Study on the failure characteristics of fractured rock with different topologies under uniaxial compression

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\textbf{Abstract.} Rock masses are characterized by many discontinuities, the distribution and interactions of which are closely related to the mechanical properties and control the stability of the rock mass. In this work, uniaxial compression tests were conducted on granite with prefabricated cracks in the form of topological branches to study the related fracture network. A high-speed camera and an industrial camera were used to capture images of the crack initiation, propagation, coalescence, and complete failure process. Digital image correlation processing was then employed to obtain the global strain field evolution diagram of the specimens. The following results were obtained. (1) The initial strain localization zone of specimens with different forms of prefabricated fractures mainly shows two initiation modes, namely, T- and H-shaped fractures. (2) Macroscopic cracks propagate along the direction of the maximum principal stress.

\textbf{Keywords:} fracture networks; topology; crack; digital image correlation; uniaxial compression

\section{1. Introduction}
Fracture network structures are formed within and on the surface of deep engineering rock masses under the influence of tectonic movement and complex geomechanical environments and dominate the mechanical properties of the underground rock\cite{1}. The damage evolution and failure law of fractured rock masses are affected by the expansion and coalescence of the fracture network. The evolution of the fracture network causes the deformation and failure of the surrounding rock mass, which could affect the safety and stability of deep-buried rock mass engineering. Therefore, studying the extension and evolution law of complex fracture networks in the surrounding rock presents important scientific significance with great engineering value.

Many scholars have performed theoretical, experimental, and numerical simulation studies to obtain the mechanical properties of fractured rock masses and the evolution mechanism of crack propagation. Laboratory tests have become the most commonly used method for studying the law of rock fracture evolution. A number of authors have conducted research on fractured rock masses by prefabricating specimens with different fracture forms. Bobet and Einstein\cite{2}, for example, performed uniaxial compression tests on prefabricated double cracks in a gypsum model and found that the...
propagation direction of secondary cracks is coplanar or approximately coplanar with the prefabricated cracks. Liu[3] studied crack propagation and failure behaviors by prefabricating T- and X-shaped cross cracks in gypsum model specimens and found nine types of cracks. However, the available literature is limited to the discussion of fractured rock masses after failure and lacks research on the process of crack propagation. The above studies provide a basis for understanding the mechanism of crack propagation in fractured rock masses, but the study of more complex fracture morphologies with fracture networks is insufficient. Given developments in technology, research on the crack propagation evolution of prefabricated fractured rocks has progressed from the macroscopic scale to the mesoscopic scale depending on the measurement techniques and theoretical methods applied. Scanning electron microscopy (SEM)[4], acoustic emission[5], and digital image correlation (DIC) technology[6, 7] are among the most commonly used methods for studying the evolution of crack propagation. DIC is a modern non-contact optical measurement technology that could compensate for the limitations of SEM, which can only observe the morphology of fractured rock masses after destruction, and acoustic emission, which can only detect the failure process indirectly. More importantly, DIC is a technology that can quantify the fracture process in laboratory rock mechanical tests[8].

Although the understanding of the extension mechanism of rock mass fractures in natural rock has improved over the last few years, this understanding is limited to simple fracture forms (i.e., single and double cracks); by contrast, the mechanisms of the more complex forms of rock mass fractures remain incompletely understood.

In this study, the mechanical properties and evolution law of crack propagation in a rock mass with prefabricated multi-fractures are studied by constructing multi-branch crack forms on natural rock. The failure properties of specimens with different forms of prefabricated cracks were investigated by uniaxial compression tests. DIC was used to analyze the strain field evolution during the loading process, and the failure mode of specimens with different forms of prefabricated cracks was explored.

2. Prefabricated Crack Form of Topological Structures

Many natural fractures of different scales and quantities occur in deep strata. From the perspective of the development degree of fractures occurring in outcrops, when the number and group of fractures reach a certain degree, the fractures exhibit complex network characteristics. Figure 1 shows an outcrop measuring 12 m × 12 m at the southern edge of the Bristol Channel Basin and a simulated pattern measuring 1.5 m × 1.5 m extracted from the right side of this basin. The characteristics of the fracture network are very obvious. In general, fractures interact with each other and, together with the rock matrix, control the physical properties of the rock. However, most traditional studies focus on the geometry of fractures; few studies on the relationship between fractures are available. The topological structure describes the arrangement and geometric relations between spatial objects. Numerous studies have confirmed the existence of topological structural characteristics in crack networks. By introducing the concept of topology to the study of fracture networks, for instance, Sanderson[9] proposed that the topology of a two-dimensional fracture network is composed of lines, nodes, and branches (Figure 2); here, each line comprises one or more branches, and each end has a node. The nodes in the network are further divided into three types: I nodes, X nodes, and Y nodes. Santiago[10] found a topological characteristic pattern in fracture networks by studying five rock samples collected from three regions in eastern Mexico. Morley[11] confirmed the existence of topological structural characteristics in a fault network by conducting a topological analysis of the two-dimensional map view of 10 natural fault networks and 2 simulated fault networks. Duffy[12] verified that topology can be used as a fault network characterization tool and pointed out that the fault network topology describes and quantifies different spatial relationships between faults, especially fault terminals and fault intersections. Procter[13] and Igbokegbe[14] also proved that the topological
structure can represent the fracture network. According to the above analysis, prefabricated cracks are studied according to the topological structure in this paper. Thus, complex fractures are formed by increasing the number of branches, which could be taken as the target in basic research on the characteristic fracture forms of fracture networks.

Figure 1. Outcrop measuring 12 m × 12 m at the southern margin of the Bristol Channel Basin[15]

Figure 2. Diagram of the fracture network topology

3. Methodology

3.1 Specimen preparation

The material used in the tests was granite, which was excavated from Shandong Province, China. The specimens measured 100 mm high, 50 mm wide, and 20 mm thick. As shown in the line segment numbered 0 in Figure 3, the main crack has a length of 11 mm, width of 1 mm, and inclination of 135°; moreover, the crack center coincides with the center of the specimen. A branch crack is added at both ends of the main crack. The length of the branch crack is 5.5 mm, and its width is 1 mm. The dip angle of the branch crack is collinear or orthogonal to the main crack. Transformation of the number and orientation of the branch cracks could lead to the formation of simple topological structures, such as X- and Y-type joints, together with the main cracks. The pre-existing cracks were cut using a high-pressure water jet.

Specimen numbers are defined for convenience. The complex crack is constructed by increasing the number of branches at both ends of a single crack. The number of the main crack is 0, and the branch cracks are numbered from 1 to 6 in a counterclockwise manner. Thus, a specimen number is expressed as “0<branch number of the upper node><branch number of the lower node>” (Figure 3). The specimen shapes and crack design are shown in Figure 4. Specimen shapes are designated T-type nodes, H-type nodes, T-X-type nodes, and X-X-type nodes according to Figure 2.
3.2. Experimental setup

The uniaxial loading equipment used in this work is the WDW-600 universal testing machine produced by Shanghai Hualong Testing Instrument Co., Ltd., China. The test equipment is composed of computers and static and dynamic material testing machines (Figure 5). The maximum loading force of the testing machine is 600 kN. The observation equipment uses a CCD industrial camera produced by Metrovision to record the complete loading process. An i-SPEED7 high-speed camera captures the crack growth and nucleation of the specimen at the moment of failure. MindVision and i-SpeedSuite software are installed on two computers to control the industrial and high-speed cameras. The light source used in the test is a 1000 W halogen lamp, which can meet the illumination requirements of the test. The entire uniaxial compression test device is shown in Figure 6.

3.3. Testing procedure

The specimen end and pressure plates were cleaned and smeared with Vaseline. Next, the specimen was positioned in the middle of the uniaxial compression instrument and aligned with the midline of the upper and lower pressure plates. Loading was performed using displacement control at a rate of 0.05 mm/min. The complete loading process was recorded by the high-speed and CCD industrial cameras. The loading process for each specimen was conducted over approximately 30 min. The frame
rate of the industrial camera was two images per second, and the resolution of a single image was 4,000 × 3,000. Approximately 3,600 8-bit gray scale images were collected in a single group of experiments. The shooting rate of the high-speed camera was set to 3,000 Hz, so 3,000 images were obtained per second. The total shooting duration was approximately 14.26 s. The resolution of a single image was 768 × 1,536, and a total of 42,793 24-bit full-color pictures could be obtained in a single experiment. The images of the granite specimens obtained during the uniaxial compression tests were subjected to DIC after the tests were completed.

4. Analysis of the Experimental Results
This section discusses the results of the uniaxial compression tests. Section 4.1 discusses the mechanical properties of specimens with prefabricated fractures in the form of different topological branches, Section 4.2 discusses the evolution of the global strain field, and Section 4.3 discusses the failure modes of the specimens.

4.1. Analysis of mechanical properties
Figure 7 shows the stress–strain curves of granite specimens with pre-existing fractures of different forms under uniaxial compression.
Figure 7. Stress–strain curves of specimens with pre-existing fractures of different forms

Compared with that of specimens with T-shaped fractures, the peak strength of the three other orthogonal multi-fractured samples decreased significantly, thereby indicating that the complexity of the prefabricated fracture structure weakens the mechanical properties of the whole specimen to a remarkable extent.

4.2. Analysis of the evolution of the global strain field

DIC was used to analyze the evolution of the global strain field during the complete process of crack propagation in granite specimens with different forms of prefabricated cracks under uniaxial compression. The strain localization zone (SLZ) obtained in this analysis can be used to predict the development of macroscopic cracks and describe the crack propagation process. Different colors in the strain cloud charts represent different strain values, and the strain range is indicated on the right side of the strain cloud atlas. Specimens with T- and H-shaped prefabricated cracks are taken as examples for the following analysis.

4.2.1. Specimen 0–13

Figure 8 shows the cloud atlas of the evolution of the global tensile strain field of the T-shaped fracture specimen. When the axial load increases to 70% of the peak strength, SLZs simultaneously occur at the tip of the No. 1 branch crack and the lower end node of the main crack (Figure 8(a)). As loading continues, SLZ–I expands stably along the loading direction, whereas SLZ–II is consistently confined to the vicinity of the crack tip. SLZ–III (Figure 8(b)) begins at the tip of the main crack and rapidly expands along the direction of the maximum principal stress. As the load continues to increase, SLZ–IV (Figure 8(c)) develops toward the tip of the No. 1 branch crack, which is initiated at the lower joint of the main crack, and the strain value of this SLZ is the highest observed throughout the specimen. SLZ–V can also be observed at the tip of the No. 3 branch crack. However, the strain value of this SLZ does not show remarkable increases over the course of the loading process. Soon after, SLZ–VI (Figure 8(d)) with high strain values appears in the anti-wing-crack propagation zone at the tip of the crack of the No. 3 branch and rapidly expands upward to the end of the specimen. As the high strain zone is further concentrated, the strain in SLZ–III reaches that necessary for macroscopic crack initiation and coalesces with the No. 1 branch crack.

![Figure 8](image-url)

Figure 8. Evolution of the global tensile strain field of specimen 0-13

4.2.2. Specimen 0–13–46

Figure 8 shows the cloud atlas of the evolution of the global tensile strain field of the H-type specimen. The crack initiation position of this specimen is slightly different from that observed in previous crack
forms. When the axial load reaches 50% of the peak strength, the SLZ simultaneously appears at the tips of the cracks of the No. 1 and No. 4 branches (Figure 9(a)). Compared with those of the previous specimen, among the four branch fractures orthogonal to the main fracture, only the No. 1 and No. 4 branch fractures influence the location of the initial SLZ. The strain concentration zone at the joints located at both ends of the original main fracture is transferred to the respective tips of the branch fracture and expands along the loading direction. Continuous axial compression initiates SLZ–III (Figure 9(b)) in the wing-crack propagation zone of the No. 6 branch crack, and the strain value of this zone rapidly increases to the global maximum. Subsequently, SLZ–IV (Figure 9(d)) appears in the wing-crack propagation zone of the No. 3 branch crack and extends to the lower end of the specimen. Further strain concentration causes SLZ–V to develop in the anti-wing-crack propagation zone of the No. 6 branch crack (Figure 9(d)).

![Figure 9](image_url)  
**Figure 9. Evolution of the global tensile strain field of specimen 0-13-46**

The above analysis also indicates that the sequence of SLZ initiation in different specimens is approximately the same; moreover, the SLZ is usually initiated at the branch crack closest to the loading end in the middle of the specimen. The distribution characteristics of the SLZ in each group of specimens reveals that the SLZ begins from the tip of the prefabricated crack or the end of the specimen, and no strain localization phenomenon occurs at the intersection nodes. The common characteristics of the evolution of the global strain field in prefabricated fracture specimens with simple topological structures can be further extended to rock masses with complex fracture networks. In general, the SLZ appears along the loading direction at the free joint at the crack tip. Strain concentration does not occur at the node. According to the different structures of the branch crack, the direction of crack initiation may be mainly divided into T and H structural fracture modes.

### 4.3. Failure modes

Figure 10 shows the macroscopic failure modes and illustrations of specimens with different forms of prefabricated cracks under uniaxial compression. The tension–shear properties of the crack are marked in the figure. For convenience, tensile cracks are denoted T, shear cracks are denoted S, and tensile–shear mixed cracks are denoted TS. Superscript numbers indicate the sequence of macrocrack initiation as captured by the high-speed camera.
5. Conclusions

This paper explores the crack evolution law of a rock mass with a complex fracture network. A topological structural model of the fracture network is established, and four types of prefabricated fractures of different forms are designed considering the changes in node types and branch fracture forms. Laboratory-scale uniaxial compression tests are conducted using the prefabricated fractured granite specimens as the research object, and the DIC technique is employed to analyze the evolution characteristics of the global strain field of each group of specimens. Finally, the macroscopic failure modes of prefabricated fracture specimens with different forms are analyzed. The conclusions can be drawn as follows:

1. The initial SLZ of specimens with prefabricated fractures of different forms shows two main types, namely, T- and H-shaped fractures. Macroscopic cracks propagate along the direction of the maximum principal stress to the tip of the specimen, and the crack is mainly in the tension–shear mixed mode.

2. The common characteristics of prefabricated fracture specimens with a simple topological structure are extended to the rock mass with a complex fracture network. The strain localization band usually appears at the crack tip along the loading direction. In general, strain concentration does not occur at intersecting nodes, so macroscopic cracks are not formed. The macroscopic crack propagation path mainly expands along the loading direction.

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