Strain localization in hydraulic fracturing of granite specimens based on DIC method

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Abstract. Hydraulic fracturing is a crucial and widely-used technology in shale gas exploitation and enhanced geothermal systems, while the fundamental mechanisms of hydraulic fracturing are not comprehensively understood. This paper aims to promote the understanding of strain localization in hydraulic fracturing of granite specimens based on digital image correlation (DIC) method. Through a specially designed pressure enclosure, the hydraulic fracturing processes were captured by a high-speed camera. The strain localization phenomenon, evolution, and coalescence of SLZs in hydraulic fracturing were analyzed. Results show that obvious strain localization occurs before the specimen failure, which gradually develops into a continuous strain localization zone. With the evolution of SLZs, the specimen will be unable to bear the liquid pressure, and macro cracks occur at SLZs. The statistical data in the query region shows that the strain localization in hydraulic fracturing occurs earlier than previously thought, and the evolution of SLZs can be divided into steady, soaring, and fracture stages according to the changing trend. The coalescence of the patchy distribution SLZs occurs frequently throughout the evolution process of SLZs, and the coalescence of SLZs may be the cause of the increasing speed of evolution.

Keywords: hydraulic fracturing; strain localization; fracture process; digital image correlation; macro cracks

1. Introduction

Hydraulic fracturing is a crucial and widely-used technology in shale gas exploitation and enhanced geothermal systems, while the fundamental mechanisms of hydraulic fracturing, such as the physical process of crack initiation, propagation, and coalescence, are not comprehensively understood.

Experimental studies both in the laboratory and in the field have been conducted [1-5]; however, due to the limitations of experimental conditions, many studies primarily employed post-testing observation or indirect acoustic emission detection. Direct observation is helpful to understand the mechanism of rock failure [6-8], while because of the difficulties in applying hydraulic pressure and observing at the same time [9], only a few studies have attempted to use high-speed cameras to record hydraulic fracturing [10, 11]. Among them, Gonçalves da Silva and Einstein [1] improved a pressure enclosure, and performed experimental research on Barre granite. The related studies [12, 13] have provided a direct observation method of hydraulic fracturing, which could meet the requirements of optic tests.
DIC is an optical testing technique for quantifying the fracturing process in laboratory rock mechanics tests [8, 14, 15]. In our latest study [16], we have improved the test method based on Silva’s design, and successfully applied the DIC to hydraulic fracturing tests. Some new understanding of the crack mechanism, fracture process, and coalescence patterns of hydraulic fracturing are addressed. In the same period, Li and Einstein [17] studied the fracturing process of Barre granite and Opalinus Clay shale in hydraulic fracturing by using a combination of DIC and AE, and their study improved the understanding of fracturing process on a microscopic scale.

In the latest two studies on hydraulic fracturing based DIC, obvious strain localization was observed before the specimens were fractured [16, 17]. Strain localization is a phenomenon in which the high-strain concentrate in a narrow zone and continues to develop before the loaded material is destroyed. Strain localization occurs before macro cracks [6, 8, 15], which is considered to closely relate to hydraulic crack evolution [16]. However, the strain localization in hydraulic fracturing has rarely been reported.

This paper aims to address the knowledge gap of the strain localization in hydraulic fracturing of granite specimens based on DIC method. The strain localization phenomenon, evolution and coalescence of SLZs in hydraulic fracturing are analyzed, which could contribute to the fundamental understanding of hydraulic fracturing.

2. Methodology
This section only briefly introduces the method, and the specific details of this experiment can be referred to Zhao, Xing [16].

2.1. Specimen preparation
The material adopted in this study was named Befast granite, which was obtained from Pingyi County, Shandong Province, China. A previous study by the Pingyi County Land and Resources Bureau [18] revealed that the mineralogy consists primarily of potassium feldspar (content 45.37–51.5%, grain size 3–5 mm), quartz (content 21.31–26.51%, granularity 1.5–2.5 mm), plagioclase (content 21.64–24.33%, granularity 1.5–3.3 mm) and biotite (content 3.92–5.41%). With medium and coarse-grained granite structure and without obvious plaques, the mineral particles are relatively uniform, mostly between 2 and 5 mm. As shown in figure 1(a), Specimens were first cut to dimensions of 20 mm×75 mm×150 mm, and the double pre-existing flaws were cut with a water-jet. The geometry of the pre-existing flaws was 13 mm×1 mm and the length of the rock bridge was 11 mm. The rock bridging angle was 0°, 30°, 60°, 90°, 120°, 150°, and 180° respectively, and there were two specimens in each bridging angle. In order to obtain images with high entropy of information through the high-speed camera, it is necessary to spray speckles on the surface of the specimens, as shown in figure 1(b). First, full spray a thin layer of white paint, and then spray random black speckles. For convenience, the specimens were numbered, for example, Hy-30-90-A means that the bridging angle was 90°, and the letters ‘A’ and ‘B’ represent groups A and B, respectively.
2.2. Test setup and procedures

The hydraulic fracturing of this experiment was performed by a pressure enclosure, a uniaxial loading machine, and a manually controlled hydraulic pump, as shown in figure 2(a). The specimens were initially loaded to 20 MPa in the vertical direction, and then the vertical load was maintained while fracturing fluid (Mobil Univis N 46, viscosity 46 mm²/s@40°C) was injected by the manually controlled hydraulic pump. The hydraulic loading rate was controlled at approximately 0.5 MPa every 30 s until the specimen was fractured. A high-speed camera (Motion pro Y7 S3) was adopted to record the fracturing process, and the shooting rate was set to 300 FPS with a resolution of 512×1016.

Figure. 1 (a) Geometry of the specimens; (b) Speckles on the surface of the specimens [16].

Figure. 2 (a) Schematic of the loading system and test setup; the uniaxial loading machine was a JXYB605C instrument made by SUNS; the pressure enclosure was modified based on Gonçalves da Silva and Einstein [1]. (b) Loading conditions of the specimens; the entire inner area of the rubber O-ring (the pressurized zone) was subjected to hydraulic pressure from the fracturing fluid.

Note that during the loading process, the entire area surrounded by the rubber O-ring was subjected to hydraulic pressure by the fracturing fluid, as shown in figure. 2(b). Besides, the rubber ring exerted a pressure perpendicular to the specimen and a transverse friction force. Related studies have shown that such effects are acceptable [19], this device is feasible for studying hydraulic fracturing [1, 16, 17, 20].
2.3. DIC method and processing parameters
DIC method is widely used in the experimental study of rock mechanics, while as an optical testing method, the DIC processing results are related to the image quality and processing algorithm. In this study, the image quality was improved by spraying suitable speckles on specimens and optimizing shooting conditions. Ncorr [21] was used to process images taken by high-speed cameras, which has been proved to be effective in previous research [15, 16, 20]. For details of speckle improvement measures and the noise errors, please refer to our published papers [16].

Processing parameters also affect the results. According to the Ncorr algorithm, the displacement obtained by this code was actually the average displacement of the subset, and satisfies the first-order deformation. The strain was obtained by numerical differentiation based on the displacement field. While the numerical differential algorithm is sensitive to error. In order to reduce the effect of noise on the strain field, the Strain Radius parameter was set to an appropriate value, and the strain was obtained by fitting the least square plane of displacement field within the radius. In this study, unless otherwise specified, the Subset Radius was 12 pixels, the Subset spacing was 0, and Strain Radius was 10 pixels.
3. Results
This part analyses the strain localization in hydraulic fracturing, mainly taking the specimens with 90° rock bridge angle as examples. The strain analyzed in this paper refers to the principal strain ($\varepsilon_1$). Note that this experiment assumed that the specimens were 2-D conditions, that is, the behavior of the specimens was consistent throughout the thickness, and the influence of out-of-plane strain can be ignored when calculating the principal strain. Since the thickness dimension of the specimens was relatively small compared to the width and height dimensions, it was a reasonable and acceptable assumption.

In this part, unless otherwise stated, the term ‘flaw’ refers to a pre-existing flaw created artificially by a water-jet, the term ‘failure’ refers to the specimen was fractured by hydraulic fluid, and the term ‘crack’ or ‘macro crack’ refers to a visible crack observed after the specimen was fractured.

3.1. Strain localization in hydraulic fracturing
Similar to the uniaxial compression tests, we observed strain localization in the hydraulic fracturing test before macro cracks initiation. As shown in figure 3, at 10 ms before failure, significant SLZs can be observed in the strain field, and the distribution position of SLSs was consistent with the macro cracks after failure. The SLZs were distributed at the flaw tips and extend a distance to both ends of the specimens. The extension length on the outside of the flaw tips was greater than the extension length on the inner side. With the extension, the width of SLZ became smaller and smaller, and the value of principal strain also decreased. Note that the strain value here may be affected by the DIC calculation parameters, this part will be discussed in Section 4. In general, the shape of SLZs was similar to macro cracks, but they were not completely consistent. For example, in figure 3(b), SLZs appeared to be more tortuous than the cracks. Before the failure, the width of the SLZs near the crack tip was about 3-4 mm, and the length of the longitudinal extension was far from reaching the end of the specimen. Specifically, macro cracks are formed at SLZs, but far from the pre-existing flaws, the macro cracks may be formed at the flash moment of failure without strain localization before failure. The strain localization is considered to be the failure process before the macro crack of the rock, which indicates that the process zone of hydraulic fracturing cracks only exists in a small range.

Figure 3 Specimens after failure and the strain field in 10 ms before failure.
3.2. Evolution of SLZs in hydraulic fracturing

The fracture process of hydraulic fracturing has not been fully understood, while the evolution of SLZs is an important way to understand the fracture process. As shown in figure 4, there was no significant SLZ 60 s before the specimen was fractured. In the 10s before the failure, sporadic high-strain spots appeared around the pre-existing flaws; as shown in the blue rectangle in figure 4(b), the wing-shaped SLZ can be seen faintly. At 2 s before the failure, SLZs can be clearly seen near the pre-existing flaws on the left, while the strain localization near the right flaw tips was not obvious at this time. At 100 ms before the failure, obvious SLZs appeared near both flaws tips. After that, the evolution speed of SLZs accelerated, the strain value in SLZs increased rapidly, and the range became wider. While the length of SLZs in vertical direction did not change significantly between 10 s and 50 ms. At 3.3 ms before the failure, the SLZs near the pre-existing flaws were connected as a whole and extended a small distance to both ends of the specimen. After that, macro cracks, which caused the specimen failure, appeared at the location where SLZs were located. Because the shooting rate was not high enough, the process of macro crack initiation and propagation was not recorded, but it could be judged that the growth speed was extremely fast (may exceed 10 m/s).

![Figure 4](image)

**Figure. 4** Evolution of SLZs in Hy-30-90-A. The t represents the time before failure, for example, t = 250 ms means the specimen was fractured by liquid pressure after 250 ms. Note: t = 0 was not the exact moment of specimen failure, but the first moment when visible crack was recorded by the 300 FPS high-speed camera.

To better analyze the strain localization in hydraulic fracturing, we selected a query region, as shown in the red rectangle in figure 4(h), and analyzed its evolution process through statistical indicators. The results are shown in figure 5. Elastoplastic rock mechanics believe that the material will enter the plastic state after the strain exceeds a certain value. In this paper, 1.5% was selected as the threshold strain value, and the strain of the query point exceeded this value were considered to enter the plastic state. For ease of description, the number of points was represented by Count. Note that this threshold
was determined by experimentation and it may be some extent subjectivity. In addition, we chose the coefficient of variation \( C_v \) to represent the discreteness of the strain field in the query region. The \( C_v \) in statistics describes the degree of variable deviation from the mean, so that the increase in the \( C_v \) indicates that the degree of strain dispersion in this area increases, that is, the distribution range of SLZs expands, or the strain value in SLZs becomes larger.

As shown in figure 5(a), under the linear coordinate system, it can be seen intuitively that the Count changed little before 0.5 s, while raised almost vertically when approaching failure. The \( C_v \) increased slowly before approaching failure and then surged rapidly. After taking the logarithm of time, as shown in figure 5b, it can be seen that obvious stages in the changing trend of the two indicators, which can be divided into steady, soaring, and fracture stages according to the changing trend.

About 30 ms before the failure, growth of the Count and \( C_v \) was relatively stable, and \( C_v \) increased almost linearly at this stage. In the early stages of this stage, almost no point strain exceeded the threshold, and in the later stage, the Count began to increase slowly. It shows that the evolution of the SLZs is a continuous process that the distribution range and strain value gradually increase during the process. Compared with figure 4, the SLZs can not be seen from the strain field cloud diagram until 10s before the failure, while the data in figure 5(b) indicates that the strain localization may have occurs earlier than previously thought. It is possible that the value and change rate of the strain field at this stage is relatively slow, and the noise masking causes the difference between the SLZs and the surrounding strain to be insignificant, which makes it difficult to visually see the SLZs from the strain field cloud diagram.

Between 30 ms and 3.3 ms, both indicators soared. At this stage, the strain increased rapidly and concentrated in the SLZs, and a large number of points entered the plastic state, indicating that the damage degree of the query region soared, and could no longer bear the liquid pressure soon. Within the next 3.3 ms, macro cracks occurred, and the count became 2.5 times the previous. As shown in figure 6(b), the accumulated count before macro crack propagation was only about one-third of the count after failure. It is considered that the damage degree of the specimen only accounts for a small part during the evolution of the SLZs, but this part of the damage causes the specimen to be unable to bear the liquid pressure, and then the unstable propagation of macro cracks occurs in last serval milliseconds.

![Figure 5](image)

**Figure. 5** The total number of points whose strain value exceeded 0.015 and the \( C_v \) in the query region. (a) The time is linear; (b) The time is logarithmic. The query region, as shown in the red rectangle in (a) and figure 4(h), contains \( 76 \times 190 = 14,440 \) pixels. The calculation formula of the \( C_v \) is shown in (a), where \( \sigma \) is the standard deviation of the principal strain values of all the points in the query region and \( \mu \) is the average value. The a-h in (b) represents the moment in figure 4. To make sense in logarithmic terms, we changed the horizontal at time \( t=0 \) to 1.
3.3. Coalescence of SLZs

During the evolution of SLZs, the strain gradually increased and the area continued to expand. A notable feature of this process is the coalescence of the patchy distribution SLZs. As shown in Figure 4, during the evolution of SLZs in the blue rectangle (Figure 4(b)), there is an obvious SLZs coalescence phenomenon. Especially before 250 ms, the patchy distribution SLZs gradually connected with others. To better understand the coalescence of SLZs after 250ms, Figure 6 uses contour maps to represent the strain field of the query region previously mentioned. It can be seen that two relatively independent "peaks" in the strain field at 250 ms, and then the strain gradually increased, finally the two "peaks" coalesced together at 50 ms. During the process from 250 ms to 50 ms, the length of the SLZs was almost unchanged. While after 50 ms, the length of SLZs began to become longer. Concerning Figure 5, both the Count and $C_v$ increased rapidly after the coalescence. It is considered that the coalescence of SLZs is the trigger for accelerated damage of the specimen, and cause the specimen to fail to withstand the liquid pressure and macro crack initiation.

4. The influence of DIC calculation parameters on strain localization

Using DIC in hydraulic fracturing tests, a topic worth discussing is that the DIC calculation parameters will affect the results. The DIC program used in this study Ncorr [21], and part of the parameters of Ncorr affect the calculation efficiency, for example, a higher spacing could reduce the computational burden, while it also reduces the density of data points. All parameter settings in this study were aimed at improving the accuracy of the calculation to obtain the most reliable results even with higher computational cost. However, the result still cannot avoid the influence of DIC calculation parameters. The most critical parameter is the Strain Radius ($r_s$) in strain calculation, whose selection requires balanced the resolution and noise.

As shown in Figure 7, the strain field obtained by using different $r_s$ at 250 ms are different. Obviously, a larger $r_s$ will result in a small strain value, and a smaller $r_s$ will result in a large strain value. Although the overall distribution trend of the strain field obtained by using different $r_s$ is consistent, the contour of SLZs becomes more blurred when $r_s$ increases, and it seems to be over-smoothed. While a too small $r_s$ will cause the strain field to appear noisy. Overall, the distribution of SLZs is less affected by the calculation parameters, and the strain value of SLZs is significantly affected by DIC calculation parameters. The parameter selected in this paper is a relatively balanced value. It is representative to analyze the distribution, evolution, and coalescence of SLZs, but it is worth noting that the strain values mentioned in this paper are not necessarily accurate.
5. Conclusions

This paper aims to promote understanding of the strain localization in hydraulic fracturing of granite specimens based on DIC method, which could contribute to the fundamental understanding of hydraulic fracturing. The strain localization phenomenon, evolution and coalescence of SLZs in hydraulic fracturing are analyzed. The main conclusions are as follows:

- Obvious strain localization occurs before the specimen failure, which gradually develops into a continuous strain localization zone. With the evolution of SLZs, the specimen will be unable to bear the liquid pressure, and macro cracks occur at SLZs.
- The statistical data in the query region shows that the strain localization in hydraulic fracturing occurs earlier than previously thought, and the evolution of SLZs can be divided into steady, soaring, and fracture stages according to the changing trend. The steady stage lasts for a long period and the evolution rate is slow; the soaring stage only lasts a few tens of milliseconds, and the evolution speed of SLZs is extremely fast; in the fracture stage, macro cracks appear in several milliseconds.
- The coalescence of the patchy distribution SLZs occurs frequently throughout the evolution process of SLZs, and the coalescence of SLZs may be the cause of the increasing speed of evolution.

Overall, the strain localization in hydraulic fracturing is the precursor of macro crack initiation and propagation, which is the process of specimen damage accumulation and reflects the physical process of hydraulic fracturing. Due to the limited accuracy of current experiments, the relationship between the evolution of SLZs and microcracks requires further microscale experimental studies.

Datasets related to this paper can be found at http://dx.doi.org/10.17632/4fjy5c4ng3.1, an open-source online data repository hosted at Mendeley Data [22].

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