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Experimental analysis and characterization of damage evolution in rock under cyclic loading

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1. Introduction

In many rock engineering fields such as underground excavation, rock slope and mining activities, rock materials often experience cyclic loading. Due to the intrinsic micro-structure of rocks, the mechanical properties and the failure process under repeated stress differ enormously from those under static loads.[1–3] Thus, the study of the damage evolution of rocks that approach failure when subjected to cyclic loading is significant because such a study can help to better understand the damage and failure mechanism of rocks for practical engineering problems. In the past decades, some theoretical work on rock damage and failure under complex loading has been developed. Xie et al. discussed the relationship among energy dissipation, energy release and strength during failure process of rock under cyclic loading.[4] Based on micromechanics, the effective properties of brittle solids with numerous interacting microcracks have been predicted.[5] An inverted S-shaped nonlinear fatigue damage cumulative model was derived based on the law of axial irreversible deformation development of rock.[6] Many experimental cyclic loading tests have also been conducted to investigate the mechanical behavior of rocks. Macro tests clearly demonstrated that cyclic loading leads to the progressive weakening of rocks[7,8] and showed that the uniaxial compressive strength weakens with the increase in the applied stress level and the number of loading cycles.[9] The effects of loading frequency and confining pressure conditions on the strength and deformation characteristics of sandstone sample subjected to cycling loading were also experimental analysed.[10,11] In addition, different types of experimental techniques, such as optics and acoustics, were used to observe the failure process of rock materials during loading. For example, fluorescent microscopy was used to observe the initiation and propagation of new microcracks in bohus granite under cyclic loading.[12] Damage to marble induced by large strains accumulated during cyclic loading was recorded using the interferometric technique.[13] Transmitted ultrasonic waves were used to assess the development of microcrack damage in a cylinder of Lac du Bonnet gray granite subjected to uniaxial cyclic loading.[14] The crack activities in rock failure tests were monitored via the acoustic emission (AE) technique, and the work indicated that crack activities increases along with an increase in the cycle number.[15] However, the influence of cyclic loading on damage evolution of rock remains not very clear, and how to effectively characterize the damage and failure process based on experimental work still need to be further investigated. As a result, it is necessary to analyze the damage evolution during the entire cyclic loading process, especially using the full-field measurement technique and corresponding experimental analysis method.

Among the types of experimental methods, digital image correlation (DIC) is an effective method for obtaining the displacement and strain fields on the surface of materials, with the advantages of providing full-field, real-time, online, and non-contact

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measurements as well as flexibility in the technique.[16–19] The method has been extensively applied to various materials, such as metallic foil,[20,21] composite,[22] the Portevin-Le Chatelier bands of aluminum alloy,[23,24] and porous carbonate.[25] Moreover, the deformation evolution and crack development of rocks under different loadings were observed using DIC.[26–37] Ma et al. have defined the standard deviation of the DIC strain field as the damage variable to describe the damage evolution of rock under uniaxial compression.[38] A localization factor L_f is proposed to characterize the strain localization of rock under uniaxial compression.[39]

In this work, axially cyclic compression tests with different amplitudes are conducted on sandstone and the damage evolution of samples are investigated using DIC. The tests record the load-time curves and exhibit the influence of loading amplitudes on the uniaxial compressive strength of rock. Based on DIC measurements, the displacement fields and apparent strain fields are presented to reflect the damage evolution and the crack development of rock till failure. Through a statistical analysis on the apparent strain fields, a main feature variable that can effectively describe the damage is determined. Furthermore, two factors, the damage localization factor and the damage severity factor, are proposed to characterize the damage evolution in sandstone under axially cyclic loading.

2. Experiment

2.1. Specimen and experimental set-up

An example specimen and the schematic illustration of the experimental set-up are shown in Fig. 1. The rock type chosen herein is Yunnan sandstone, and the dimensions of each specimen are 25 mm × 25 mm × 50 mm. The front surface of the rock specimen was sprayed with artificial random speckles for a better DIC analysis. The experiments were performed on a CSS-44100 electric universal machine at a constant displacement loading velocity of 0.12 mm/min. During the loading process, the images of the surface were continually captured by a Basler A202k charged couple discharge (CCD) camera (1004 × 1003 pixels) at a rate of 1 fps (frame per second). The field view of CCD camera is 62 mm × 62 mm, i.e., the length-pixel ratio is 61.7 μm/pixel.

2.2. Digital image correlation method

Digital image correlation is an optical measurement technique that has been widely used for deformation field measurements of the object surface.[16,17] The basic principle of DIC is to track the same pixel points based on comparison of the undeformed image with the deformed image. Normally, instead of tracking a single pixel, a subset centered at the considered point is tracked in the deformed images using a selected correlation coefficient. The correlation coefficient in that process is defined as follows:

$$C(X)=\frac{\sum_{i=1}^{m}\sum_{j=1}^{m}\left[f\left(x_i,y_j\right)-\bar{f}\right]\cdot\left[g\left(x_i^*,y_j^*\right)-\bar{g}\right]}{\sqrt{\sum_{i=1}^{m}\sum_{j=1}^{m}\left[f\left(x_i,y_j\right)-\bar{f}\right]^2\cdot\sum_{i=1}^{m}\sum_{j=1}^{m}\left[g\left(x_i^*,y_j^*\right)-\bar{g}\right]^2}} \quad (1)$$

where $f(x,y)$ is the gray level value at coordinate (x,y) for the reference image; $g(x^*,y^*)$ is the gray level value at coordinate (x^*,y^*) for the target image, $\bar{f}$ and $\bar{g}$ are the average gray values of the image $f(x,y)$ and $g(x^*,y^*)$. By searching maximum value of image correlation, the displacement fields can be determined. Then the strain fields of the analysis region can be obtained from displacement fields.

In this paper, the image was processed by our written-in-house DIC software, the calculation subset size is 21 × 21 pixels, and the step length is chosen as 10 pixels. The displacement measurement accuracy in our test was at least 1 μm based on calibration. The strain fields were calculated from displacement fields by the point-wise least squares method proposed in Ref. 40 with a window size of 21 × 21 pixels.

2.3. Experimental procedure

The behavior and the failure process of rock are strongly linked to the loading history. In order to investigate the damage evolution of rock under cyclic loading, uniaxial cyclic compression tests with different loading levels and equal cycle numbers were performed on a typical rock material. Uniaxial compression tests were first conducted on sandstone specimens under no confining pressure condition, and the maximum axial load was approximately 55 kN. It was found from tests that the damage was close to be localized under static compression when the load reached to 30 kN, which may due to the heterogeneous of sandstone and experimental constraint condition. Thus three groups of uniaxial cyclic loading tests with peak amplitude P of 10 kN, 20 kN, and 30 kN were performed to discuss the relationship between damage evolutions and loading amplitudes. Considering that the effect of cyclic loading on damage evolution is obvious when the localized damage is closed to be formed in the specimen, six cycles of load-unload were conducted on sample and then the rock was compressed to failure in each test.

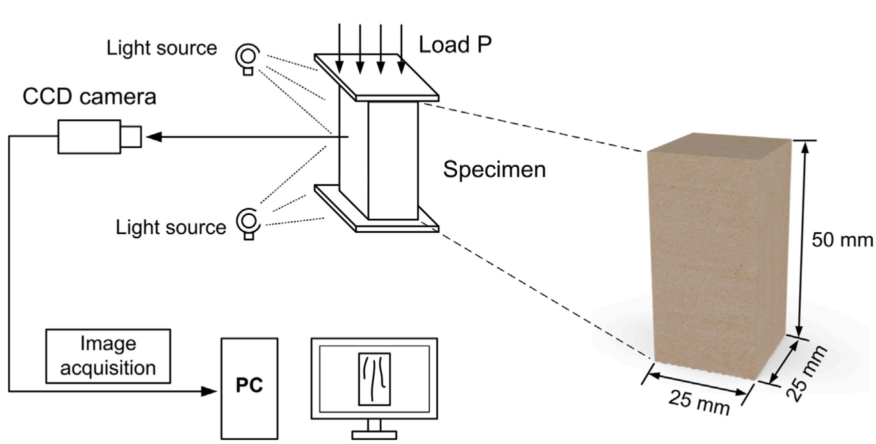

Fig. 1. Schematic illustration of the experimental set-up and a specimen.