090 (2022).

[8] X. Wang, Y.Q. Song, N. Sha, G.L. Qiu, J. Liu. Analysis of Rock Fracture Propagation Based on ABAQUS Extended Finite Element [C]//. Proceedings of the 18th Annual Academic Conference of Beijing Mechanical Society. [Publisher unknown], 2012: 226-227.

[9] H.F. Sun, Y.G. Yang, Y. Ju, Q.G. Zhang, R.D. Peng. Numerical analysis of deformation, failure and energy release of coal and rock under excavation unloading conditions [J]. Journal of Coal Industry, 2014,39 (02): 258-272.

[10] W.J. Zhao. Numerical simulation system for rock mechanics test based on secondary development of ABAQUS [J]. Higher Architecture Education, 2019, 5:160-165.

[11] H. Wang, P.Q. Zheng, Q.B. Wang. A numerical simulation method for rock mechanics test based on ABAQUS [P]. Chinese patent: CN108182335A, 2018-06-19.

[12] C.T. Li. Experimental Study on the Difference of Fracture Propagation of Different Types of Rock [D]. Shandong University of Science and Technology, 2020.