Fracture Paths and Acoustic Emission Characteristics of Layered Brazilian Disc Specimens with Different Monolayer Thickness

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Abstract. The Brazil disk test is carried out for thin layered rock with different thickness by numerical simulation method, with the load and AE data of samples analyzed. The following are some findings: (1) When the thickness of a single layer of layered rock increases, its tensile strength does not simply increase. Instead, they roughly show a U-shaped relationship. (2) Layered rock’s load-displacement curve is multimodal. (3) Shear rupture occurs at the upper and lower ends of the disk, tensil and mixed rupture occurs more frequently in the middle of the disk. (4) There are three stages of interacting cracks’ coalescence: initial crack and the secondary fracture generate, then they interact and extend, finally coalesce.

1. Introduction

Layered rock mass widely exists in all kinds of engineering[1]. Unlike homogeneous rock mass, layered rock mass has obvious due to its control of the direction of the layers[2]. Weak bedding has a significant effect on stability and continuity of rock mass[3].

Many scholars have studied the anisotropy of tensile strength of layered rock mass by Brazilian splitting test. Based on experiments, Nasseri analyzed the mechanical properties of schist strength and deformation anisotropy[4]. Chen studied the 5 elastic properties of tensile strength and transverse isotropy of layered rock mass[5]. The elastic parameters and strength anisotropy of gneiss, shale and schist under uniaxial compression and Brazilian splitting tests at different angles were studied by Chao[6]. The analytical solution of tensile strength of layered rock mass and 5 elastic parameters and bedding angle was put forward by Claesson[7].

Previous studies focused more on the anisotropy of layered rock, i.e., differences of rock mass properties in different directions. However, the difference of rock mass properties in the same direction is less concentrated. This study focuses on the similarities and differences in the properties of five groups of layered rock mass with different monolayer thickness.
2. Numerical simulation and test scheme
This research adopts the method of numerical simulation based on cohesive element. Compared with the extended finite element method, the cohesive element method can highlight the properties of weak bedding planes of rock mass[8]. As a numerical simulation software, ABAQUS is widely accepted with preferable stability and simulation effect, which is adopted in this paper[9]. Next is the specific scheme and parameter selection of this numerical simulation experiment.

2.1 Establishment of model
The standard Brazil disk specimen was used in this test, with a diameter of 128mm[10]. As shown in Figure 1, each disk sample contains equidistant weak beddings when the spacing of the layers is set to d. The values of d are sequentially 4 mm, 8 mm, 16 mm, 32 mm, and 64 mm.

![Figure 1. Schematic diagram of model (d represents monolayer thickness).](image)

2.2 Meshing
The rock of the model is divided into tetrahedral meshes with advanced algorithm. The approximate global mesh size is 1.5mm. CPE4 (four-node bilinear plane strain quadrilateral element) is used in the solid element, and COH2O4 (four-node two-dimensional bonding element) is used in the cohesive element between the solid elements.

![Figure 2. Sketch map of meshing.](image)

2.3 Physical property
Shale is a common rock with thin layer structure in nature[11]. The physical and mechanical properties of rocks simulated in this study are taken from shale samples from Fuling, Chongqing[12]. The following table shows the mineral composition of the shale and its corresponding physical and mechanical properties. In this experiment, all grids were divided according to the measured mineral content of the rock. Each region represents a different kind of mineral. The number of grids contained
in each part-ition represents the content of that mineral. Then the mechanical parameters of the mineral are assigned to the corresponding grid area.

| Rock (Shale) | Composition Percentage | Modulus (GPa) | Poisson ratio | Tensile Strength (MPa) |
|--------------|------------------------|---------------|---------------|------------------------|
| Quartz       | 49                     | 40            | 0.2           | 20                     |
| Albite       | 11                     | 21            | 0.24          | 17                     |
| Microline    | 4                      | 20            | 0.25          | 16.5                   |
| Calcite      | 6                      | 27            | 0.23          | 10                     |
| Moscovite    | 17                     | 18            | 0.27          | 3                      |
| Kaolinite    | 4                      | 22            | 0.23          | 6                      |
| Dolomite     | 5                      | 21            | 0.23          | 13                     |
| Pyrite       | 4                      | 35            | 0.22          | 18                     |

At the same time, the edges of each unit are given cohesive properties. The boundary of units that are not weak layer are given a strong cohesive property. All specific property settings are shown in the Table 1 below.

| Cohesive unit | Stiffness coefficient | Tensile strength (MPa) | Shear strength (MPa) | Failure displacement (mm) |
|---------------|-----------------------|------------------------|----------------------|--------------------------|
| High strength cohesive edge | 17000 | 6 | 20 | 0.05 |
| Low strength cohesive edge | 15000 | 3 | 12 | 0.1 |

2.4 Analysis step and load setting
The total load time is set to 2S, the minimum increment step is $1 \times 10^{-10}$s, and the maximum increment step is 0.02s.

There is a pressure plate on each of the upper and lower sides of the disc to apply uniaxial pressure. The lower platen is fixed and the upper platen is moved down by 2mm over the entire process.

3. Test results and analysis

3.1 Load-displacement curves and peak load

![Figure 3. Load-time curves (a) and peak load broken line (b) in different layer thickness.](image)
As can be seen from Figure 3, tensile strength of layered rock mass does not vary linearly with the thickness of the monolayer. In contrast, that’s a process of reducing first and then rising. When the monolayer thickness of rock mass is 16 mm, the peak-load curve of rock mass reaches the peak value earliest with its peak strength is also the lowest in the meantime. Figure 3 indicates that the rock mass is most likely to emerge tensile failure when the monolayer thickness is 16mm.

3.2 Acoustic emission characteristics
As shown in Figure 4, the load-displacement curve is multimodal. As only after each peak occurs, a large number of AE events will emerge closely, which indicates rock material’s damage occurs after the load reaches the ultimate strength.

From (f) in the Figure 4, we can find that accumulated AE counts is minimum when the layer thickness is 16mm, corresponding to the peak load broken line in Figure 3. That indicates when the layer thickness is 16mm, rock mass is most prone to damage. The difficulty degree of rock failure is not linear with the thickness of rock mass.

The acoustic emission data MMIXDME in the process of crack propagation were extracted. When the value is 1, shear failure occurs. When the value is 0, pure tensile failure occurs. When the value is between 0 and 1, mixed failure occurs. Using the extracted acoustic emission data, the acoustic emission location map during the experiment is depicted in Matlab (see Fig. 5). Each dot in the picture represents an acoustic emission event, which represents the magnitude of the acoustic emission energy. The type of rupture is represented by color. Purple at value 1 represents pure shear failure, red at value 0 represents pure tensile failure, and mixed between two colors represents two kinds of failure, i.e. mixed failure.

![Figure 4. AE event count histogram and accumulative AE counts line chart.](image-url)
The obvious end effect was simulated, i.e., shear rupture occurs at the upper and lower ends of the disk, tensile and mixed rupture occurs more frequently in the middle of the disk.

There is friction between the end face of the specimen and the backing plate, and the Poisson effect is restrained. A conical compression zone is formed at both ends of the specimen, in which the rock is under triaxial compression [7].

![Acoustic emission mapping and fracture type](image)

Figure 5. Acoustic emission mapping and fracture type. Every dot represents an AE event. The legend represents the value of MMIXDME.

### 3.3 Crack evolution

![Rupture diagram of specimen with layer thickness of 16mm](image)

Figure 6. Rupture diagram of specimen with layer thickness of 16mm.

![Local crack propagation process of specimen’s layer thickness is 64mm](image)

Figure 7. Local crack propagation process of specimen’s layer thickness is 64mm.
For all specimens, intermittent cracks were observed in the simulation results. As shown in the Fig 6, the two branches of intermittent cracks are more prone to be straddled by weak layers. As we all know, one of the causes of intermittent cracks is the heterogeneity of rocks[8]. It can be observed that the existence of weak bedding planes has hindered the expansion of cracks.

In Fig 7, three stages of the coalescence of interacting cracks were observed[9]. When the time was 0.4838s, initial crack was formed. Then secondary fracture emerged in the area not far from the first one. In the same time, crack interaction between these two branches emerged too, and localized stresses increased. Small-scale cracks coalesced along with cracks propagating and interacting. In the last stage, when the time was 0.4864, cracks coalesced and energy was released, large permanent axial strains induced.

4. Conclusion
Weak bedding is an important cause for the difference of rock properties[10]. In this study, the effect of bedding on the fracture characteristics of rock mass is further researched. Here are several discoveries:

1) When the thickness of a single layer of layered rock increases, its tensile strength does not simply increase. Instead, they roughly show a U-shaped relationship. And layered rock’s load-displacement curve is multimodal.

2) Shear rupture occurs at the upper and lower ends of the disk, tensile and mixed rupture occurs more frequently in the middle of the disk.

3) There are three stages of interacting cracks’ coalescence: initial crack and the secondary fracture generate, and then they interact and extend, lastly coalesce.

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