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PFC^{2D} numerical simulation of sandstone damage evolution based on MATLAB image processing

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Abstract: *In this paper, mesoscopic parameters of sandstone are obtained by SEM and image processing, and mechanical parameters of sandstone are obtained by uniaxial compression experiment, based on which the PFC^{2D} model of red sandstone is established. Through numerical simulation of uniaxial compression, crack propagation of sandstone was observed, and parameters such as stress-strain curve and number of bond fractures were obtained. Fractal dimension of sandstone was calculated by MATLAB, and the relationship between damage degree, fractal dimension and crack propagation was analyzed. The results show that the crack development of sandstone can be divided into four stages: elastic deformation, crack initiation, crack propagation and penetration. The damage degree corresponds to each stage of fracture development, the minimum is in elastic deformation stage, and the maximum is in penetrating stage. The fractal dimension changes differently in each stage, and shows an increasing trend in the germination stage. In the expansion stage, it shows a downward trend. At the through-through stage, there is a substantial growth trend. Therefore, the box dimension can be used to indirectly evaluate the internal damage and study the damage evolution characteristics, which provides a new idea for studying the damage evolution of sandstone and has important significance for evaluating the stability of engineering rock mass.*

Keywords: *MATLAB image processing; PFC^{2D}; fractal dimension; damage degree; red sandstone*

1. Introduction

The solution process of discrete element method of particle flow is dynamic and constantly changing, which depends on time-step algorithm to achieve, and requires the computer to have powerful computing power and data processing ability. It can reproduce the complex mechanical behavior of rock from the mesoscopic level. Therefore, the particle flow program is used to carry out the numerical simulation of sandstone. With the help of MATLAB software, image processing technology is used to lay a physical foundation for the model generation. Bian Kang et al. [1-2] established a two-dimensional particle flow numerical model based on particle discrete element method to study the mechanical properties and failure characteristics of rocks under different water absorption time, confining pressure and bedding dip Angle. Huang Yanhua et al. [3-4] used PFC to numerically simulate the fracture process of precast fractured rock samples under uniaxial, biaxial and triaxial conditions. However, the discrete element can simulate the evolution process of rock fracture, but it can only describe qualitatively, rather than accurately and quantitatively. Fractal dimension can not only be used to quantitatively evaluate disordered, irregular and intrinsically regulated systems, but also be applied to the study of material cracks. In order to realize the quantitative characterization of pore distribution [5-6], crack evolution law [7-8] and other geometric parameters of the specimen, scholars introduced fractal dimension into it. The proposal of fractal dimension can not only describe the distribution characteristics of particle pores inside rocks [9], but also quantitatively describe the damage degree and failure mode of rock mass, which has been studied by many scholars. Zou Fei et al. [10] used fractal theory to describe the evolution law of material surface damage, and the results showed that with the increase of fractal dimension, the damage degree of rock intensified.

Therefore, this paper combines SEM and image processing technology, and establishes a discrete element model of red sandstone with the help of PFC^{2D}, analyzes the change characteristics of fractal dimension of sandstone based on fractal theory, and provides a new idea for studying the damage evolution of red sandstone.

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2. Laboratory Experiment

2.1 Uniaxial compression experiment

Red sandstone was selected from Xinwen coalfield, its structure was relatively stable. The rock sample was processed in the laboratory to make a sample of 50*100mm, and the uniaxial compression test was carried out on it, as shown in Figure 1.

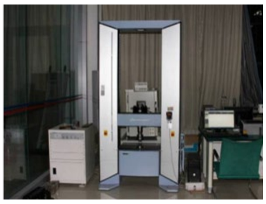

Figure 1: Uniaxial compression test instrument

2.2 SEM experiment

The surface of sandstone was scanned by JSM-6510LV tungsten filament scanning electron microscope, and the meso-structure image of red sandstone was obtained. Samples were randomly selected from the upper, middle and lower parts of the sample respectively, and then ground with abrasive paper into a sample with the size of 1cm*1cm*2cm and the shape of a cylinder. The final observation results are shown in Figure 2.

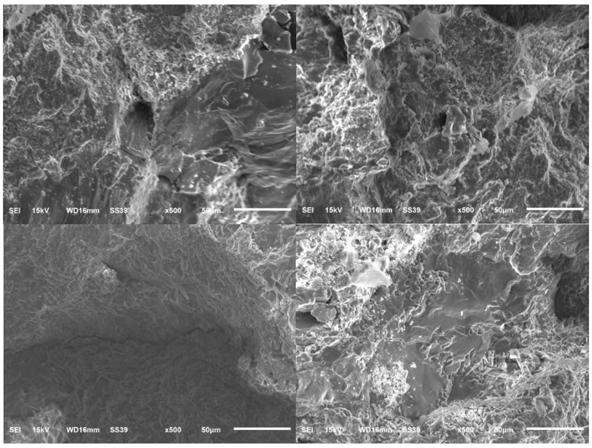

Figure 2: Partial electron microscope images

3. PFC numerical simulation test

In this section, the uniaxial compression process of red sandstone is simulated by particle flow, crack growth during loading is analyzed, and the damage evolution law of red sandstone is further studied [11].

3.1 Geometric parameters obtained by MATLAB image processing

In order to extract pore and fissure information in SEM images, image preprocessing, image segmentation and morphological processing are used to process the images. Firstly, equalization is used to eliminate the influence of factors such as uneven brightness. Secondly, the region growth segmentation method is used to segment SEM images of sandstone, and the mesostructure binary image is obtained. Finally, morphological post-processing is used to remove some over-segmentation background, narrow notch, edge "burr", etc., so that the final sandstone mesostructure binary image only contains pure target structure information [12]. This process was programmed and calculated by MATLAB [13], and part of the code was shown in Figure 3 below.

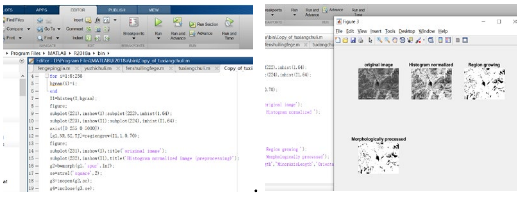

Figure 3: Image processing part of the code

After image processing of the above scanning electron microscope images, the porosity parameters of an electron microscope image [14] were obtained. The porosity of the three parts of samples was respectively 0.0944, 0.1041 and 0.0988 through statistical analysis. The average value of the three samples was calculated to obtain the porosity of the samples as 0.0991, and the results were used for model generation.

3.2 Generating the PFC model

PFC is used for numerical simulation of uniaxial compression, and parallel bonding model is selected for numerical simulation in this section. The established numerical model is shown in Figure 4, with a size of 50mm*100mm.

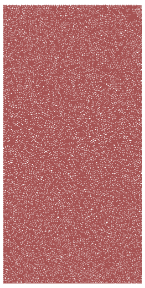

Figure 4: PFC numerical model constructed

Displacement loading is used in this simulation. The loading plate is loaded axial at a rate of 0.05m /s, and the loading stops when the sample is damaged.

3.3 Selection of contact constitutive parameters

In the parallel bond model, the macroscopic mechanical response of the material is mainly affected by ten meso parameters, which are porosity, particle size ratio, particle contact modulus, particle stiffness ratio, friction coefficient, parallel bond modulus, particle contact and parallel bond stiffness ratio, and normal and tangential bond strength. Different mesoscopic parameters correspond to different macroscopic mechanical responses. The "trial and error method" was used for debugging, and a set of meso-parameters as shown in Table 1 were obtained. The simulated peak strength, elastic modulus and failure mode of this set of meso-parameters were close to the laboratory uniaxial compression test results of sandstone [15], which could reflect the mechanical properties of red sandstone, as shown in Figure 5.

Table 1: Mesoscopic parameters

Meso-structure parameter	Numerical value	Meso-structure parameter	Numerical value
Porosity	0.0991	Parallel bond modulus /GPa	3.984
Particle diameter ratio	1.33	Parallel bond stiffness ratio	3.0
Density (kg/m3)	2500	Normal strength of parallel bond /MPa	34
Particle contact modulus /GPa	3.984	Tangential strength of parallel bond /MPa	68
Particle contact stiffness ratio	3.0	Friction coefficient	0.577

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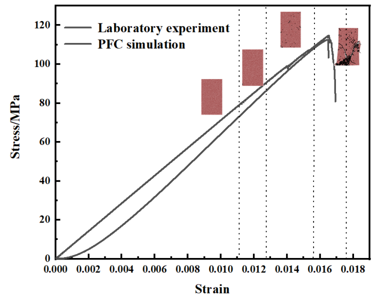
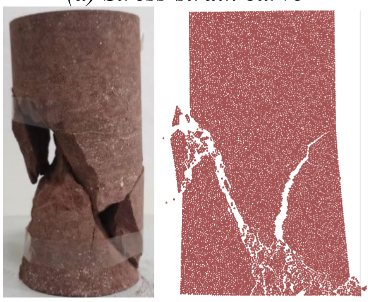


(a) Stress-strain curve



(b) Failure characteristics

Figure 5: Comparison of test and simulation results

4. Test results and analysis

4.1 Crack growth analysis

In the numerical simulation test of uniaxial compression, the process of crack propagation is shown in Figure 6. The fissure image was obtained every 5000 steps. Since no fissure was generated before 58000 steps, the extraction was started from 58000 steps.

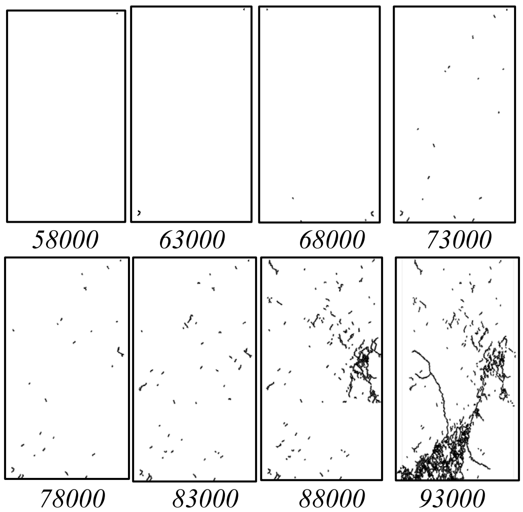


Figure 6: Model crack during test loading

According to Figure 6, fracture evolution can be divided into four stages: elastic deformation stage, fracture initiation stage, fracture propagation stage and fracture penetration stage: (1) when the calculation step is 0-58000, there is no crack, which is the elastic deformation stage of sandstone(The contact between particles in PFC^{2D} model was uniform, and the simulated curve showed linear growth without compaction section); (2) When the calculation step is 58001-68000, a small number of cracks begin to occur, so it is in the stage of fracture initiation; (3) When the calculation step is 68001-83000, there are some short fractures in the middle, which are in the stage of fracture expansion. (4) When the calculation step is 83001-93000, long fractures are formed in the central and lower regions and connected into one piece, which is in the stage of fracture penetration.

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4.2 Evolution law of internal damage

After a certain amount of mesoscopic damage evolution and accumulation, the sandstone is damaged, so the damage is caused by the propagation of microcracks, whose failure is marked by crack connection or the formation of macroscopic main cracks [17].

In the numerical simulation of PFC, the generation of cracks is accompanied by the fracture of the bond between particles, so the development of microcracks can be reflected by the change of the number of bond fractures.Damage refers to the deterioration of mechanical properties of materials due to certain stresses, such as the initiation and propagation of micro-cracks [18-19]. According to the meso-statistical damage idea, the damage degree is proposed based on the number of bond fractures. When the sample is completely destroyed, the damage degree is recorded as 100%, and the formula is:

$$\mathrm{D} = \frac{N}{N_A} \tag{1}$$

Where: N_A is the total number of bond breaks when the model is broken.

According to Figure 8, it can be seen that: (1) when the calculation step is 0-58000, there is no crack, and the damage curve is 0; (2) When the calculation step is 58001-66000, the fracture is in the initiation stage, and the number of fractures is small, and the damage degree is [0%, 0.3%]. (3) When the calculation step is from 66001 to 87000, the damage degree curve shows a saw-tooth slowly increasing trend, and the damage degree is [0.3%, 8.64%]. In line with the characteristics of fracture expansion stage; (4) When the calculation step is 87001-91001, the damage degree increases rapidly until the model is completely destroyed, which is in the stage of fracture penetration. Therefore, the damage degree inside the specimen can be estimated by studying the crack propagation.

4.3 Evolution characteristics based on MATLAB box dimension

(1) Calculation Method

Box dimension is the most widely used method to calculate the fractal dimension of graphics. Its principle is to cover the image with square grids with different side lengths (*r*). When the value of side length (*r*) changes, the number of squares $N(r)$ with image information also changes.

$$\mathrm{D}_b = -\lim_{r\to 0}\frac{lnN(r)}{lnr} \tag{2}$$

Where: D_b- box dimension; $N(r)$- Number of squares containing image information; *r*- the length of the sides of the square.

The box dimension can be approximated by experiments. With the rapid development of computer technology, MATLAB programming can be used for initial preprocessing of images, and then combined with Fraclab program in the toolbox, the box dimension of images can be calculated. Part of the code is as Figure 7.

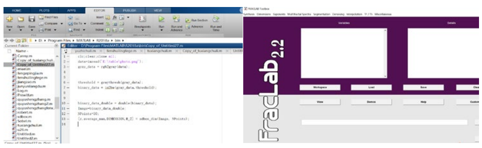

Figure 7: Code of box dimension part

(2) Relationship between fracture fractal dimension and sandstone fracture propagation

The box-counting dimension can reflect the fractal characteristics of the self-similar system. Therefore, if the distribution characteristics of sandstone fractures change, the fractal characteristics will also change.

As shown in Figure 8, the fractal dimension has two turning points with the development of the number of steps, namely 69,000 steps and 73000 steps. (1) When the number of steps is between 58000 and 69000, the fractal dimension increases from 0.4664 to 0.8944, and most of the samples are in the crack germination stage, and cracks begin to appear. (2) When the number of steps is between 69001-73000 steps, the fracture begins to expand, and the fractal dimension decreases from 0.8944 to 0.6979. (3) When the number of steps is between 73001-93000 steps, the fractal dimension increases significantly, because at this stage, cracks gradually increase, forming through cracks, and finally tend to be stable with the failure of the specimen.

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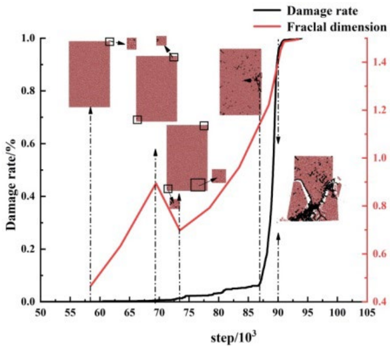

Figure 8: Damage rate and fractal dimension change with the number of steps

5. Conclusion

Through the research of this paper, the following conclusions can be drawn:

(1) Microscopic images of red sandstone were obtained through scanning electron microscopy experiment, and the parameters of mesoscopic geometric structure were obtained by combining with digital image processing technology, which laid the foundation for the establishment of particle flow model. The mechanical parameters of red sandstone were obtained through uniaxial compression experiment, and the peak strength and fracture mode of indoor red sandstone experiment were compared with the simulation results. The results show that the mesoscopic parameters are reasonable.

(2) Through geometric structure parameters and mechanical parameters, The PFC model is established. In the process of PFC simulation, sandstone crack propagation has obvious stages, which can be divided into four stages: elastic deformation, crack initiation, crack propagation and penetration.

(3) There is an obvious correlation between the mesoscopic damage degree and the development stage of sandstone fractures. In the elastic deformation stage of sandstone, the damage curve is 0. In the initiation stage, the damage degree of sandstone is [0%, 0.3%]; in the expansion stage, the damage degree of sandstone is [0.3%, 8.64%]; in the penetration stage, the damage degree curve of sandstone rises rapidly until the model is damaged.

(4) At the germination stage, the fractal dimension increases from 0.4664 to 0.8944; In the expansion stage, the fractal dimension decreases from 0.8944 to 0.6979. At the through-through stage, the fractal dimension increases greatly. Red sandstone has good fractal characteristics, so the box dimension can be used to indirectly evaluate the internal damage of red sandstone, which provides a new way to study the damage evolution of red sandstone.

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