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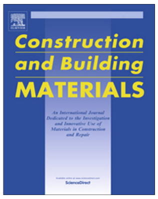

Characteristics of dissipated energy of concrete subjected to cyclic loading

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HIGHLIGHTS

- Dissipated energy and damage variables in CDT have similar evolution characteristic.
- Damage evolution and maximum load level can be well fitted by exponential functions.
- Damage evolution and minimum load level can be well fitted by logarithmic functions.
- The damage evolution inside the concrete is inhomogeneous.
- Energy dissipation and damage evolution is stress path dependent.

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ABSTRACT

Based on dissipated energy approach (DEA), the energy dissipation characteristics of concrete samples subjected to uniaxial cyclic loading have been investigated. The effect of different cyclic load levels on energy dissipation is quantitatively analyzed by different damage indicators during cyclic fatigue tests. It is concluded that the cumulative speed of energy dissipation and increasing growth-rate of damage indicators in Continuum Damage Theory (CDT) follow an exponential function in relation to the maximum cyclic load level and follow a logarithmic function in relation to the minimum cyclic load level. The loading strategy has an effect on total energy dissipated during fatigue tests, in other words: Energy dissipation and damage evolution are stress path dependent.

1. Introduction and state of the art

The brittle and quasi-brittle materials, such as rocks and concrete, are widely used in civil engineering, mining, tunneling and the energy sector. Cyclic loading can lead to severe damage or failure even when the load level is significantly lower than the static short term strength. 80% of all failure cases of engineering structures are caused by fatigue damage [1,2]. In literatures, concrete and different types of rocks subjected to cyclic loading have been investigated. A systematical experiment on the size effect of cylindrical concrete was conducted by Sinaie et al. [3] and found the sample diameter and aspect ratio have the obvious effect on strength and strain, the DEM model was further established by Sinaie et al. [4] which can well reproduce the cyclic features of concrete specimens and can be used to predict residual strength by considering damage. Bagde et al. [5] studied the fatigue properties of sandstone subjected to uniaxial cyclic loading and it was concluded that the cyclic loading amplitude and frequency can influence the fatigue strength and dynamic deformation characteristics. The fatigue characteristic of Alvand monzogranitic rock was studied by Momeni et al. [6], they found that fatigue life increases according to a power function with decreasing maximum stress and fatigue life increases in an exponential way with rise of loading frequency. Ghuzlan et al. [7] investigated the fatigue behavior of asphalt concrete and found that energy dissipated during cyclic loading is influenced by maximum load and load amplitude. Furthermore, the fatigue behavior of Maha Sarakham rock salt was investigated by Fuenkajorn et al. [8]. They stated that elastic modulus decreases slightly during first few cycles and then tend to remain constant and the elastic modulus is independent of maximum load.

The CDT and DEA are the two important approaches to investigate fatigue damage [9]. Researchers adopted CDT to establish constitutive equations between the selected variables and damage evolution. A continuum damage model for fatigue load of concrete

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was established by Alliche [10]. This damage model can describe the material degradation under fatigue load by introducing tensorial damage parameters. Xiao et al. [11] suggested that the damage variables should have distinct physical meaning and should be measured and applied conveniently. The authors stated that axial residual strain is the most appropriate variable to reflect the damage evolution. Oneschkow [12] investigated the evolution of strain and stiffness of high-strength concrete subjected to fatigue load. He found that the change of waveform from sinusoidal to triangular leads to larger values of strain and an increasing loss of stiffness. Baluch et al. [13] established a damage model based on CDT for predicting the fatigue properties of concrete subjected to cyclic loading, which is able to predict the residual strength of concrete subjected to initial damage induced by a given number of stress cycles. Lee et al. [14] proposed a fatigue prediction model for asphalt concrete based on the elasto-visco-elastic correspondence principle. This model can account for the effects of loading rate and stress level on fatigue features. Generally, CDT can describe the evolution of damage based on constitutive equations, however, the damage variables selected in CDT always reflect single aspect, such as axial/radial strain or elastic modulus.

The DEA is able to reflect damage of materials during cyclic loading by considering the energy dissipated or absorbed by the sample. Compared to CDT, the DEA has the following advantages: 1. DEA can consider strain and stress concurrently. In comparison to the CDT which only considers a single damage variable the damage characterized by DEA can more accurately describe material behavior observed in laboratory testing; 2. During the stationary stage of fatigue test, the increment of strain is hard to measure to characterize the damage due to the extremely small change of strain. However, the DEA can still clearly reflect the dissipated energy in the stationary stage, which can continuously represent the progressive damage. Badge [15] found that the dissipated energy is increasing with frequency and load amplitude. The energy dissipated by the rock could be treated as an inherent characteristic. Lei et al. [9] proposed a concrete fatigue life prediction method, which is based on accumulated dissipated energy. It was concluded that the dissipated energy within each cycle has the direct relationship to the stress level. Tepfers et al. [16] investigated the energy absorption of plain concrete in fatigue tests and found that the absorbed energy at failure under uniaxial compression seems to be the same for static load as well as for fatigue load. Xie et al. [17,18] discussed the intrinsic relations between dissipated energy, energy release, and structural failure of rocks during loading and unloading stages and stated that dissipated energy acts as an internal factor connected with damage and irreversible deformation. Naderi [19] performed a series of fatigue tests on glass/epoxy laminates. He concluded that when the load is relatively low, the dissipated energy due to damage is small compared to dissipated energy due to heat. With increasing of load level, the proportion of dissipated energy due to damage increased. Jiang [20] and Tong [21] suggested that the accumulated dissipated energy can be used as a proper variable to reflect the damage of materials because there is no discontinuity in the curve. Shadman et al. [22] proposed an approach based on dissipated energy to predict fatigue life of porous asphalt. The authors found that the total dissipated energy at failure can be forecasted by regression equations relating cycle number and total dissipated energy. Shen et al. [23] pointed out that the fluctuation of energy dissipation between two consecutive cycles can indicate the development of damage.

For visco-elastic materials, such as asphalt and epoxy/glass laminate, the strain-controlled loading method is usually adopted in fatigue tests [14,19,22,24], and the failure is defined when a certain reduction in modulus is reached (typically a 50% reduction is used [24], see Fig. 1(a)). For brittle or quasi-brittle materials, such as concrete, rock and cement, the stress-controlled loading method is usually adopted in fatigue tests [9–13]. The failure is defined when the hysteresis loop can't form any longer, as illustrated in Fig. 1(b), or macro cracks appear at the sample surface.

Many researchers found that maximum load level during cyclic loading has influence on fatigue of the material. Ge et al. [25,26] investigated the threshold value of load level during fatigue tests. He mentioned that in case the maximum load level is smaller than the threshold value, the axial, radial and volumetric irreversible strain tend to be constant. However, when maximum load level is larger than the threshold value, the axial, radial and volumetric irreversible strain increase with increasing number of loading cycles. Rao et al. [27] conducted fatigue tests on Hyderabad granites. He concluded that when load level is larger than threshold value, the Kaiser Effect and AE events are more pronounced and that the threshold value is comparable to the dilatancy limit.

This paper is based on DEA to investigate the characteristics of dissipated energy of concrete samples subjected to stress-controlled uniaxial cyclic loading. The effect of cyclic load level on the characteristics of dissipated energy is quantitatively investigated. The dissipated energy within the DEA concept is compared with variables used in CDT and the evolution of damage variables in the two approaches are analyzed.

2. Lab test set-up

Twelve cylindrical samples (125 mm height (H) and 50 mm diameter (Φ)) have been produced using concrete of type C25/30 XC4 XF1. Before fatigue test, the ultrasonic wave speed was measured to evaluate the scatter of the physical properties (see Fig. 2). The numbers #1 to #12 were assigned to the samples indicating increasing values of p-wave speed. The physical properties of the samples are listed in Table 1. Sample #4 and #9 were selected to measure the uniaxial compressive strength (UCS) with monotonically increasing load (no cycles) at a rate of 5 MPa/min. In order to prevent pre-failure in fatigue tests, a reference value of 18 MPa was adopted as UCS based on the results listed in Table 2.

The TIRA 28500 Test System illustrated in Fig. 3(a) was used for the fatigue tests. The system is able to perform static and dynamic compression tests, has a compressive loading capacity of 500 kN, a piston stroke length of 1300 mm and a maximum loading velocity of 100 mm/min. The axial deformation of the whole sample l_w can be directly measured through the displacement of the loading plate. The used external measuring system which consists of vertical and radial strain gauges is shown in Fig. 3(b). The external axial strain measurement (ε_a) is performed at the central part of the sample and has a gauge length l_m of 50 mm. Radial (circumferential) strain ε_r is measured through a strain gauge also placed at the central part of the sample.

The characteristics of dissipated energy are investigated by two strategies: 1. fixing minimum load level and enhancing maximum load level; 2. fixing maximum load level and reducing minimum load level; the detailed testing scheme is evident from Table 3 to Table 4.

3. Test results

Concrete as quasi-brittle material is always exchanging (absorbing and releasing) energy with its surrounding system during cyclic loading [9,28]. The amount of dissipated energy during one single cycle reflects the ability of the material to resist damage induced by external loading. The more energy during one cycle is dissipated the more damage is generated inside the material. Total dissipated energy of sample can be generally divided into two parts: one is dissipated by heat convection, conduction and