Direct observations of hydraulic fracturing in rock bridge of granite specimens in grain-scale

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Abstract. Hydraulic fracturing is a crucial and widely-used technology in shale gas exploitation and enhanced geothermal systems; the rock bridge will significantly affect the crack type and coalescence pattern of the hydraulically induced cracks. This paper aims to directly observe the fracturing process in rock bridge of granite specimens in grain-scale. Speckles are sprayed directly on the granite surface, which avoids covering hair-line cracks, and image quality assessment shows that the speckle pattern performs well in digital image correlation (DIC) calculations. Hydraulic fracturing was performed on two double-flawed granite specimens; a high-speed camera captured the entire specimens, and another recorded the rock bridge in grain-scale at a high frame speed simultaneously. The strain localization, crack propagation and morphology were analyzed based on the DIC method. Results showed that strain localization occurs for the first time approximately 20 seconds before failure, which is earlier than previously observed. When the displacement jump reaches a specific value, hair-line cracks appear, and then the crack propagation is the process of crack width increasing. The competition between hydraulically induced cracks often occurs in 120° rock bridge, which will cause one of the hair-line cracks near the inner tip of the flaw to close before failure.

Keywords. hydraulic fracturing; rock bridge; digital image correlation; fracture process

1. Introduction

Using hydraulic fracturing technology to produce hydraulically induced cracks in reservoirs is crucial and widely used in shale gas exploitation and enhanced geothermal systems. The industry is particularly concerned about controlling hydraulically induced cracks, so it is of great significance to study the hydraulically induced fracturing process.

In recent years, hydraulic fracturing experiments based on direct observation have promoted the understanding of the mechanism. Jeffrey et al. [1] directly observed the hydraulic fracturing process using a high-speed camera through a scaling device, and measured the displacement using the DIC method with 10-micron resolution [2]. Gonçalves da Silva and Einstein[3] improved a pressure enclosure based on Miller’s [4] work, and using a high-speed camera to directly record the hydraulic fracturing process of Barre granite [5]. On this basis, Zhao[6] further improved the method to meet the requirements of optical testing and reveal the fracture process of Befast granite by DIC. Moreover, Xing [7, 8] further described the strain localization phenomenon in hydraulic fracturing. Recently,
Gunarathna and Silva[9] also reported the effect of the triaxial state of stress in the hydraulic fracturing process of granite through direct observation. However, the above studies are all carried out on a macro-scale. For granitic rocks, according to the microscopic observation after the tests, the local mineral grain distribution will affect the mechanism of hydraulically induced cracks[5, 6, 9]. Therefore, it is necessary to further observe the hydraulic fracture process in grain-scale.

Bing Li and Einstein[10] used a macro lens to achieve real-time recording of micron-scale crack growth in four-point bending, and achieved DIC measurement by regular mesh speckling configuration. After that, Bing Li and Einstein[11] directly observe the microstructural changes in hydraulic fracturing of Barre Granite and Opalinus Clayshale using a high-speed camera attached to a 5X magnification lens, and microstructural shearing in the form of distinct en echelon microcracks are recorded. Those methods provide references for current study. While the above work only reported hydraulic fracturing in specimens with a single pre-existing flaw. However, literature[5, 6, 12] shows that the rock bridge will significantly affect the crack type and coalescence pattern of the hydraulically induced cracks.

This paper aims to directly observe the fracturing process in rock bridge of granite specimens in grain-scale based on the DIC method. Direct observation in grain-scale reveals the mechanism of hydraulically induced cracks in the 120° rock bridge, including the evolution of the strain localization, the crack propagation, and the crack morphology. Related studies could be helpful to understand the hydraulic fracturing mechanism in granitic reservoirs.

2. Methodology

2.1. Speckle spraying in Specimen preparation

The specimens used in this study were made of Befast granite, which has natural red and white spots. The mineral composition[13] is potassium feldspar (content 45.37–51.5%, grain size 3–5 mm, flesh red), quartz (content 21.31–26.51%, grain size 1.5–2.5 mm, translucent white), plagioclase (content 21.64–24.33%, grain size 1.5–3.3 mm, white) and biotite (content 3.92–5.41%, black). DIC method was intended to analyze the data in this study. According to the theoretical research of the DIC algorithm[14], the speckle pattern has a significant impact on its accuracy. Specifically, if the speckle size is too small, it will lead to image under-sampling and cause great system errors; if the speckle size is too large, it will result in insufficient image details and poor contrast, which will cause a lot of random errors. Although the specimens have abundant natural speckles, it is still not enough to meet the needs, so additional speckles should be sprayed to improve the image quality.

2.1.1. Speckle spraying method. In most similar studies, the usual method of spraying artificial speckles is to first coat the entire specimen surface with a layer of white paint, and then spray black speckles. Although the paint covering the surface of the specimen is very thin, the toughness of the thin layer of paint is much better than rock, so that the deformation of the specimen and speckles will have a slight difference. The effect of this difference can be ignored in macro-scale. However, in grain-scale, such slight differences are unacceptable. We found in the pre-experiment that the thin paint layer will cover up some extremely tiny cracks; no cracks can be observed under the optical microscope, while hair-line cracks can be seen after the paint on the surface was washed with acetone. In addition, the white patching that quartz and calcite may whiten before fracture[5, 15] may also be covered by the paint layer.

Therefore, we improved the speckle spraying process. First, calculate the best speckle size according to the observed scale and the camera resolution. Generally, according to experience and theoretical analysis, the image has the best quality when the average speckle size is 4-7 pixels. Then, directly spray white and black speckles on the surface of the specimen; the speckle size is mainly controlled by the pressure and nozzle diameter. After spraying, the image taken by a black and white high-speed camera is shown in figure 1. The black and white paint speckles, together with the flesh-
red potash feldspar and biotite, formed the random speckles, so that only a small number of speckles cover the surface of the specimen, which will not cover up the hair-line cracks and white patching.

![Image](image1.png)

**Figure 1.** Schematic diagram of speckle spraying.

2.1.2. *Image quality assessment.* The mean speckle size can be estimated using the autocorrelation function of the image[16]; The full width at the half-height of the normalized autocorrelation function of the reference image [16, 17] could represent the mean speckle size. The mean speckle size in this study is about 6.6 pixels (the subset is 15 pixels*15 pixels), which shows that the mean speckle size is in an appropriate interval.

In order to further evaluate the random error of the displacement obtained by DIC method, we first estimated the image noise in the actual experiment. The standard deviation of image noise was about 3.72 pixels, which was get from two consecutive images. It is worth mentioning that the images taken by high-speed cameras are 10-bit depth. Then, the displacement measurement accuracy of DIC was assessed by the first-order shape function random error estimation method proposed by Bing Pan et al. [18]. The standard deviation error of the displacement measurement in horizontal and vertical directions was evaluated; the displacement standard deviations in both directions are mostly less than 0.02 pixels, which shows that the speckle pattern produced by this method can meet the requirements of high-precision displacement fields measurement in this study.

2.2. *Specimen, test setup, and procedures*

The dimensions of the specimens used in this study are 20 mm×75 mm×150 mm. Two pre-existing flaws were cut with a water-jet at the center of the specimen, and the rock bridge was 120°. The force state of the specimens during the tests is shown in figure 2(a). The device shown in figure 2(b) sealed the water pressure by rubber O-ring. The vertical load was applied by a uniaxial loading machine, and the water was injected through a water pump. The test process can be divided into three steps:

Step 1, after the prepared specimen was sealed in the water pressure sealing device, water was injected into the device in pressure control mode to make the fluid pressure reach 1 MPa, and then keep the water pressure stable.

Step 2, apply the vertical load at a loading rate of 0.4mm/min until the axial load reaches 20MPa, and then keep stable. After loading, adjust the focal length setting, aperture and exposure time, and the positions of the lighting, etc., to obtain the best image quality. Then collect and save the current images as reference images for DIC analysis.

Step 3, inject water at a rate of 0.2ml/min until the specimen was hydraulically fractured. The fracturing process was recorded by two high-speed cameras, of which i-SPEED 716R captured the entire specimens at a low frame speed (60 fps), and MotionPro Y7 S3 recorded the rock bridge at a high frame speed (300 fps for D30-120-A, and 7000 fps for D30-120-B), which used trigger control to ensure a period of time before fracturing can be recorded. The high-speed camera employed Laowa 100mm f/2.8 2x Ultra Macro APO Lens, which has up to 2x optical magnification.

2.3. *DIC method and processing parameters*
The open-source code Ncorr[19] was used to analyze the images of the fracture process, which has been widely and successfully used in geotechnical engineering. In this study, the Subset Radius was 15 pixels, the Subset spacing was 0, and Strain Radius was 5 pixels.

Figure 2. (a) Loading conditions of the specimens; (b) The water pressure sealing device used in this study, which was improved based on previous research[6, 7] and Silva and Einstein[3].

3. Results

Unless otherwise stated, the term ‘flaw’ refers to a pre-existing flaw; the term ‘failure’ refers to the specimen was fractured by water pressure; the term ‘crack’ refers to a visible crack observed after the specimen was fractured.

3.1. Evolution of strain localization zone in rock bridge

The peak water pressure of the two specimens was 4.53MPa and 4.29MPa, respectively, and the water pressure versus time is shown in figure 3(a). The failure statuses, shown in figure 3(b), were similar to previous research[6], although the fracturing fluid in the previous tests was silicone oil, and the peak liquid pressures were 7.5MPa and 8.5MPa.

In the reports of direct observation of the hydraulic fracturing process, scholars generally judged the early damage by observing the white patching, and the white patching initiation occurred at approximately 60% of the peak pressure in marble[9]. In contrast, the white patching is not evident in granite, so the evolution of the strain localization zone was used to characterize the damage evolution of granite. However, due to the limitation of the observation scale, obvious strain localization zones could be observed within 0.5 seconds before failure in macro-scale. While, in grain-scale, we could detect strain localization more sensitively. D30-120-A showed a small strain localization zone about 20 seconds before the failure, and the corresponding water pressure at this time was 3.65 MPa, about 81% of the breakdown pressure. D30-120-B only recorded the image within 10 seconds before the failure (because the frame rate was 7000fps), and there was an apparent strain localization zone in 10 seconds before the failure. In the two specimens, visible cracks finally appeared where the strain localization zone first appeared in the early stage. The current result indicates that the strain localization occurs earlier than previously observed.

The evolution of the strain localization zone in the rock bridge of the two specimens is shown in figure 4. It is worth noting that because the DIC algorithm has defects when processing discontinuous
displacements, the value of the principal strain does not the actual strain; but it still could reflect the change trend, so this paper only focuses on the change trend of the strain localization zones.

The first strain localization zone, Zone I, appeared in D30-120-A 20 seconds before failure, located in the upper left corner of the rock bridge, near the pre-existing flaw, and it was already self-evident at 5 seconds (because of the color bar range, the zone I at that time in figure 4 is not evident). The second strain localization zone, Zone II, appeared about 500ms before failure. While Zone II became smaller at about 30 ms before failure; at the same time, Zone III appeared directly under Zone I. Finally, visible cracks appeared immediately in Zone I and Zone III positions, while only hair-line cracks visible under the microscope in Zone II. This phenomenon indicates that there seems to be a competition between Zone II and A. Although no macro cracks were formed in Zone II, there were hair-line cracks could be observed; these hair-line cracks could still significantly accelerate the efficiency of fluid migration, which is of great concern in industrial hydraulic fracturing. In D30-120-B, a strain localization zone formed 10s before failure, and gradually developed until the specimen was fractured; and no competition phenomenon was observed.

**Figure 3.** (a) Water pressure versus time for specimen D30-120-A and D30-120-B; the starting point of the relative time was the moment when started the injection in step 3. (b) Failure statuses of the specimens; the left image was taken in macro-scale, and the right is taken in grain-scale; The red rectangle indicates the region of the strain localization analysis in figure 4.

![Figure 3](image1.png)

![Figure 4](image2.png)

**Figure 4.** Evolution of principal strain in two specimens. The bottom labels represent the relative time before failure, and the failure moment was defined as the first moment when the high-speed cameras recorded macro cracks. Point A-I represents the query points in 3.2.

3.2. Crack propagation in rock bridge

Take some query points on the strain localization zones of D30-120-A; there were 9 points in total, namely A-I. Once the crack appeared, the displacement on both sides of the crack will be
discontinuous, so the displacement jump at each query point were used to describe the crack propagation process. The displacement jump defined in this paper is the difference between the displacements of two points with a distance of 30 pixels (about 0.69 mm) centered on the query point. For the sake of brevity, only the displacement jump in the horizontal direction will be discussed here.

Figure 5 shows the displacement jumps in the horizontal direction within 5 seconds before failure. It can be seen that point A in Zone I showed about 7 microns displacement jump in 5 seconds before failure, while there were almost no displacement jumps at F-I in Zone II until about 2 seconds before the failure. Then the displacement jumps gradually increased, which indicated that the crack at Zone II began to propagate and the width gradually increased. However, the crack width at F-I began to decrease when approaching failure, and at the same time, the displacement jumps at the query point B-E in Zone III increased rapidly. In the end, the macro crack appeared at the location of the query points A-E; only extremely tiny cracks with a width of about 10 µm could be observed under microscope in Zone II, as shown in figure 5(b). The hair-line cracks in Zone II indicate that extremely tiny cracks will be initiated when the displacement jump reaches about 10µm. In addition, from the displacement jumps in the horizontal and vertical directions, combined with the slightly inclined shape of the crack, it can be obtained that the mechanism of these cracks is mainly tensile.

In order to further understand the competitive behavior in crack propagation, we extracted the displacement jumps in the last 50 ms before the failure. Among them, the time interval of data points is 3.3 ms, as shown in figure 6. The displacement jump in Zone II was greater than that in Zone III at 50 ms, and the displacement jump at both Zone II and Zone III continues to increase, maintaining competition. Approximately 10 ms before the failure, the displacement jump of Zone II reached its maximum value; then the displacement jumps in the horizontal and vertical directions decreased rapidly, which indicated the hair-line crack in Zone II was beginning to close. Meanwhile, the width of hair-line crack in Zone III increased rapidly, and finally, the macroscopic hydraulic-induced crack formed.

**Figure 5.** The displacement jumps in the horizontal direction within 5 seconds before the failure of D30-120-A at the query points. (a) The query points in Zone I and Zone III; (b) The query points in Zone II. The position of the query points is shown in figure 4. Gradually increased displacement jumps in the horizontal direction indicate the crack width increased.
Figure 6. The displacement jumps within 50 microseconds before the failure of D30-120-A at the query points. (a) The query points in Zone I and Zone III; (b) The query points in Zone II.

Summarizing the above phenomena that hair-line cracks appear when the displacement jump reaches a specific value (about 10 microns), and the induced crack propagation is the process of width increasing of these hair-line cracks. The competition, determining whether these hair-line cracks could develop to macro cracks, may occur within about 10ms before failure. It is worth noting that these hair-line cracks are different from microcracks, because although the width of the hair-line cracks is minimal, they are already connected to each other.

3.3. Crack morphology in the rock bridge
In the previous research[6], we used silicone oil as the fracturing fluid in tests, and the final hydraulically induced crack morphology is shown in figure 7(a). For comparison, figure 7(b) shows the crack morphology in current research. Although different fracturing fluids were used, the crack morphology was very similar. The induced cracks in the rock bridge all extend from the inner tip of one pre-existing flaw to the middle of the other pre-existing flaw; according to the classification of crack coalescence pattern proposed by Wong[15], they all belong to Category 7. The similar crack morphology indicates that the fracturing fluid may be not the main factor affecting the crack morphology under the current test conditions. In addition, through post-test observation, we found hair-line cracks in the two previous specimens in the rock bridge, which indicates that the competition between hydraulically induced cracks often occurs in the 120° rock bridge.

Figure 7. Crack morphology in the rock bridge. (a) Result of previous research[6]; (b) Results of current research. The dotted line indicates hair-line cracks.

4. Conclusions
This paper introduces and evaluates the method of directly observing hydraulic fracturing in grain-scale, and analyzes the strain localization, crack propagation and the morphology of hydraulically induced cracks in the 120° rock bridge of two granite specimens. The main conclusions are as follows:

(1) The method of spraying speckle directly on the granite surface could prevent extremely tiny cracks from being covered by paint, and the image quality assessment shows that the speckle pattern produced by this method performs well in DIC calculations.

(2) The strain localization occurs earlier than previously observed. Specifically, strain localization occurs for the first time approximately 20 seconds before failure under current test configuration.

(3) When the displacement jump reaches a specific value, hair-line cracks appear, and then the crack propagation is the process of crack width increasing.

(4) The competition between hydraulically induced cracks often occurs in 120° rock bridge under current test configuration; as a result of the competition, a hair-line crack near the inner tip of the flaws will eventually close.

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