Experimental study of the shear failure of granite based on full-field-strain monitoring using digital image correlation

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Abstract. Shear failure is a common failure form of engineering rock mass. As a typical engineering rock mass, granite is widely present in reservoir dams, mine slopes, mine roadways, and other projects in China. Therefore, in this study, the direct shear testing of granite was conducted by taking granite as the research object and using an RLW-3000 shear creep biaxial testing machine. The complete process of shear failure was monitored by using digital image correlation non-contact full-field strain measurement technology, and the spatial evolution of the shear-failure process of granite was studied to reveal the shear-failure mechanism of the material. Results show that the strain nephogram of granite during shear failure could be divided into four stages: uniform strain distribution, strain-localization band generation, strain band expansion, and strain-band expansion acceleration. Strain localization is an important feature of the shear failure of a rock mass; it is characterized by the uneven distribution of strain on the surface of the specimen and the appearance of strain-concentration bands, which indicate the initiation and propagation of macroscopic shear cracks. According to the principal strain–time curve obtained, the principal strain curve exhibits a sharp upward trend when strain localization occurs, and the stress is approximately 76%–79% of the peak stress. The space–time evolution characteristics of the above strain reflect the spatiotemporal variations in the stress field on the surface of the specimen, and the spatial extension of the banded strain-concentration area corresponds to the formation and development of shear failure in the rock. Therefore, the direction of the spatial development of shear microfractures can be predicted by capturing the spatial development of strain-localization bands. The results of this work provide an important theoretical basis and guidance for reservoir dam seepage prevention, highway and mine slope support, and goaf face instability early-warning systems.

1. Introduction
Rock is encountered in most underground engineering work. In geotechnical engineering, most rocks cracks are shear cracks, and the main failure mode is shear failure, which is caused by the stress state and prevailing geology [1]. The shear failure of a rock mass could cause accidents, such as the sliding of mine slopes [2, 3], destabilization of the working faces of a goaf [4], and gas outbursts in downhole operations [5], all of which could lead to casualties and loss of property and equipment. Therefore, research into the mechanism of the evolution of shear cracks in a rock mass is of great theoretical
significance and practical value to reveal the destabilization mechanisms of engineering rock masses and prevent geological disasters.

Scholars generally use acoustic emission, infrared thermal radiation, computed tomography (CT), and other techniques to study the mechanism of rock shear fracture. Using acoustic emission monitoring technology, for instance, Liu et al. [6] conducted rock shear-failure experiments under different normal forces, studied the distribution and expansion mode of fractures, and obtained the acoustic emission b-value precursory characteristics of rock instability. Wu et al. [7] monitored the change in temperature during rock shear fracture by using an infrared thermal imager to explore the thermal mechanical coupling effect and fracture precursor phenomenon during shear fracture. Lei et al. [8] conducted CT scanning analysis of the triaxial shear process of undisturbed expansive soil and combined their findings with CT data and images to illustrate that the shear-failure process involves the expansion and evolution of internal fractures.

Digital image correlation (DIC) technology presents the advantages of non-contact analysis, high measurement accuracy, and robustness to high-temperature, high-pressure, and vibration impact-affected environments. It is widely used in geomechanics-related experimental research. Spatiotemporal variations in rock strain and the effective strain evolution curve can be obtained by the DIC technique. Ma et al. [9] developed a DSCM system that was found to be especially suitable for measuring rock failure processes. Tang et al. [10] conducted an experimental study on the fracture of granite three-point bending notched beams under a cyclic load by using the DIC and acoustic emission techniques; specifically, the authors determined the strain field, displacement field, and fracture process zone at the crack tip by DIC. Zhang et al. [11] combined DIC and infrared thermography to monitor sandstone specimens with different fissure inclinations under uniaxial compression and then analyzed the evolution and variation of full-field information during deformation and fracture. Song et al. [12] used the DIC method to study frictional sliding in rock subject to creep-stick slip. Using the DIC method, Wang et al. [13] conducted triaxial loading tests based on the stress path applied when mining a coal and rock mass and studied the fracture network structure and surface fracture evolution process of this mass. Sun et al. [14] recorded and investigated the strain field evolution and crack generation, propagation, and penetration processes of sandstone treated at different temperatures during Brazilian splitting tests by using DIC. However, although several scholars have made many valuable contributions to rock fracture research by using DIC technology, most data are only analyzed from the perspective of spatial variation. In addition, the strain information of the DIC analysis area is affected by the joint action of strains in the X- and Y-directions; unfortunately, most scholars focus only on the independent analysis of single-directional strain and ignore the simultaneous effects of strain in different directions.

In the present work, the DIC technique is used to monitor the direct shear test complete test process in a non-contact manner. Three parameters, namely, the spatial strain nephogram, shear–load curve, and principal strain–time curve, are introduced to explore the strain evolution in granite undergoing shear failure in the X- and Y-directions and explore the spatiotemporal strain evolution characteristics of the rock. Observations of the main strain nephogram and the mechanisms of the change in acceleration of the main strain curve as the shear load reaches the peak value are then explained according to the characteristics of these three parameters when the local stress changes to predict the strain-localization phenomenon of shear fracture. The results can reveal the spatial development of the strain-localization band and elucidate the shear-failure mechanism of granite.

2. Experimental design

2.1. Specimen preparation

Fine-grained granite from Laizhou, Shandong Province, was selected and processed into six granite blocks measuring 150 mm × 150 mm × 35 mm. We ground the upper and lower ends of the specimens to reduce their unevenness to less than 0.05 mm and the length error of all sides to less than 0.3 mm. The specimens were labeled from WJQHG-1 to WJQHG-6 (Figure 1(a)).

We sprayed white matte paint evenly on the observation surface of each test piece. The white paint was allowed to dry, and a black marker was used to mark sub-intervals randomly by using three to four black spots (Figure 1(b)).
2.2. Test equipment

The RLW-3000 shear creep biaxial testing machine (Changchun Chaoyang Testing Instrument Co.) was selected for this study (Figure 2). This instrument can provide a maximum axial force of 3000 kN and a maximum tangential force of 1000 kN. The digital image acquisition component of the DIC monitoring system consists of two industrial cameras and two LED cold light sources (Figure 2). The VIC-3D measurement system was selected as the image analysis component of the DIC monitoring system (Figure 2).

The VIC-3D measurement system was optimized and upgraded to enhance its capabilities compared with those of traditional digital image analysis software. The strains in the X- and Y-directions were investigated by the unique algorithm of the VIC-3D measurement system to give the main strain field characterizing the strain in the area of interest. Figure 3(a) shows the main strain cloud diagram of specimen WJQHG-6 in the strain-band expansion stage, while Figures 3(b) and (c) show the strain cloud diagram of specimen WJQHG-6 in the X- and Y-directions. The calculated main strain field can reflect the strain in the X- and Y-directions simultaneously, thereby overcoming the deficiency of single directionality in the strain field when describing rock localization effects. The algorithm can also comprehensively characterize the extension of the shear zone in two directions and the development of strain localization on the observation surface. Analysis of the spatial variation of the principal strain...
nephogram can help investigate the evolution characteristics of multi-directional strain fields during the shear failure of granite.

Figure 3. Strain nephogram of specimen WJQHG-6.

2.3. Test process

The acquisition angles of two industrial cameras were adjusted before the experiment, and a CSI correction board was used to correct the two cameras. LED white lights were also placed on both sides to provide a stable cold light source and capture the digital speckle image accurately. The acquisition rate of the VIC-3D measurement system is two images per second. The load in the vertical direction was increased to 1000 N, and then a shear load in the horizontal direction was applied to the specimen. The cross-head displacement rate was 0.15 mm/min. Timing synchronization was applied across all equipment to ensure temporal correspondence. The testing machine and VIC-3D measurement system were operated at the same time until the specimen failed in shear, whereupon the two devices were stopped.

3. Spatial evolution of the strain nephogram during the shear-failure process

The experimental results show that the final fracture forms of the six specimens are similar. Thus, specimen WJQHG-6, which revealed the most representative shear fracture after final failure, was selected for further study. Figure 4(a) shows the time–shear load curves of WJQHG-6 during shear failure. Six typical identification points are selected, as shown in Figure 4(a), according to the different rock failure stages: compaction stage (identification point 1), elastic stage (identification points 2 and 3), plastic stage (identification points 4 and 5), and post-failure stage (identification point 6). The area of the principal strain was determined according to the form of the ultimate fracture and crack extension range to analyze the strain evolution characteristics of the shear-failure process (Figure 4(b)).

Figure 4. Identification points and observation area of specimen WJQHG-6

Figure 5 shows the principal strain nephogram of WJQHG-6 corresponding to each identification point. The nephogram could be divided into four stages according to the evolution of the strain field: (1) Uniform strain distribution stage (identification points 1 and 2): Under the action of a shear load, the
specimen undergoes compaction. During this time, the original open structural plane and microcracks are gradually compacted and closed, and the strain nephogram exhibits a “porphyritic” random distribution (Figure 5(a)). (2) Strain-localization band generation stage (identification points 2 and 3): As the shear force increases, the specimen reaches the elastic stage, the stress curve retains its original linear slope, and the microcracks in the specimen demonstrate further development. The strain nephogram at identification points 2 and 3 shows a strain-concentration area on the left side of the analysis area (Figure 5(b)). As the applied shear load increases, this strain-concentration area evolves into a strain-localization band (Figure 5(c)), and cracks form under this area (Figure 6(a)). (3) Strain-band propagation stage (identification points 3–5): The specimen remains in the elastic stage. According to the strain nephogram in Figures 5(c) and 5(d), the red strain-localization band initiated on the left expands continuously along the direction of the shear force, the crack inside the specimen is in a stable state of propagation, and a crack develops at the red strain-localization band outside the specimen (Figure 6(b)). (4) Accelerated strain-band growth stage (identification points 5 and 6): As the shear–load approaches its maximum value, the crack inside the specimen accelerates along the direction of extension of the strain-localization band. When the peak shear is reached, the crack penetrates the rock sample and forms a macroscopic shear fracture surface (Figure 6(c)). The shear–load curve then drops sharply; when the strain-localization band of the cloud image extends to identification point 5 (Figure 5(e)), it stops extending. This point represents the final state of the strain-localization band, which is maintained until the peak load is reached, and the cloud image expands (Figure 5(f)).

Analysis of the evolution of the principal strain nephogram of granite specimens under shear failure indicates that the strain in the observation area on the specimen surface gradually evolves from a uniform distribution to a concentrated area including crack initiation at the left-hand loaded end. A strain-localization band is subsequently generated in the strain-concentration area and extends along the direction of the shear load. Strain localization, an important feature of the shear failure and instability of a rock mass, is characterized by the uneven distribution of local strain on the specimen surface, which could initiate and propagate macrocracks

!(a) Identification point 1 ![b) Identification point 2](image)

!(c) Identification point 3 ![d) Identification point 4](image)

!(e) Identification point 5 ![f) Identification point 6](image)

**Figure 5** Changes in the main strain field of specimen WJQHG-6.
4. Variation of the principal strain curve under shear failure

The foregoing discussion clearly shows that strain localization is an important feature of the shear-failure instability of a rock mass and that the spatial extension of banded strain-localization regions indicates the formation and development of internal shear-failure. Thus, prediction of shear microfractures may be achieved by evaluating the spatial development trend of the strain-localization band.

Figure 7 shows the shear load and principal strain–time curve for specimens WJQHG-2, WJQHG-4, and WJQHG-6. According to the mechanism behind the changes in the principal strain–time curve and the evolution of the spatial cloud map, the principal strain–time curve could be divided into four stages: (1) Initial stage: No obvious change is noted in the principal strain curve, and the principal strain tends to approximate 0, which indicates that the strain distribution is relatively uniform. At this point, the principal strain nephogram presents a “patchy” random distribution (Figure 5(a)). (2) Microcrack acceleration stage: The principal strain–time curve rises slowly, thereby indicating that the strain distribution in other regions remains relatively uniform except at the left-hand strain region (Figure 5(b)). (3) Acceleration stage: The increase in principal strain shows acceleration at point 3. Figure 8 shows the principal strain nephogram at the acceleration points of specimens WJQHG-2, WJQHG-4, and WJQHG-6. The nephograms show red strain-localization regions developing at the acceleration points of the three specimens. As the curve continues to rise, the strain-localization regions extend in the form of strips (Figures 5(c)–(e)). (4) Sudden increase stage: The principal strain abruptly increases to a peak value, and the granite is completely destroyed under shearing action (Figure 5(f)).

The initial stage, microcrack acceleration stage, acceleration stage, and sudden increase of the principal strain observed during the direct shear-failure process of granite correspond to the four-stage characteristics of the strain nephogram. Specifically, the appearance of the acceleration point of the principal strain curve marks the beginning of the acceleration stage and indicates that the strain band is about to expand.
The strain localization is quantified by calculating the shear stress values and percentages of peak stress at the acceleration points of specimens WJQHG-2, WJQHG-4, and WJQHG-6 (Table 1) on the basis of the established strain–load relationship. The shear stresses at the acceleration points of the strain localization of specimens WJQHG-2, WJQHG-4, and WJQHG-6 are 47.2, 47.6, and 47.2 MPa, respectively, which account for 75.6%, 77.9%, and 78.8% of the peak load. Lei et al. [15] found that compressive tensile fractures are dominant in the low-stress stage (<80% of the peak strength) of fine-grained granite. Under greater levels of stress, shear cracking becomes dominant with increasing stress. Shang [16] and other researchers used the acoustic emission technique to monitor intact rock samples under shear and demonstrated that the stress value at which shear crack formation is initiated is approximately 80% of the peak strength. The experimental results show that the peak stress under shear is 75.6%, 77.9%, and 78.8%, respectively, when strain localization occurs; these values are close to 80% of the critical peak stress, at which point tensile failure evolves into shear failure. Therefore, the acceleration point obtained from the principal strain curve may be regarded as the precursor to shear failure, that is, the onset of strain localization indicates that shear failure is imminent.

### Table 1. Ratio of peak stress at the acceleration point of different specimens

| Specimen | Stress at the acceleration point (MPa) | Peak load (MPa) | Percentage of peak stress (%) |
|----------|----------------------------------------|-----------------|-------------------------------|
| WJQHG-2  | 47.2                                   | 62.4            | 75.6                          |
| WJQHG-4  | 47.6                                   | 61.1            | 77.9                          |
| WJQHG-6  | 47.2                                   | 59.9            | 78.8                          |

### 5. Conclusion

1. The strain nephogram of granite during direct shear failure first shows a uniform distribution followed by a small area of strain concentration at the damage location. This strain-concentration area continues to expand to form a banded shear zone. The development of strain clouds can be divided into four stages, namely, uniform strain distribution, strain-localization strip generation, strain-band growth, and strain acceleration. These stages can describe the initiation, propagation, and penetration of shear-failure cracks in spatial terms.
2. The principal strain curve obtained during the direct shear failure of granite can quantitatively describe the spatiotemporal evolution characteristics of the strain nephogram. The curve can be divided into the initial stage, the microcrack acceleration stage, the acceleration stage, and the sudden increase stage, which correspond to the four-stage characteristics of the strain nephogram. Entry into the acceleration stage means the strain-localization band has been generated and is beginning to expand.
3. Strain localization is an important feature of the direct shear failure of granite. When the strain-localization area begins to expand, a strain-concentration band appears in the strain cloud diagram and the upward trend of the acceleration point appears in the principal strain curve. The shear stress at this point is approximately 76%–79% of the peak stress. The Above phenomenon can be used as a precursory indicator of rock shear failure and is of great significance to the early warning of rock shear failure.

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11th Conference of Asian Rock Mechanics Society

IOP Conf. Series: Earth and Environmental Science 861 (2021) 022061
doi:10.1088/1755-1315/861/2/022061

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Acknowledgments
This study is supported by the National Natural Science Foundation of China (Grant Nos. 51804122 and 51904105), the Hebei Province Graduate Innovation Funding Projects (Grant Nos. cxzzbs2020136 and cxzzbs2021098), and the Postgraduate Innovation Projects of North China University of Technology (Grant Nos. x2017024 and x2018067).