Evolution of the deformation field and earthquake fracture precursors of strike-slip faults

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Abstract: Seismic hazard analysis is gaining increased attention in the present era because of the catastrophic effects of earthquakes. Scientists always have as a goal to develop new techniques that will help forecast earthquakes before their reoccurrence. In this research, we have performed a shear failure experiment on rock samples with prefabricated cracks to simulate the process of plate movement that forms strike-slip faults. We studied the evolution law of the deformation field to simulate the shear failure experiment, and these results gave us a comprehensive understanding of the elaborate strain distribution law and its formation process with which to identify actual fault zones. We performed uniaxial compression tests on marble slabs with prefabricated double shear cracks to study the distribution and evolution of the deformation field during shear failure. Analysis of the strain field at different loading stages showed that with an increase in the load, the shear strain field initially changed to a disordered-style distribution. Further, the strain field was partially concentrated and finally completely concentrated near the crack and then distributed in the shape of a strip along the crack. We also computed coefficients of variation (CVs) for the physical quantities $u$, $v$, and $\varepsilon_{xy}$, which varied with the load. The CV curves were found to correspond to the different loading stages. We found that at the uniform deformation stage, the CV value was small and changed slowly, whereas at the later nonuniform deformation stage, the CV value increased sharply and changed abruptly. Therefore, the precursor to a rock sample breakdown can be predicted by observing the variation characteristics of CV statistics. The correlation we found between our experimental and theoretical results revealed that our crack evolution and sample deformation results showed good coupling with seismic distribution characteristics near the San Andreas Fault.

Keywords: strike-slip fracture; digital image correlation method; evolution of deformation field; rock failure; fracture precursor

1. Introduction
The surface and interior of the Earth are continuously affected by geodynamic processes, which are the major cause of complex tectonic movements. The movement and deformation of the Earth’s crust are comprehensive manifestations of the geodynamics on the Earth’s surface (Teng JW, 2001). Earthquakes induced by plate movement sometimes create catastrophic natural disasters, such as landslides, tunnel failure, and mine collapse, which are attributed to rock deformation and failure (Zhang YS, 2018). The main concern in the previous era (as well as in the current era) was to develop new techniques that would help minimize megastructural damage caused by earthquakes. It was common practice to consider that the rock or rock structure would undergo damage through a long process of accumulating stress and that because of these processes, instability would occur in the Earth’s crust within a short span of time. These two processes are essential to clearly understand the phenomenon of instability and the mechanism governing the instability of the Earth’s crust.

The scientific community is divided into two schools of thought related to the study of rock deformation evolution. The first has explored the evolution of the deformation phenomenon by studying the different morphological orientation patterns of cracks under laboratory conditions. Furthermore, some have used a statistical attribute to elaborate on rock failure and the deformation evolution mechanism. For example, Zhao YH et al. (1995) carried out uniform pressure experiments on hexagonal marble specimens with prefabricated central slit cracks to explore the relationship between the evolution of microcracks and loading. They also compared their results with the development process of tensile basins at the end of the Eryuan–Heqing Fault in Northwest...
Yunnan. Li YP et al. (2005) experimentally studied the growth of wing cracks and secondary cracks in marble with prefabricated cracks. They found that the direction and geometry of the prefabricated cracks determined the types of wing cracks and secondary cracks that developed. Some scholars have designed rock sample models and explored the growth and development of microfractures in the process of sample destruction. Dyskin et al. (2003) explored the three-dimensional crack growth of samples within internal cracks by using mortar and resin under uniaxial compression. Ma SP et al. (2005) observed structural changes in circular rock pores by using the digital speckle correlation method. Choi and Shah (1997) used the digital image correlation method (DICM) to obtain the displacement field state of the entire field when concrete was destroyed, and they analyzed the axial and horizontal displacement field deformation information. Ma SP and Zhou H (2008) used statistical methods to analyze data on rock structure failure and obtained statistics on the maximum shear strain field (standard variance $S$) with the evolution of loading. Wang XB et al. (2015) used the DICM to conduct uniaxial compression experiments on sand samples with different water contents, and they studied the influence of water contents on the maximum shear strain field.

The approach of the second group to estimating the deformation evolution phenomenon is to observe the actual fault zone directly to calculate its deformation field or restore its topographic and geomorphological characteristics. Many scholars (e.g., Wang H et al., 2013; Xie XP et al., 2019) used the remote-sensing interferometric synthetic aperture radar (InSAR) method to observe the fracture of an actual fault zone. Wang H et al. (2013) used InSAR data to study the Xianshuihe Fault in the Western Sichuan area to obtain an apparent deformation rate map of the active fault, and they sorted the transparent deformation gradient related to the fault.

Different scholars have done intensive work with the traditional global positioning system (GPS) monitoring method to obtain actual fault zone deformation data. Numerous scientists (Jiang GY et al., 2015; Bayer, 2006) have done comprehensive work to identify the evolution of deformation by using a GPS monitoring technique to elaborate on an active seismic zone of concern, with special consideration given to the three-dimensional slip rate of the fault and the residual slip of the earthquake. Li WH (2017) used high-precision GPS monitoring data from 2010 to 2015 to obtain the horizontal velocity field of the current crustal movement based on different reference data in the San Andreas Fault and its neighboring area. Lv ZP et al. (2014) calculated the velocity field of the eastern margin of the Qinghai–Tibet Plateau based on the velocity field results of the GPS station in China. Jiao JS et al. (2017) used coseismic GPS data from the Wenchuan earthquake to analyze the coseismic strain characteristics of the earthquake.

As shown in the previous discussion, comprehensive work has been done on rock deformation and its failure mechanism by considering the internal law of crack evolution under laboratory conditions. Likewise, intensive effort has been made by different researchers to evaluate seismic activity through field observations. However, only a few researchers have combined the experimental and actual observations. Many ambiguities must still be resolved to properly understand the crack formation and evolution process. To understand rock deformation and the failure phenomenon, comprehensive comparative research is required to understand the two main categories of the rock deformation mechanism under laboratory conditions and the deformation mechanism of a fault through natural domain observations.

In this research, we have attempted a comprehensive elaboration on the distribution characteristics of the deformation field in actual strike-slip fracture formation by conducting marble failure experiments with prefabricated double-shear cracks under laboratory conditions. The incremental displacement fields $u$ and $v$ and the incremental shear strain $\varepsilon_{xy}$ of samples at different loading stages were calculated by the DICM, and the distribution and evolution characteristics of the shear strain fields were analyzed. Using the coefficient of variation (CV) to reflect the degree of data dispersion in the statistics, we calculated the CV values of the physical quantities $u$, $v$, and $\varepsilon_{xy}$ at different loading stages and analyzed the fracture precursor characteristics of the samples at different CV curves.

2. Digital Image Correlation Method for Computing the Deformation Field

The DICM is a noncontact deformation field measurement method based on image analysis that was first proposed by Yamaguchi (1981) and Peter and Ranson (1981). The DICM is a type of displacement field observation method with some characteristics in common with present conventional methods. For example, it is capable of observing full-field information and noncontact measurements of the target zone. One notable characteristic of this method that differentiates it from other methods is that the layout for performing an experiment is very easy. Furthermore, the method is applicable for measuring a wide range of deformation. Another useful attribute of the DICM is that the resolution of the targeted deformed image is easily adjustable.

When compared with traditional optical observation methods, the DICM has the advantages of reducing the equipment and light source requirements, and because of its simplicity, it is easy to use. It also allows an adjustable range of measurements to fulfill various research needs. When compared with remote-sensing techniques, it is adequate for changeable weather conditions. Notably, the DICM can obtain a massive amount of full-field information and can capture the full deformation of the object, which is not achievable with conventional measurement methods, such as the macroscopic geological monitoring, geodetic precision measurement, and GPS measurement. The measurement accuracy of the DICM is 0.01 pixels, at a subpixel level.

Our main concern was identifying the similarity in gray-level distribution characteristics between two points in a reference image and a target image (here, we refer to the original image as the reference image and the deformed image as the target image). The similarity in the two search subareas was evaluated to determine points having the same characteristics.

2.1 Method Principle

The primary principle of the DICM is to acquire two images of an object, one before and one after deformation. The images are ob-
To make a comparative study of the reference image and target image, we used the correlation coefficient formula to statistically measure the linear correlation between two random variables:

\[ \rho_{XY} = \frac{\sigma_{XY}}{\sqrt{\sigma_{XX}} \sqrt{\sigma_{YY}}}. \]

\[ \sigma_{XY} = E[(X - E(X))(Y - E(Y))]. \quad (1) \]

In Equation (1), \( \rho_{XY} \) is the correlation coefficient, and its statistical significance describes the approximation degree of a linear relationship between X and Y. Generally, if we see that \(|\rho_{XY}| \approx 1\), the linear approximation between X and Y is large. Furthermore, \( \sigma_{XY} \) is the covariance formula used to describe the relationship between two random variables X and Y. The mean values of the random variables X and Y are \( E(X) \) and \( E(Y) \).

The mathematical relationship for the correlation coefficient is given in Equation (2), where \( I_1(x) \) and \( I_2(w(x)) \) represent the grayscale feature functions of the speckle field before and after deformation of the object:

\[ C(x) = \frac{\sum_{x \in \Lambda} [I_1(x) - \bar{I}_1] \cdot [I_2(w(x)) - \bar{I}_2]}{\left[ \sum_{x \in \Lambda} (I_1(x) - \bar{I}_1)^2 \cdot \sum_{x \in \Lambda} (I_2(w(x)) - \bar{I}_2)^2 \right]^{1/2}}. \quad (2) \]

### 2.2 Searching for and Matching the Reference and Target Images

Before searching for the position of the deformed points, we can often predict the deformation scale of the points to be matched in the reference image. Therefore, we do not need to search the full target image; we need only select the appropriate search region near the points to be matched in the target image to calculate the correlation coefficients between the reference image and a series of target images in the search region. We can then obtain a correlation coefficient distribution map of each point in the search area, as shown in Figure 2.

Because the correlation coefficient obtained at this time is generated at the integer pixel point, it does not provide evidence for points whose deformation scale is less than 1 pixel. To further improve the matching accuracy of the DICM, we would need to carry out a subpixel search method. The most commonly used subpixel search method are Parabolic Interpolation Method and Gauss Surface Interpolation Method. The basic principle is to interpolate or fit the correlation coefficient function of the entire pixel and obtain the maximum correlation coefficient at the subpixel level by solving for the parameter value of the interpolation polynomial.

Assuming that the geometric shape of the principal peak of the correlation function conforms to a mathematical model, then the maxima of the main peak and its corresponding position are estimated by polynomial interpolation based on the correlation coefficients of some known integer pixels. The formula of Parabolic Interpolation Method and Gauss Surface Interpolation Method are as follows.

\[ C(x, y) = ax^2 + by^2 + cxy + dx + ey + f, \quad (3) \]

\[ C(x, y) = \frac{1}{\sqrt{2\pi}} e^{-\frac{x^2+y^2}{2}}. \quad (4) \]

Equation (3) is the formula of Parabolic Interpolation Method, Equation (4) is the formula of Gauss Surface Interpolation Method.

The fitting formula used in this paper is the Parabolic Interpolation Method, and the unknown parameters in the model above are solved by the correlation coefficients of some known integer pixels. The extremum point and the maximum correlation coefficient of subpixels are solved by the extremum formula shown in Equation (5). The position of the maximum correlation coefficient is the position of the deformed point in the target image:

\[ \frac{\partial C(x, y)}{\partial x} = 0, \]

\[ \frac{\partial C(x, y)}{\partial y} = 0. \quad (5) \]

### 2.3 Solution of the Deformation Field

From the integer pixel search and subpixel fitting, we obtain the deformed position \((x', y')\) of the calculated point in the target image. We can use the reference coordinates \((x, y)\) and the target coordinates \((x', y')\) to calculate the subpixel displacement fields \(u\) and \(v\), and the strain field \(e_{xy}\) can be obtained by deriving the values as shown in Equation (6):
3. Failure Experiment of a Marble Plate with a Double Shear Crack

In this section, we describe the material and instrument parameters used in the uniaxial compression experiment. We also describe how we processed the sample data.

3.1 Samples and Experimental Settings

The rock samples used in the experiment were taken from marble, the physical parameters of which are listed in Table 1. In the first step, a block of marble was cut into 100 × 80 × 5 mm thin plates, and then two prefabricated cracks were carved onto the 100 × 80 mm plane with a diamond grinding wheel. The crack length was 100 mm, the width was 0.5 mm, and the depth was 1 mm. Fault steps of 5 mm were set at the top and bottom of the sample (on an 80 × 0.5 mm surface), respectively, so that the sample was convex and concave. No material was filled in the prefabricated crack. Figure 3 shows a schematic diagram of the sample.

![Figure 3. Schematic diagram of the sample and experimental loading.](image)

| Sample no. | Young’s modulus (GPa) | Poisson ratio | Compressive strength (MPa) |
|------------|-----------------------|--------------|---------------------------|
| D20161020  | 35.82                 | 0.19         | 182.12                    |
| D20181018a | 36.01                 | 0.28         | 191.80                    |
| D20181018b | 36.17                 | 0.21         | 175.82                    |
| D20181019  | 35.62                 | 0.37         | 177.85                    |
| D20181020  | 36.76                 | 0.28         | 185.25                    |

The loading instrument used in the experiment was a single-axis press (NYL-60) with a maximum load of 15 t. The instrument recording the loading process of the sample was a digital camera (DH-HV1310FM), with a resolution ratio of 1,280 × 1,024 pixels and a sampling frequency of 3.73 sheets/s. The DICM algorithm program was written in the data processing software of MATLAB.

3.2 Experimental Process

The experiments were conducted under normal temperature and pressure conditions, and the size parameters of the sample were initially measured. The theoretical schematic diagram of this experiment is shown in Figure 4a, and the actual experimental process is shown in Figure 4b. To prevent the sample from tilting or rotating during loading, the sample was placed in a specific mold. First, the contact surface between the sample and the mold was polished, which ensured that the lower surface of the sample was horizontal. Next, the mold was cleaned before the experiment to ensure that the contact surface between the mold and the sample was smooth. These two steps ensured that the sample would not rotate and deform during loading. In addition, we selected the measuring range of the press and placed the sample in the center of the lower disc of the press to adjust the level of the lower disc. We then rotated the upper disc of the press to make it on the drop position which exactly touched the upper surface of the sample. We set up the DH-HV1310FM camera in an appropriate direction and adjusted the length of the camera focus and aperture to find a clear position from which to observe the sample image. We then connected the camera to the computer and turned on the press while the computer controlled the camera and began collecting data. We also adjusted the oil delivery rate of the press to make it load slowly in a stable way, as well as to stop sampling when the sample fractured, close the press and camera in order to record the damage load of the sample, take down the sample, and store the data.

![Figure 4. Schematic diagram of the sample destruction experiment and data acquisition. (a) Schematic diagram of the experiment. (b) Laboratory setup of the experiment.](image)

3.3 Data Processing

In this study, five double-shear cracked marble plate failure experiments were carried out. The experimental results for the marble samples with prefabricated cracks are listed in Table 2. We selected sample D20161124y as an example to illustrate how data were processed and how the deformation field was calculated. Figure 5...
Table 2. Experimental results for marble samples with prefabricated cracks.

| Sample no.     | Length (mm) | Width (mm) | Thickness (mm) | Crack length (mm) | Crack width (mm) | Crack depth (mm) | Maximum stress (MPa) | Maximum strain | Remarks            |
|----------------|-------------|------------|----------------|-------------------|------------------|------------------|----------------------|-----------------|--------------------|
| D20161124y     | 99.50       | 78.65      | 5.00           | 90.00             | 0.50             | 1.00             | 21.42                | 2.55 × 10⁻³     | One-sided crack    |
| D20161124z     | 99.80       | 78.90      | 5.00           | 90.00             | 0.50             | 1.00             | 30.77                | 2.75 × 10⁻³     | One-sided crack    |
| D20181114l     | 98.12       | 79.80      | 5.10           | 92.30             | 0.50             | 1.00             | 19.18                | 2.69 × 10⁻³     | One-sided crack    |
| D20181117j     | 98.41       | 79.97      | 5.07           | 91.60             | 0.50             | 1.00             | 24.70                | 2.41 × 10⁻³     | One-sided crack    |
| D20181118s     | 98.00       | 79.80      | 5.11           | 92.30             | 0.50             | 1.00             | 19.53                | 2.79 × 10⁻³     | One-sided crack    |

shows the fractured state of sample D20161124y after the experiment was performed. A pressure sensor was used to record the sample damage load, and a strain gauge was placed in the center of the sample to record the strain. Figure 6 shows the stress–strain curve of the sample. During the entire loading process, 855 sample images were captured by the camera. To observe information on the deformation field of the sample near a rupture, images of A, B, C, and D at four later loading stages during the loading process were selected for calculating correlations. As shown in Figure 6, A, B, C, and D correspond to stresses, respectively, of 90%σmax (image 769), 95%σmax (image 812), 98%σmax (image 837), and 100%σmax (image 855).

According to the location of the prefabricated cracks, the calculation area was selected by using the DICM program. (As shown in Figure 3, the observation area of the camera was 58 × 73 mm, and the calculation area of the DICM was 45 × 60 mm). Furthermore, we set the sampling points, subpixel search areas and search range to carry out the related calculations. We obtained the incremental displacement field $u$ in the vertical loading direction, the incremental displacement field $v$ in the parallel loading direction, and the incremental shear strain field $e_{xy}$.

4. Experimental Results

In this section, we discuss the deformation evolution of marble samples with one-sided double-shear cracks that were selected for five repeated experiments. The physical parameters, namely, Young’s modulus, Poisson’s ratio, and compressive strength, are shown in Table 1. The experimental results of the marble samples, such as the size of the parameters, the maximum stress, and the maximum strain at failure are shown in Table 2. In the experiment, we have taken the corresponding values of Young’s modulus and Poisson’s ratio for each marble sample. Our experimental layout was the same for different marble samples, but the elastic parameter values were different. As mentioned, the experimental process involved repeated experiments on different samples. As shown in Table 2, the maximum stress and strain values in the five experiments were in the range of 20 to 30 MPa pressure and about 2.50 × 10⁻³ maximum strain. The results obtained in the five experiments were consistent with one another. We selected sample D20161124y to illustrate how we processed the data and calculated the deformation field. We selected four images (A, B, C, and D) of loading moments on the stress–strain curve, which corresponded to different percentile load values, such as 90%σmax ($\sigma$: 19.28 MPa), 95%σmax ($\sigma$: 20.35 MPa), 98%σmax ($\sigma$: 20.99 MPa), 100%σmax ($\sigma$: 21.42 MPa), and the initial image at 0%σmax ($\sigma$: 0), to carry out the related calculations. By calculating the correlations, we obtained the incremental displacement fields $u$ and $v$ and the incremental shear strain field $e_{xy}$, where $u$ is perpendicular to the loading direction, $v$ is parallel to the loading direction, and $e_{xy}$ was calculated from $u$ and $v$. 

Figure 5. Sample loading failure.

Figure 6. Classification basis for the loading phase of sample D20161124y.
4.1 Evolution of the Incremental Displacement Field $u$ in a Vertical Loading Direction

Figure 7 shows the evolution of the incremental displacement field $u$ in a vertical loading direction ($x$-axis). The positive values on the color bar represent movement along the positive $x$-axis. In Figure 7a and 7b at different maximum stress loads of (0%–90%)$\sigma_{\text{max}}$ and (90%–95%)$\sigma_{\text{max}}$, the incremental displacement distribution of the sample appeared in such a way that the displacement of the left crack with the dominant blue color moved toward the $x$-axis on the negative side and the right crack with a prominent reddish color moved toward the positive side. Furthermore, the displacement of the middle part, which lay in between these two cracks, tended to zero. This phenomenon indicated that with an increase in load, the strain in the sample accumulated gradually before the load reached 90%$\sigma_{\text{max}}$. The region of concern on both sides of the crack tended to move outward in the $x$-direction, and the displacement field began to concentrate near the crack. In Figure 7c and 7d, at the maximum stress loads of (95%–98%)$\sigma_{\text{max}}$ and (98%–100%)$\sigma_{\text{max}}$, the incremental displacement of the crack was $1.5 \times 10^{-3}$ mm, the displacement of the left crack was $-1.2 \times 10^{-3}$ mm, and the displacement increment in the middle of the sample approached zero. This showed that at a later load stage, when the load value range was (95%–100%)$\sigma_{\text{max}}$, a distinct separation appeared near the area of the two cracks. The displacement field $u$ was completely concentrated near the crack, and the sample was near failure.

4.2 Evolution of the Incremental Displacement Field $v$ in a Parallel Loading Direction

Figure 8 shows the evolution of the incremental displacement field $v$ parallel to the loading direction, which is along the $y$-axis. The positive values on the color bar represent movement along the positive $y$-axis. Figure 8a and 8b shows a significant concentration of displacement on the right side of the crack and an incremental displacement of about 0.25 mm at stress loads of (0%–90%)$\sigma_{\text{max}}$ and (90%–95%)$\sigma_{\text{max}}$, respectively. It also shows that the displacement was concentrated along the upper and lower sides of the sample. At this time, we could see that the strain accumulated gradually, that the displacement field on the right side of the crack was concentrated in a more obvious way, and that the trend on the right side of the crack showed displacement in an upward direction. In Figure 8c and 8d, the displacement was concentrated on both sides of the prefabricated crack at stress loading stages of (95%–98%)$\sigma_{\text{max}}$ and (98%–100%)$\sigma_{\text{max}}$. The displacement increment along the right and left sides was about 0.4 mm, and the displacement increment in the middle of the crack tended toward a negative value of 0.1 mm. This indicated that at the
later stages of loading at (95%–100%)σ\text{max}, the region near the two cracks in the sample exhibited obvious upward and downward dislocation. The displacement field \(v\) was completely concentrated near the crack, and the sample was near failure.

### 4.3 Evolution of Incremental Shear Strain Field \(\varepsilon_{xy}\)

Figure 9 shows the evolution of the shear strain field \(\varepsilon_{xy}\), which reflects the overall effects of the vertical and parallel loading directions. In Figure 9a and 9b, shear strain was elevated at the two stress loading stages of (0%–90%)\(\sigma_{\text{max}}\) and (90%–95%)\(\sigma_{\text{max}}\). The shear strain field near the right crack was concentrated at a high value, as shown by the reddish color. The value of the shear strain along the right side of the crack was 0.002, and the distribution of the shear strain field near the left crack was irregular. Figure 9c and 9d shows the corresponding shear strain value at stress loading stages of (95%–98%)\(\sigma_{\text{max}}\) and (98%–100%)\(\sigma_{\text{max}}\). Two obvious shear strain bands could be seen along the prefabricated cracks, with a high value of about 0.0025. We conducted a comparison of the shear strain field concentrations and found that strain accumulation initially created irregular patterns on the left side. Furthermore, when the load was increased, the strain distribution showed a changing pattern such that the strain distribution changed from irregular to regular where the strain field was concentrated more precisely along the prefabricated crack.

### 4.4 DICM Comparisons with Strain Gauge Measurements

When the results of the shear strain field \(\varepsilon_{xy}\) calculated by the DICM (Figure 9) were compared with the results recorded by the strain gauge (Figure 6), we found that the variation of the shear strain field \(\varepsilon_{xy}\) calculated by the DICM ranged from 0.001 to 0.002 at loading stages of (0%–90%)\(\sigma_{\text{max}}\) and (90%–95%)\(\sigma_{\text{max}}\). Whereas (Figure 6) the variation of the shear strain field \(\varepsilon_{xy}\) recorded by the strain gauge ranged from 0.0016 to 0.0018. At loading stages of (95%–98%)\(\sigma_{\text{max}}\) and (98%–100%)\(\sigma_{\text{max}}\), the variation of the shear strain field \(\varepsilon_{xy}\) calculated by the DICM ranged from 0.002 to 0.0025, whereas the variation of the shear strain field \(\varepsilon_{xy}\) recorded by the strain gauge in Figure 6 ranged from 0.0017 to 0.0023. The results of the DICM and the shear strain field \(\varepsilon_{xy}\) recorded by the strain gauge were similar; thus, we concluded that the results of the DICM were reasonable.

![Figure 9](image)

**Figure 9.** Evolution of the incremental shear strain field \(\varepsilon_{xy}\). (a) at a (0%–90%)\(\sigma_{\text{max}}\) loading stage; (b) at a (90%–95%)\(\sigma_{\text{max}}\) loading stage; (c) at a (95%–98%)\(\sigma_{\text{max}}\) loading stage; (d) at a (98%–100%)\(\sigma_{\text{max}}\) loading stage.

### 5. Precursory Characteristics of Fault Activity

To explore whether the sample had some numerical precursory characteristics before rupture, we selected a cross-sectional area to calculate the sample in a vertical direction in relation to the prefabricated crack. The black dotted line in Figure 10 shows the position of the cross section. In this section, we discuss our attempts to analyze the variation in physical quantities of various characteristics on the cross section under different loading stages to find indicators reflecting precursors of the sample rupture.

First, we extracted data on the incremental displacement fields \(u\) and \(v\) and the incremental shear strain \(\varepsilon_{xy}\) from the experimental results. We then observed the variation characteristics of physical quantities \(u\), \(v\), and \(\varepsilon_{xy}\) on the cross section under different loading stages. Figures 11, 12, and 13 give the distribution of \(u\), \(v\), and \(\varepsilon_{xy}\) that correspond to the four percentile stress values of 90%\(\sigma_{\text{max}}\), 95%\(\sigma_{\text{max}}\), 98%\(\sigma_{\text{max}}\), and 100%\(\sigma_{\text{max}}\).

Figures 11, 12, and 13 show the spatial and temporal distribution of the physical quantities of \(u\), \(v\), and \(\varepsilon_{xy}\) at the cross section under a series of loads. From the point of view of spatial distribution, abrupt numerical change in each physical quantity occurred at the prefabricated crack, especially at the corresponding 98%\(\sigma_{\text{max}}\) loading stage.

This result indicated that during the loading process, the region near the prefabricated crack was prone to instability and that rupture would occur in the first step. This phenomenon was verified by the experimental results. To predict fracture, we were the most concerned with the relationship between the fracture index and time characteristics. However, from the time characteristics of the three physical quantities \(u\), \(v\), and \(\varepsilon_{xy}\) mentioned above at the four loading stages of (0%–90%)\(\sigma_{\text{max}}\), (90%–95%)\(\sigma_{\text{max}}\), (95%–98%)\(\sigma_{\text{max}}\), and (98%–100%)\(\sigma_{\text{max}}\), the results in Figures 11, 12, and 13 did not clearly reflect which physical quantities of the sample would undergo abrupt changes immediately before rupture.

After a comprehensive analysis of our results, we identified the following shortcomings in our scheme for analyzing the sample immediately before rupture: (1) It failed to make full use of the data characteristics of the entire field; (2) it failed to analyze the rupture precursor index characteristics with respect to the true time of rupture; (3) it incorporated the characteristic spatial in-
formation, which influenced judgment; and (4) it failed to reflect the changing characteristics of the physical quantities with time throughout the loading stages. Therefore, the shortcomings in the above scheme needed to be improved.

In the next section, we lay out a comprehensive plan for improving these shortcomings. We used the entire field and continuous loading stage data to select the appropriate rupture precursor index. Additionally, we studied its relationship with the time. We used the coefficient of variation (CV) to analyze the incremental displacement fields $u$ and $v$ and the incremental shear strain field $e_{xy}$ at each loading stage, and we calculated the CV values of $u$, $v$, and $e_{xy}$ with the load. To observe the changing trend in physical quantities in the process of sample destruction from a statistical perspective, we analyzed the characteristics of precursors to sample rupture.

5.1 Coefficient of Variation Principle
In statistics, the CV is used to describe the difference between homogeneous individuals or the degree of dispersion between two sets of data. It uses the ratio of standard deviation and the mean value of data to eliminate the influence of the measurement scale and dimensions, and it reflects the discrete degree of sample data. The mathematical relationship of CV is given in Equation (7):

$$CV = \sqrt{\frac{D(X)}{E(X)}}$$

In Equation (7), CV represents the value of the coefficient of variation, and $D(X)$ and $E(X)$ represent the variance and mean value of the calculated data. We calculated the CVs for the incremental displacement fields $u$ and $v$ and the incremental shear strain field $e_{xy}$ for different loading stages. After computing the CVs, we plotted

Figure 10. Diagram of the selected section. The cross section, located in the middle of calculation area, is perpendicular to the prefabricated cracks.

Figure 11. Incremental displacement field $u$ distribution at the cross section under a series of loads. The vertical dotted lines correspond to the prefabricated cracks.

Figure 12. Incremental displacement field $v$ distribution at the cross section under a series of loads. The vertical dotted lines correspond to the prefabricated cracks.
CV values and analyzed the responses in relation to different loading stages. The discreteness of the sampling data was visualized, after which we decided conclusively whether a numerical mutation was present in the corresponding loading stage.

5.2 Image of CV Values for Different Physical Quantities

For each loading stage, we extracted data for the incremental displacement fields $u$ and $v$ and the incremental shear strain field $e_{xy}$ for all the sampling points and calculated their CV values. Additionally, we plotted the CV values of $u$, $v$ and $e_{xy}$ with the variation in loads. The results are shown in Figures 14, 15, and 16.

When we examined the CV value results for the incremental displacement fields $u$ and $v$ and the shear strain field $e_{xy}$ as they varied by load and compared them with the sample stress–strain curves in Figure 6, we identified that the CV value distribution in Figures 14, 15, and 16 had similar variations toward the loading axis.

In the stress and strain variation trend depicted in Figure 6 at a loading range of $(0\%–70\%)\sigma_{\text{max}}$, the curve had a linear trend. However, the CV values shown in Figures 14–16 showed a gentle variation response. Furthermore, in Figure 6, for the loading stage at $(70\%–85\%)\sigma_{\text{max}}$, the sampling curve lay in the softening stage.
whereas the variation response for the CV values shown in Figures 14–16 increased slightly, followed by an obvious change. In Figure 6, at the loading stage of $(80\%–100\%)\sigma_{\text{max}}$, the stress-strain curve lay in the nonlinear stage and the stress was approaching its peak value, whereas in the variation response in Figures 14–16, the CV values increased rapidly and varied sharply. The CV curve appeared to reflect the different deformation stages of the sample. In the uniform deformation stage, the CV value was small and changed slowly, whereas in the later nonuniform deformation stage, the CV value increased sharply and its frequency of variation also showed sharp variation behavior. Therefore, the precursor of sample breakdown could be predicted by observing the variation characteristics of CV statistics. The experimental results could be supplemented by the trend for crack evolution and the characteristics of crack precursors. We could say that the strain field of the sample had to bear the following stages from damage to failure:

(1) In the linear phase of the stress–strain curve, the CV value was small and changed slowly, and the sample was uniformly deformed without an obvious strain concentration.

(2) When the stress–strain curve bent, the CV value increased slightly, and it changed in an obvious way. The local strain concentration appeared in the sample, but strain development did not have a uniform distribution.

(3) The stress–strain curve reached its peak value, and the CV value increased sharply and varied sharply. Two strain concentration zones appeared near the prefabricated crack and gradually strengthened.

(4) During the response of the stress–strain curve at the later peak stage, the CV value reached its maximum point. The two strain concentration zones interacted with each other, and the samples were damaged along the prefabricated cracks.

6. Application of Experimental Results to Seismic Activity

By studying the failure process of rock samples, we were able to obtain information on the quantitative deformation field as well as the evolution law of internal cracks in the process of rock damage. These experimental results have profound theoretical significance for understanding the formation process of actual large faults and their structures. By combining the experimental rock failure law with the observed results from an actual fault zone, we could comprehensively understand the information lacked in an actual inter-seismic deformation field, which will provide a theoretical and analytical basis for future studies of fault activity and earthquake-generating mechanisms.

Li WH (2017) extracted five consecutive GPS observations from 2010 to 2015 for the San Andres Fault and its adjacent areas ($\sim31.5^\circ–40^\circ\text{N}, \sim237^\circ–246^\circ\text{E}$), as shown in Figure 17, and analyzed the horizontal crustal velocity of the area. The distribution of the crustal shear strain rate field in the area was calculated by using least square collocation method based on sphere, as shown in Figure 18.

From the shear strain contour map in Figure 18, we can see that the high values of the maximum shear strain rate are distributed along the San Andres Fault Zone and are basically located on the fault zone. The distribution of the shear strain field is similar between the San Andres Fault zone and the marble plate failure test. The high shear strain values in both zones are distributed near the fault zone. Regarding tectonic movement, the double-shear crack samples in the experiment accumulated internal strain...
under the continuous, increasing pressure of the uniaxial press, and the shear strain field was redistributed from initial disorder to concentration along the crack. After the sample reached the stress threshold, the internal cracks connected to each other, and the sample shifted along the crack and was then destroyed. The San Andreas Fault Zone is located at the plate boundary, and differential horizontal movement continues for long periods along both sides of the fault zone because of this continuous phenomenon. As this occurs, the strain potential energy accumulates and shear strain concentration bands appear at the junction. When the energy accumulates because of the high level of stress and strain, it leads toward instability in the crust. A rupture in the crust takes place suddenly, and the energy is released on a large scale, which triggers the occurrence of earthquakes. From this comparison of our experimental results with practical studies, we found that faults and strong earthquakes mainly occur at the boundary zone of active blocks with a highly inhomogeneous distribution of crustal movement and conspicuous movement characteristics.

We consulted the National Earthquake Information Center catalog to obtain historical earthquake distribution maps of the San Andreas Fault System, as shown in Figure 19.

The historical seismogram of the Saint Andreas Fault System in Figure 19 shows that a large number of moderate to strong earthquakes of magnitude 5–7 occurred in the Saint Andreas Fault and adjacent areas, especially in the high-strain areas. Some occurred in the interior of the plate, some at the boundary of the plate, and most along the same large fault zones. The major earthquakes greater than magnitude 7 occurred mainly in the boundary zone of the active plate, namely the San Andres Fault and a series of large-scale fault zones.

From these results, we found that the seismic distribution characteristics near the San Andreas Fault zone were similar to the crack evolution characteristics observed in the marble failure experiments. From the evolution process of the shear strain field, we could see that with an increase in load, the shear strain field changed from a disorderly distribution at the beginning to partial concentration and finally to complete concentration near the crack, when it was redistributed as a strip along the crack. Our results showed that with the increase in load, it was easier for the stress concentration to generate near the main crack and form new secondary cracks. With the accumulation of stress, secondary cracks were generated continuously and distributed linearly along the main crack zone. This process reflects the influence of secondary cracks in an actual fracture zone that will cause moderate to strong earthquakes. This phenomenon is consistent with the characteristics observed in the San Andres Fault Zone, where medium to strong earthquakes have a high probability of recurrence and are linearly distributed along the fault. Therefore, by comparing our experimental results with a theoretical research layout, we found that earthquakes and secondary earthquakes mainly occur near large active faults, and most are distributed linearly along the fault zones. The distribution of the epicenters is in good agreement with the strike of the faults.

7. Discussion and Conclusions
The analysis of our experimental results related to the deformation field and the variation in CV values in the incremental displacement fields $u$ and $v$ and the shear strain field $e_{xy}$ with respect to load variation resulted in extracting the following innovative findings. The failure process of double-shear marble samples with prefabricated cracks is a complex phenomenon. The failure process undergoes an accumulation and localization of damage, and failure ultimately occurs along the prefabricated cracks. With an increase in the shear strain field, it changes from a disorderly and partially concentrated distribution initially to entirely concentrated near the crack and then distributed as a strip along the crack.

We have identified the behavior of CV values and their variation response at different loading stages as depicting the degree of
deformation in a rock sample. In the linear stage of a stress–strain curve of marble samples with prefabricated double-shear cracks, the CV value is small and changes slowly, and deformation of the sample takes place uniformly without an obvious concentration of strain. When the stress–strain curve bends, the CV value increases slightly, and a local strain concentration appears in the sample but the distribution of strain development is not uniform. When the stress–strain curve reaches its peak value, the CV value increases sharply and changes abruptly. Two strain concentration zones near the prefabricated crack are gradually strengthened. The stress–strain curve lies at a later peak stage, when the CV value reaches the maximum. The two strain concentration zones interact with each other, and the samples are destroyed along the prefabricated crack. Therefore, the precursor to sample breakdown can be predicted by observing the variation characteristics of the CV statistics.

Our experimental work has some constraints, such as that the structure of the experimental samples was relatively simple. We considered only a single rock material with a simple prefabricated crack, which we compared with the complicated conditions of temperature, confining pressure, rock material, and stress during the formation of an actual strike–slip fracture. The experimental results also reflect only the distribution of the deformation field during the formation of the simplest strike–slip fracture model (i.e., uniaxial compression of a single material under constant temperature and pressure conditions). In a follow-up study, we will consider redesigning the sample material, crack distribution, and temperature and pressure conditions of the experiment to explore the influence of different experimental conditions on the distribution of the deformation field of a strike–slip fracture.

From the present results, we found that the seismic distribution characteristics near the San Andreas Fault Zone were similar to the crack evolution characteristics observed in the marble failure experiments. Therefore, from this comparison of our experimental results and the layout of crack evolution in the San Andreas Fault Zone, we found that earthquakes and secondary earthquakes mainly occur near large, active faults, and most are linearly distributed along fault zones. The distribution of the epicenters agrees well with the strike of the faults.

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