International Journal of Rock Mechanics & Mining Sciences 94 (2017) 82–89

Contents lists available at ScienceDirect

International Journal of Rock Mechanics & Mining Sciences

journal homepage: www.elsevier.com/locate/ijrmms

Dynamic mechanical behavior and fatigue damage evolution of sandstone under cyclic loading

Bi Sun[a,b], Zhende Zhu[a,b], Chong Shi[a,b,*], Zhihua Luo[a,b]

[a] Key Laboratory of Ministry of Education of Geomechanics and Embankment Engineering, Hohai University, Nanjing 210098, China
[b] Jiangsu Research Center for Geotechnical Engineering, Hohai University, Nanjing 210098, China

A R T I C L E I N F O

Keywords:
Load-Unload Response Ratio (LURR)
Fatigue damage model
Multilevel amplitude
Cyclic loading

1. Introduction

A number of earthquake aftershocks triggered by mainshock can cause severe damage to mainshock-damaged rock engineering such as deeply buried tunnels and chamber. They also can also lead to the increase of the direct loss, downtime, and fatalities of mining equipments during an earthquake sequence.[1–6] The mechanical behavior of rocks is more complicated when the rock materials experience cyclic loadings induced by earthquakes, aftershocks, etc.[7–9] The fatigue damage evolution of rocks is crucial to the stability of the engineering structure under the cyclic loading. Therefore, many researchers have carried out the study on the fatigue damage of rocks subjected to cyclic loadings.

Bagde et al.[10,11] performed uniaxial compression tests on rock samples subjected to dynamic cyclic loading with various amplitudes and frequencies. The results meant that the fatigue strength of the rock under dynamic cyclic loading was found to be influenced mainly by the quartz content, texture and structure in the rock. With the increasing of the loading frequency and amplitude, the average Young's modulus and the dynamic axial stiffness of the rock were reduced. The dynamic energy was found to be independent of the testing conditions, and the dynamic energy sustained by the rock trends to increase with the frequency and amplitude. Fuenkajorn et al.[12] investigated the effect of cyclic loading on the mechanical properties of Maha Sarakham salt. They found that the salt compressive strength decreased with the number of loading cycles according to a power function, and that the elastic modulus decreased slightly during the first few cycles and kept constant until failure. Xiao et al.[13,14] proposed an inverted-S damage model which can represent the whole fatigue damage process of both the constant amplitude and variable amplitude cyclic loadings. Chen et al.[15] applied the fluorescent method, which can observe the morphogenesis of the microcracks using an optical microscope, to investigate the fatigue process of granite subjected to the cyclic loading of uniaxial compression. Liu et al.[16,17] applied several levels of confining pressure and frequency during axial cyclic loading in order to assess the effects of the confining pressure and frequency on the mechanical properties and fatigue damage evolution of sandstone samples subjected to the cyclic loading. Their results showed that the axial strain at the position of sample failure increased with the confining pressure and frequency. Meanwhile, they proposed a damage variable D which could investigate the dynamic damage evolution of sandstone samples subjected to axial cyclic loadings. Zhang et al.[18] wanted to investigate the damage behavior of rock under cyclic uniaxial compression by means of digital image correlation (DIC) method which can be efficient to track the deformation behavior and to identify the length of cracks formed. Momeni et al.[19] performed a series of laboratory tests to explore the fatigue damage process of the granitic rock, and thought that: with the decrease of maximum stress, the fatigue life increased because of the decrease of the plastic deformation. Zhou et al.[20] aimed to study the effects of the frequency and the lower limit load ratio on the fatigue life using MTS servohydraulic landmark test system. They found that: with the increase of frequency and lower limit load ratio, the fatigue life of sandstone decreased at first and then increased; in addition, the rock has memory effect under multi-level cyclic point loadings.

However, there are few researches on the evolution law of rock fatigue damage under the condition of multi-level amplitude cyclic loading with confining stress, but the rock masses are likely under the

* Corresponding author at: Key Laboratory of Ministry of Education of Geomechanics and Embankment Engineering, Hohai University, Nanjing 210098, China.
E-mail address: shichong81@126.com (C. Shi).

http://dx.doi.org/10.1016/j.ijrmms.2017.03.003
Received 20 April 2016; Received in revised form 4 February 2017; Accepted 7 March 2017
1365-1609/

cyclic loading with different amplitudes in practical engineering. In this study, the damage evolution law and the damage accumulation mode of sandstone were analyzed based on the Load-Unload Response Ratio (LURR) by the multi-level amplitudes cyclic loading tests under the different confining pressure. A method is proposed for the fatigue damage evolution model of rock under multi-level amplitudes cyclic loading with confining pressure, which can provide theoretical basis for the stability analysis of rock and soil engineering structure, and have practical engineering application value.

2. Basic test plan

2.1. Sample preparation

The natural sandstone obtained on site was sealed with plastic film in order to prevent the change of water content and maintain the status quo of rock. The sandstone was light gray with a middle grain sand structure. The sandstone specimens consist of minerals of mainly quartz and feldspar. The density of sandstone is 2620 kg/m^3, with a Poisson ratio of 0.22. The sandstone was hard and compact with porosity of 2.64%. The sample was processed to the standard cylinder with the size of 50 mm in diameter and 100 mm in height, which is suggested by the American Society of Testing Materials (ASTM) in the laboratory, and was grinded to make the upper and lower ends of the cylinder parallel and smooth. At least twenty-seven samples divided into five groups are tested under the triaxial cyclic loading.

2.2. Test equipment

The cyclic loading tests were performed with the rock servocontrolling rheological testing machine. This equipment is composed of a data collection system, an operating platform, a pressure pump and a triaxial cell. It can realize the automatic self-compensation of the pressure by three pumps with high precision and high pressure, which can control the confining pressure, the deviatoric stress and the pore pressure. It can be realized by the rock servocontrolling rheological testing machine that the whole computer course control, operation is fully automatic and data collected automatically is exchanged with a computer. It can complete the uniaxial compressive test, triaxial conventional compression test and cyclic loading test, etc. The confining pressure ranges from 0 to 60 MPa, and the maximum deviatoric stress could reach to 500 MPa. Axial displacement is measured by the LVDTs (linear variable displacement transducer) installed inside the triaxial chamber. During the test, the experimental data of the stress-strain curve was recorded by the acquisition system thanks to the corresponding sensors.

2.3. Test procedure

The samples were applied under axial compressive loading with increasing rate of 1 kN/s until the deviatoric stress reaches to the lower limit value $\sigma_{\min}$ with the confining pressure of 1 MPa, 3 MPa and 5 MPa respectively, and then were applied under cyclic loading. The lower limit value $\sigma_{\min}$ was set to 10% of the sample compressive strength under the same confining pressure. The cyclic loading was divided into 4–5 levels and each level includes thirty loading cycles. The stress speed control mode was adopted in the test. The load condition of the test is shown in Table 1.

In order to confirm the tests under the condition of multi-level amplitude cyclic loading with confining pressure, the uniaxial and triaxial static compression tests of sandstone samples were carried out before the multi-level amplitude tests. The uniaxial compressive strength of sandstone is 123.44 MPa. Under the confining pressure of 1 MPa, 3 MPa and 5 MPa, the compressive strength of sandstone is 132.47 MPa, 166.20 MPa, and 182.99 MPa, respectively, as shown in Fig. 1.

Table 1
Load condition.

Confining pressure/MPa	Level	Lower limit of loading/MPa	Upper limit of loading/MPa
1	4	12	20,40,60,80
3	4	15	40,60,80,100
5	5	18	40,60,80,100,120

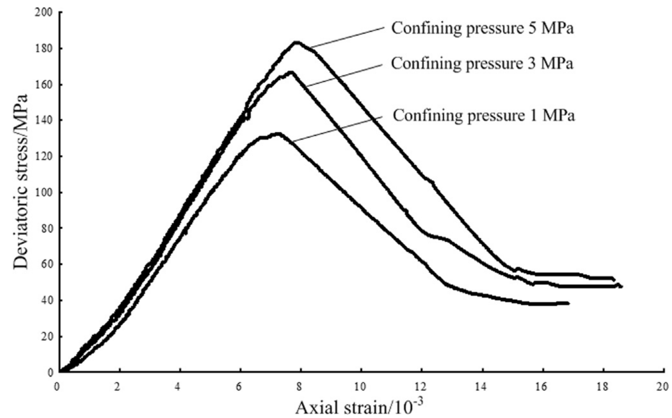

Fig. 1. Typical static stress-strain curves of sandstone under different confining pressures.

3. Analysis of test results

From Fig. 2, it can be found that the stress-strain hysteresis loop of every cyclic loading is with a cusp-shape instead of oval-shape at the place of stress inversion. It indicates that the elastic deformation responses of the samples are rapid when the external load is inverted. The axial strain increases with the dynamic stress, and the hysteresis loop moves gradually to the right. The hysteresis loop area increases gradually with the stress amplitude, which represents the degree of closure and opening of the micro fracture as well as the damage accumulation and energy dissipation in a cycle.[21] Therefore, it shows that the loss of energy and the irreversible deformation of the sample caused by damage increase with the stress amplitude.

4. Rock fatigue damage model

4.1. Rock fatigue damage model under constant amplitude cyclic loading and constant confining pressure

The condition of constant amplitude cyclic loading with constant confining pressure is different from that of the uniaxial or multi-axial cyclic loading. Therefore, the dimension parameter of the Chaboche multi-axis fatigue damage model[22] is redefined to adapt to the calculation of fatigue damage accumulation under the constant confining pressure.

$$\frac{\mathrm{d}D}{\mathrm{d}N} = [1-(1-D)^{(1+\beta)}]^{\alpha}\left[\frac{\sigma_s}{M(1-D)}\right]^{\beta} \tag{1}$$

where D is the damage variable; N is the times of cycle; β is a material constant related to the temperature; σ_s is the amplitude of the deviator stress; M is a parameter which depends on the confining pressure, the material parameter and the temperature; α represents the stress exponent as below:

$$\alpha = 1 - \gamma\left(\frac{\sigma_{\max}-\sigma_f}{\sigma_u-\sigma_{\max}}\right) \tag{2}$$

where $\sigma_{\max}$ is the upper limit of the deviatoric stress; σ_f is the fatigue damage threshold of rock; σ_u is the ultimate stress; γ is the material parameter.