Deformation field around a thrust fault: A comparison between laboratory results and GPS observations of the 2008 Wenchuan earthquake

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Abstract: On May 12, 2008, an Mw 7.9 earthquake occurred in Wenchuan County, Sichuan Province, China. Movement of Yingxiu–Beichuan Fault in the Longmenshan Fault Zone was considered to be the main cause of the earthquake. Earthquakes are closely related to fault activities. Therefore, studying the strain distribution and evolution process around active fault zones is important to the understanding of seismic activities. In this study, we conduct laboratory experiments with uniaxial compression applied to marble sheets with intentionally fabricated cracks. The speckle patterns of the rock samples under different loading conditions are recorded in real time by a digital camera. To calculate the deformation fields of the deliberately cracked marble sheets during different stages of the loading processes, the recorded images are processed by the digital image correlation method. The distribution and variation of the displacement and strain are further analyzed in order to understand the strain localization of and observed damage in the experimental fracture zones. Finally, we compare these laboratory results with the GPS-observed coseismic displacements during the 2008 Wenchuan earthquake, to assess the consistency between our laboratory observations and the field observations of the earthquake, but also to suggest how laboratory results can improve thinking about how earthquake patterns do and do not reflect fault patterns.

Keywords: deformation field; thrust fault; Wenchuan earthquake; GPS observations; experimental results

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1. Introduction

Earthquakes are processes in which rocks are damaged by forces resulting from fault activities, and therefore have a close relationship with faults. Fault is a common form of structure in the Earth’s crust, and fault geometry reflects the state of geostresses. A fault zone is an integrated system of fractures of different scales (King, 1983; Scholz and Mandelbrot, 1989). The Longmenshan Fault Zone (LFZ) is the boundary between the Tibetan Plateau and the South China Block, and is a segment of the north-south seismic belt of the Chinese mainland (Zhang PZ, 2008). It consists of a series of generally parallel-stacked thrust faults, running for ~500 km from Guangyuan in the northeast to Tianquan in the southwest, with a width of ~30 km. Figure 1 presents an overview of the study area.

On May 12, 2008, an Mw 7.9 earthquake occurred in Wenchuan County, Sichuan Province. The movement of the Yingxiu-Beichuan Fault (YBF) in the LFZ was considered to be the main cause of the earthquake. GPS data show that the coseismic displacement of the Wenchuan earthquake is concentrated only in the epicenter region centered on the YBF, and decays rapidly away from the fault.

In recent years, various methods have been applied to monitor coseismic displacement fields. Bai YZ et al. (2011) used the Stekete (1958) and Okada (1985, 1992) static fracture dislocation model to study the depth distribution of the deformation (strain) from the hypocenter to the surface in the LFZ region in the Wenchuan earthquake. The “10th Five Year Plan” of the China Earthquake Administration has established nearly 100 high-precision borehole strain observation stations nationwide by either deployments of new stations or reconstruction of existing ones (Qiu ZH et al., 2011). Liu Q et al. (2016) used GPS, leveling and strong motion data to jointly invert for the coseismic slip distribution of the 2013 Lushan earthquake. Wang et al. (Wang T and Jónsson, 2014; Wang T et al., 2015) applied the SAR image correlation method to obtain coseismic displacements. Stress and strain are the basic physical quantities that characterize rock failures. Thus, making full use of the regional seismic observations is very effective for studying seismic activities. In the laboratory, studying the strain field and its evolution process in rock samples at different development stages under uniaxial compression helps to understand the relevant properties of the faults, the strain concentration in fault zones, and their implications for seismic activities. Zhao YH et al. (1995, 2004) studied growth of microcracks and crack propagation during the failure process. The germination,
propagation, and connectivity of microcracks during uniaxial compression failure of limestone slabs were observed in real time by scanning electron microscopy. Pan YS and Yang XB (2001) used the white light digital image correlation method (DICM) to study localized deformation of rocks. Zhao YH et al. (2002) used scanning electron microscopy to obtain speckle patterns on the surface of fine sandstones, and processed the images using DICM to obtain displacement components for quantitative analysis of rock damage evolution. Song YM et al. (2011) carried out an experimental study on the rock deformation and failure process under uniaxial compression conditions, and obtained the deformation field evolution of the whole process as well as transient behavior during rock failure.

Previously published studies have shown that research based on field observations of coseismic deformation field is quite extensive, but joint analysis of field observations and experimental laboratory results is still lacking. In this study, we conduct laboratory experiments on marble samples containing fabricated cracks and use DICM to calculate the displacement and strain fields of the samples under different loading processes. The evolution of the deformation field is then analyzed to establish rules of strain concentration. Based on the GPS observations of the Wenchuan earthquake deformation field, we discuss the relevance of our experimental results to the monitoring of deformation fields near active fault zones.

2. Laboratory Setting and Digital Image Processing
In the laboratory experiments conducted in this study, five marble samples with fabricated cracks were subjected to plate compression (see Figure 2); the initial state of the rock samples, as well as four states of adjacent damage, were deliberately chosen. The loads of these states during the four loading intervals of $0–0.4\sigma_m$, $0–0.6\sigma_m$, $0–0.8\sigma_m$, and $0–\sigma_m$, where $\sigma_m = 150$ GPa is the marble’s fracture stress (acquired from the uniaxial compression experiment of intact cylindrical marble in the laboratory), were obtained for analysis. The displacement components $v$ in the loading direction and $u$ perpendicular to the loading direction, the strain elements $\varepsilon_{yy}$ in the loading direction, and $\varepsilon_{xx}$ perpendicular to the loading direction, and the shear strain $\varepsilon_{xy}$ corresponding to the four loading intervals were calculated. In our analysis, tension is positive and compression is negative. A positive shear strain represents the left-lateral (counterclockwise) motion, and a negative value represents the right-lateral (clockwise) motion. We calculate the evolutions of the displacement and strain fields of the marble samples and analyze the magnitude and distribution of their strain concentration.
2.1 Rock Samples
The rock sample used in this study are all Fangshan marble sheet with sample size 105mm × 80mm × 5mm, density 2.83 g/cm³, Young’s modulus 65 GPa and Poisson’s ratio 0.25. The sample information is listed in Table 1, and the loading and observation settings are shown in Figure 2.

2.2 Loading Processes
The experiments were carried out at room temperature and pressure. The experimental apparatus is shown in Figure 3. Using a NYL-60 uniaxial press with a maximum load of 15 tons, the samples were gradually pressurized, their states changing from external force-free to final fractures. The rock damage processes were recorded using a DH-HV1310FM camera; the sampling rate was 4 frames per second, the image resolution was 0.01 mm. The photos recorded under different loading conditions were processed by the digital image correlation program, so that the deformation fields of the rock samples under different loadings could be calculated and analyzed.

2.3 Digital Image Correlation Method
The digital image correlation method (DICM) is a very effective way to study the process of rock failure. It can fully capture the whole process of complex deformation on a rock surface during loading, allowing subsequent quantitative and specific deformation analysis (Russell and Sutton, 1989). The principle is that in pairs of scanned images acquired by the digital camera, before and after deformation of an object (the reference image P and the target image Q), regions with similar gray-scale distribution features are matched. The deformation information of the point (Wang HW et al., 2005; Pan B et al., 2010) is shown in Figure 4.

The core of scan and match is to judge the degree of correlation between two sub-areas, with the correlation coefficient defined as follows:

\[ C = \frac{\sum \sum (f_i - \bar{f}) \cdot (g_j - \bar{g})}{\sqrt{\sum (f_i - \bar{f})^2} \cdot \sqrt{\sum (g_j - \bar{g})^2}} \]

where \( f_i \) and \( g_j \) are speckle fields corresponding to the reference image P and the target image Q, respectively, and \( \bar{f} \) and \( \bar{g} \) are the average values of \( f_i \) and \( g_j \), respectively (Pan B et al., 2009).

In the processing program, patches measuring 30mm × 30mm are selected within the digital camera photos that recorded the rock destruction processes under the different loadings, beginning from the lower left corner of the observation area. The evolution of the speckle patterns in each patch, over the time of the deformation, allows calculation of the deformation field. Sample photos of the two consecutive loading states are supplied into the program as the reference and target images in order to calculate the
deformation fields of different loading stages. Then, a second patch is selected next to the first one, and the same calculation is carried out by the program. The process is repeated until the entire observation area is processed.

3. Laboratory Experimental Results
In this study, the experimental approach described in the previous sections was used to investigate the strain and deformation of marble samples with fabricated cracks, and the distributions of deformation fields of the sample were calculated.

We find that as loading increases, the displacement and strain fields increase in amplitude. The magnitude of the displacement component in the loading direction is $10^{-3} - 10^{-1}$ mm (Figure 5) while the displacement component perpendicular to the loading direction is $10^{-3} - 10^{-2}$ mm (Figure 6). Also, as the pressure applied to the sample gets closer to the breaking point, the strain field of the sample changes more severely by going through the same load ratio. The magnitude of the strain element in the loading direction is $10^{-2}$ (Figure 7) while the magnitude of the strain element perpendicular to the loading direction is $10^{-3}$ (Figure 8), and the shear strain is on the order of $10^{-2}$ (Figure 9). The strain value at the fabricated crack increases most obviously. The strain field gradually concentrates to the two sides of the crack, and the strain concentration on both sides decays with distance from the fabricated crack. The deformation field of the samples has different distribution characteristics in different directions: in the loading direction, the deformation field concentrates along the crack while in the direction perpendicular to the loading, the deformation field first distributes on both sides of the crack and then gradually concentrates toward the fabricated crack. The strain concentration in the upper part of the rock sample at a distance of 20 mm from the fabricated crack has an amplitude of $\sim 10^{-3}$ and is 2 to 3 times larger than in the surrounding area, which may be due to sample heterogeneity.

In uniaxial compression experiments, it is usually expected that the sample will crack along the fabricated fractures. However, in our experiments the marble samples did not always break entirely along the fabricated crack, but sometimes experienced a layered stripping, as shown in Figure 10. The stress here was concentrated in the area of the fabricated crack, but it did not distribute strictly along the crack. The experimental results can explain the strain anomaly distribution in the upper left area of Figure 10 during the evolution of the deformation field. We suggest that it is

![Figure 5](image-url)

**Figure 5.** Evolution of the displacement component $v$ of the marble sample in the loading direction. The solid black line depicts the fabricated crack. (a), (b), (c) and (d) Loading intervals $0-0.4\sigma_m$, $0-0.6\sigma_m$, $0-0.8\sigma_m$, $0-\sigma_m$, respectively.
precisely the anomalous distribution of stress during the compression that led to the final rupture in the form of the layered delamination. This laboratory observation suggests that misjudgment of seismic activity may be caused by erroneous expectations applied to short-term observations.

The displacement of the sampling points that are closer to the prefabricated crack is numerically larger than of the ones far away, which is more apparent as the marble sample approaches breaking load, as shown in Figure 11.

4. Comparison with Wenchuan Earthquake

There are various types of fracture systems on different scales in the Earth’s crust. Laboratory rock experimental results on strain concentration and crack development can be used to analyze the characteristics in fracture development and distribution around active fault zones. It is of great practical significance to monitor seismic activities in areas with frequent earthquakes, such as plate junctions and concentrated fault zones. Today’s data acquisition techniques for monitoring the Earth surface displacement usually include GPS observation and radar and optical satellite imagery. After processing the raw data by established professional software, information such as a description of the coseismic deformation field can be obtained (Wen YM et al., 2014; Shan XJ et al., 2014). Here we take the 2008 Wenchuan earthquake as an example to evaluate the relevance of our laboratory experimental results by comparing the GPS observed coseismic displacement of the Wenchuan mainshock with our laboratory observations.

The Global Positioning System (GPS) is a space-based radio navigation and positioning system that provides three-dimensional coordinate and time information for any location on the Earth’s surface or near-Earth space (Ning JS et al., 2013). Figure 12 shows the GPS-observed coseismic horizontal displacement field around the LFZ during the mainshock of the 2008 Wenchuan earthquake (National Major Scientific Project “China Crustal Movement Observation” Network Project Team, 2008). It can be seen clearly that all sites west of the YBF moved eastward, while all sites east of the fault moved westward, leading to a significant horizontal shortening of the crust. We select seven GPS observation points along a line across the LFZ (see Table 2 for detailed information).

Figure 13 shows the GPS observed coseismic horizontal displacements at these points as a function of their distances from the LFZ. In Figure 13, it can be seen that the coseismic displacement of the Wenchuan earthquake is concentrated only in the region centered on YBF, and quickly decays away from the fault. The GPS observations show clearly that the coseismic deformation field is closely related to the location of the fault zone. The coseismic dis-

![Figure 6](image-url)

Figure 6. Same as Figure 5 but for the displacement component perpendicular to the loading direction $u$.  

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Figure 7. Same as Figure 5 but for the strain element in the loading direction $\varepsilon_{yy}$.

Figure 8. Same as Figure 5 but for the strain element perpendicular to the loading direction $\varepsilon_{xx}$.

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placement amplitude at a point depends strongly on its distance from the fault zone (Bai YZ et al., 2012). This relationship demonstrates that strain concentration decays with distance from the fault zone (Gu GH et al., 2011; Zhao YH et al., 2014), which is consistent with our laboratory experimental results.

5. Conclusion and Discussion

In this study, laboratory images of marble samples containing fabricated cracks are processed by the DICM to analyze the evolution of deformation fields under different loading conditions. We find that the displacement and strain fields increase in amplitude with increase in load. The displacement field changes more and more severely as the load increases, especially the strain near the fabricated crack. Moreover, the strain gradually concentrates on both sides of the crack, and the strain concentration decays with distance from the crack. In the experiments, the samples do not always rupture along the crack, as expected, but break into layered pieces, a result that may...
be due to the heterogeneity induced by anomalous distribution and evolution of the strain fields. Therefore, in future experiments, we will adjust the crack design to improve the verisimilitude of the experiment. In addition, the experimental samples used in the laboratory have been relatively uniform, which makes it comparatively easy to measure physical parameters such as Young's modulus, while the actual field rocks are influenced by joints, water, and other inhomogeneities, making physical parameters difficult to measure. Thus, results obtained in the laboratory cannot be directly applied and must be at best suggestive. In future experiments, multiple sets of controlled operations can be carried out by changing the laboratory conditions such as temperature and pressure.

We have compared the results of our laboratory experiments with the GPS-observed coseismic horizontal displacement around the LFZ during the 2008 Wenchuan earthquake, and found consistency between field observations and laboratory experimental results. In addition to GPS observations, the InSAR technique can also be used to monitor coseismic displacements. Table 2 presents the information of the seven GPS stations along the yellow line in Figure 12 and their coseismic horizontal displacements.

**Table 2. Information of the seven GPS stations along the yellow line in Figure 12 and their coseismic horizontal displacements**

| Station name | Geographical coordinates | East-west displacement (m) | North-south displacement (m) |
|--------------|--------------------------|---------------------------|----------------------------|
| H028 (Aba)   | 101.71, 32.90            | 0.047±0.0036              | 0.029±0.0036               |
| H031 (Hongyuan) | 102.50, 32.79         | 0.066±0.0030              | −0.046±0.0029              |
| H037 (Heishui) | 103.17, 32.08           | 0.222±0.0015              | −0.113±0.0015              |
| H044 (Mianzhu) | 104.19, 31.35           | −0.983±0.0026             | 0.397±0.0026               |
| H048 (Deyang) | 104.44, 31.16           | −0.303±0.0015             | 0.099±0.0015               |
| 2037 (Sabtai) | 105.07, 31.08           | −0.115±0.0029             | 0.026±0.0027               |
| 2052 (Suining) | 105.55, 30.51           | −0.042±0.0026             | 0.020±0.0024               |

**Figure 12.** Coseismic horizontal displacement field of the 2008 Wenchuan earthquake observed by GPS. The yellow line across the Longmenshan Fault Zone shows the locations of the seven points whose GPS observations of coseismic horizontal displacements are displayed in Figure 12.

**Figure 13.** Variations of GPS observed horizontal coseismic displacements with distance from the Longmenshan Fault Zone.
be used to monitor fault zone deformation, which provides detailed description of how the regional strain field changes with time. Therefore, activities during an earthquake and even before an earthquake can be monitored and analyzed, which may provide useful data for the detection of earthquake precursors in the future.

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