Study on Fracture Mode of Gypsum under Shear Box Loading

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Abstract: The fracture mode under compressive shear loading is the research focus of rock fracture mechanics. In this paper, rock-like material with cracks was used to investigate its fracture mode. The physical and mechanical parameters of gypsum with specific paste-to-water ratio and curing time were measured by uniaxial compression test, and then, the shear box tests with loading angles of 0°, 15°, 30°, 45°, 60°, and 70° were carried out on gypsum specimens with initial double edge cut cracks. Finally, the strain field was monitored by the DIC method to analyze and summarize the phenomenon of crack initiation and propagation, and to analyze the fracture mode under shear box loading. The results show that the failure process of gypsum under uniaxial loading is a tensile split failure, and the fracture propagates through the entire specimen. Under the shear box loading, when the loading angle is less than 30°, the crack propagation presents a splitting tensile failure mode, that is, the crack propagation belongs to Mode I. When the loading angle is greater than 60°, the crack propagation shows shear failure mode after loading, that is, the crack propagation belongs to Mode II. While, when the loading angle is 45°, both the above two conditions exist, and the specimen presents both wing crack and secondary crack, in other words, the failure mode of the specimen is a superposition of shear fracture and tensile fracture. The research results can improve the understanding of the crack propagation mechanism of rock-like materials.

Keywords: Rock-like materials; Shear box loading; Crack propagation; Fracture mode

1 Introduction

Due to the differences in tectonic and environmental factors in the diagenesis process, natural rock masses often have defects such as the random layout of cracks and voids inside the structure. Under load, the internal defects of the rock mass may initiate and propagates, which can lead to its failure [1].
As a rock-like material, gypsum has become a commonly used material for model tests in geotechnical engineering due to its low price, high safety, and strong plasticity [2].

Many scholars have conducted a lot of discussions on the law of crack propagation and the evolution of rock-like materials through experimental tests. Gypsum specimens with three closed cracks were used to study the propagation and penetration laws of rock-like materials [3-4]. In recent years, with the rise of digital image correlation (DIC), many scholars have adopted this method to observe the crack initiation and evolution of samples [5-6]. The crack initiation of preformed cracks with different inclination angles in rock-like materials under uniaxial compression has been widely studied. In addition, the strain field measurement technique has been used to track crack growth, and analyze fracture modes with different inclination angles [7-8]. Some scholars have also carried out uniaxial compression tests on gypsum samples with cracks at different initial angles, using acoustic emission methods and wave velocity monitoring technique, and divided the failure modes of gypsum with initial cracks into three modes: crushing, shearing, and splitting [9].

At present, the research on crack initiation and propagation of rock-like materials mainly focuses on the central crack, while the research on double edge crack is still insufficient. In this paper, the rock-like material-gypsum samples were poured, and the samples with different loading angles were tested by shear box loading. Based on the strain field measured by the DIC method, the influence of different loading angles on edge crack initiation during the loading process has been analyzed. The research results in this paper can improve the understanding of crack initiation and propagation, and provide a reference for related research.

2 Experiments and methods

2.1 Sample preparation
The test material in this paper was high-strength gypsum, which has strong fluidity, with an initial setting time of 6-8 minutes and a final setting time of about 30 minutes. The gypsum slurry was prepared with a mass ratio of gypsum to the water of 3:1, stirred rapidly for 5 minutes, and poured into the mold which surface was brushed with oil. In the experiment, 3 uniaxial specimens and 6 shear box specimens were poured respectively. The dimensions of the uniaxial compression samples were 50mm in diameter and 100mm in height. The samples of shear box test were some cracked gypsum plates whose size was 150mm*150mm*30mm, and the initial crack with a length of 30mm was cut as triangle shape on two symmetric edges of the gypsum plates as shown in Figure 1.

The pouring process of the shear box gypsum sample required special attention. Triangular steel sheets with a length of 30mm need to be placed on both sides of the self-made mold as the initial cracks. At the same time, the surface of the steel sheets was required to be flat to keep a uniform thickness. So, a stainless steel blade was used to scrape the excess gypsum on the surface. After 2 hours, the gypsum could be demolded and placed in a curing environment. The whole process should require the meticulous operation to ensure that no secondary defects were generated in the samples. The prepared gypsum specimen containing cracks was placed in a dry and ventilated indoor environment for natural curing for 20 days [10]. After the curing was completed, two layers of black and white speckles were randomly sprayed on the surface to measure the strain field by the DIC
method. The sample preparation process is shown in Figure 1.

![Sample preparation and test development.](image)

**Figure 1.** Sample preparation and test development.

### 2.2 Experimental procedure

The experiments in this paper were divided into two types, which were used to observe the uniaxial failure mode of gypsum and study the crack initiation mechanism of gypsum under shear loading. The first type was the conventional uniaxial experiments, and the second type was the shear box test with the loading angle ($\alpha$) of 0°, 15°, 30°, 45°, 60°, and 70° respectively. The laboratory test loading system included MTS-815 and HUT-electro-hydraulic servo testing machine.

1. The uniaxial compression test of gypsum was carried out on MTS-815, and the displacement-controlled loading process was adopted. The preloading was carried out to 0.2kN and the loading rate was controlled as 0.06 mm/min. The failure mode of gypsum samples was studied and the basic physical and mechanical parameters were analyzed after the test.

2. The shear box test was carried out on the HUT-electro-hydraulic servo testing machine. The test system was shown in Figure 2. Displacement controlled loading process was also adopted, and the preload was set to 2kN, and the loading rate was controlled to 1mm/min. The test was terminated when the crack expanded through the entire specimen. Meanwhile, a high-frame-rate industrial camera was used to capture and photograph the global strain field during the loading process to analyze the evolution of crack growth.

![Shear box test system.](image)

**Figure 2.** Shear box test system. (a) Test setup. (b) Angle-adjustable shear box device.
3 Experimental results and analysis

3.1 Basic physical and mechanical parameters of the sample
The uniaxial compression tests were carried out on the cylindrical specimen, and a typical stress-strain curve during the test loading process is shown in Figure 3. The uniaxial compressive strength is 32 MPa, the elastic modulus is 11 GPa, and the Poisson's ratio is 0.32.

![Figure 3. Stress-strain curve.](image)

The failure morphology of gypsum under uniaxial loading is shown in Figure 4. There are multiple crack propagation surfaces along the axial direction, and the failure process is manifested as tensile split failures. It is worth noting that the damage mechanism exhibits an obvious wedge splitting effect. Once a wedge split is formed at both ends of the sample, the specimen would be split. It is also observed that the initiation form of uniaxial crack in gypsum is mainly perforation type, which is caused by the relatively low uniaxial compressive strength of gypsum sample and the interaction effect between the specimen and loading platen, as well as the flatness and heterogeneity.

![Figure 4. Main fracture morphology of gypsum sample.](image)

3.2 Shear crack propagation
In this paper, the gypsum specimens containing initial cracks were carried out in 6 sets of shear box tests with the loading angle $\alpha$ of 0°, 15°, 30°, 45°, 60°, 70°, respectively. The axial load-displacement curves in the test are shown in Figure 5. It shows that the load on the samples increases rapidly to
about 7 kN in the initial stage of loading, and then remains stable. This stage is shown as the initial compaction stage of the samples and setups. As the loading continues, the load on the samples increases linearly, and the samples can be considered in the linear elastic deformation stage. While, no crack appears on the surface of the samples, and its initial cracks do not affect the test loading at this stage. As the loading continues, the load reaches its peak rapidly after the crack is initiated. The load-displacement curves of all samples after peak load can be roughly divided into two modes. The first mode presents a brittle failure, such as the samples corresponding to the loading angles of 0° and 15°. These samples can be rapidly damaged and the curves drop sharply with large values of peak loads, and the reason is that the crack initiation of the specimen presents a typical tensile split failure, which is similar to the uniaxial specimen, and the crack would rapidly propagate after the initiation. The other mode presents a ductile failure, such as the samples with loading angles of 30°, 45°, 60°, and 70°. Their post-peak curves show a slow decline, and the post-peak curves are last for a long time, and the peak loads are small. Because the small loading angle yields a large normal load on the initial fracture plane, which could further increase the shear capacity of the specimen.

The shear force-displacement curves of some samples are shown in Figure 6. There is no tangential load when the loading angle is 0°, so its curve is not drawn in the figure. It could be seen from the figure that the shear force of the sample in the compaction stage increased gradually with the increase of loading angle.

**Figure 5.** Axial load-displacement loading curves of each sample.  
**Figure 6.** Shear force-displacement loading curves of some samples.
Figure 7. shows the peak load of samples with different loading angles based on the results of laboratory tests. The conclusions reveal by the figure are as follows: (1) When the loading angle $\alpha$ increases from 15° to 70°, the peak loads of the samples shows a downward trend, and there is a linear correlation from 30° to 70°. The overall phenomenon shows that when the loading angle is greater than 15° and the other conditions remain the same, the increase of the loading angle would reduce the loading strength of the rock-like material with initial cracks. (2) It is worth noting that when the loading angle was 0°, the peak load of the sample is lower than that at 15°, indicating that the loading angle has a significant impact on the strength of the sample. Meanwhile, we could infer that the loading angle is 15° for the optimal uniaxial compressive strength of the fractured rock mass.

3.3 Shear displacement field

To further analyze the crack initiation and fracture mode of the samples at the micro-level, the shear displacement distribution of each sample at the failure stage is extracted as shown in Figure 8. It is worth noting that when analyzing the strain field, the image of specimens could be rotated through a certain angle, and the shear direction coincides with the horizontal direction. The shear displacement distributions at the failure stage of each sample show that the shear displacement near the tip of the initial crack presents a large value under the shear box loading, and with the increase of the loading angle, the fractures in the shear displacement field gradually shift from normal direction to shear direction.

When the loading angles are 0°, 15°, and 30°, the shear displacement field is centrosymmetric, and the sample presents a splitting tensile fracture mode, whose failure is controlled by tensile stress, thus the crack propagation belongs to Mode I. When the loading angles are 60° and 70°, the shear displacement field is symmetrically distributed on both sides of the initial crack plane, and the sample fails in shear fracture mode. The crack propagation is mainly controlled by shear stress, so the crack propagation belongs to Mode II. When the loading angle is 45°, the shear displacement field presents the above two conditions, the failure mode of the sample is a superposition of shear fracture and tensile fracture, which indicates that the crack propagation is controlled by both tensile stress and shear stress, and the crack propagations belong to both Mode I and II.
3.4 Analysis of crack types and fracture modes of specimens

In the last section, not only the shear strain field of each sample under different loading angles was analyzed, but also the fracture modes and crack types were analyzed and discussed. To further analyze the propagation of new cracks and the fracture mode of the specimen, Figure 9. shows the failure images containing the crack propagation paths of the specimens. According to the results of section 3.3 and the analysis of Figure 8, the following conclusions could be drawn. When the loading angle is small, such as 0°, 15°, and 30°, the propagation of new cracks after loading shows as wing cracks, which are mainly controlled by tensile stress. When the loading angle is large, such as 60°, 70°, the new crack growth after loading presents a secondary crack, and the crack growth is controlled by shear stress. However, when the loading angle is 45°, the new cracks propagate simultaneously as wing cracks and secondary cracks, which indicates that the loading angle of 45° is the critical value for the transition between two fracture modes.

Figure 8. Shear displacement field on the surface of specimen before failure.

Figure 9. Failure patterns and crack types of specimens.
4 Conclusions

In this paper, uniaxial compression tests and shear box tests were carried out. The uniaxial compression test show that the uniaxial compressive strength of the studied gypsum was 32 MPa, and its elastic modulus was 11 GPa, and its Poisson's ratio was 0.32. Under the uniaxial loading, the failure process of gypsum was manifested as tension splitting failure, and the fracture propagates through the entire specimen. Based on the analysis of the strain field, the phenomenon of crack initiation and propagation and failure evolution of the gypsum sample under the shear box loading were studied by laboratory tests. Through the comparative analysis of the results, the conclusions are as follows:

(1) The load-displacement curve shows that when the loading angles of the shear box test are 0° and 15°, the crack initiation showed a typical tensile split failure, and the crack propagates and penetrates the specimen rapidly after the peak load. When the loading angles are 30°, 45°, 60°, 70°, the curve behind the peak is obvious.

(2) When the loading angle ranges from 0° to 30°, the shear displacement field is centrosymmetric. New cracks propagate as wing cracks, and the sample presents a splitting tensile failure mode. This type of crack propagation belongs to Mode I.

(3) When the loading angle is greater than 60°, the shear displacement field appears symmetrically distributed on both sides of the initial crack plane. New cracks grow as secondary cracks, and the sample shows a shear failure mode. The crack propagation belongs to Mode II.

(4) The shear displacement field with the loading angle of 45° shows the above two conditions. The failure modes of the sample have both wing cracks and secondary cracks. The failure mode of the sample is a superposition of shear failure and tensile failure, and the crack propagations belong to both Mode I and II.

References

[1] Liu X L, Wang S J and Wang E Z 2008 Evolution of Defects in Uniaxial Compression Rock and Rock Strength Chinese Journal of Rock Mechanics and Engineering 1195-1201
[2] He S L, Huang X, Zhang Z X 2016 Study on the mechanical properties of gypsum specimens Chinese Journal of Underground Space and Engineering 49-55
[3] Park C H and Bobet A 2009 Crack coalescence in specimens with open and closed flaws: A comparison. International Journal of Rock Mechanics and Mining Sciences 819-829
[4] Park C H and Bobet A 2010 Crack initiation, propagation and coalescence from frictional flaws in uniaxial compression Engineering Fracture Mechanics 2727-2748
[5] Song Y M, Mang S P and Yang X B 2011 Research on Digital Speckle Correlation Method of Rock Deformation and Failure Chinese Journal of Rock Mechanics and Engineering 170-175
[6] Song Y M, Jang Y D and Meng S P 2012 Research on deformation field and energy evolution in the whole process of rock deformation and failure Rock and Soil Mechanics 1352-1356
[7] Zhao C, Tian J S and Song T H 2015 Research on rock crack propagation and damage evolution characteristics based on global strain field analysis under uniaxial compression Chinese Journal of Rock Mechanics and Engineering 763-769
[8] Zhao C, Liu F M and Tian J S 2016 Study on the law of single crack propagation and damage evolution of rock based on uniaxial compression test Chinese Journal of Rock Mechanics and
Engineering 3626-3632.

[9] Wang S G, Liu Y R and Chen X 2019 Failure analysis of cracked gypsum specimens based on acoustic emission technology Journal of Hydroelectric Engineering 110-120

[10] Yang A Y and Song Y 2019 Gypsum model making and property experiment The 25th Annual Academic Conference of the Beijing Society of Mechanics

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