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Effect of loading frequency and stress level on low cycle fatigue behavior of plain concrete in direct tension

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HIGHLIGHTS

- Cyclic tension tests at different frequencies and stress levels were carried out.
- Fatigue life increases with the increasing of the loading frequency.
- Stiffness degradation shows a typical three-stage process with cyclic number.
- A damage model based on stiffness degradation and the strain rate were developed.
- A fatigue model is proposed to characterize the deformation and damage behavior.

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ABSTRACT

Due to the difficulties of direct tensile testing on concrete, only limited and often conflicting data are available. In this paper, to investigate the effect of loading frequency on the low cycle fatigue behavior of plain concrete in direct tension, several series of cyclic tension tests at different frequencies and stress levels were carried out. Especially the behavior before the initiation of macroscopic fatigue cracks in concrete, such as irreversible strain accumulation and damage evolution with the number of fatigue cycles through experiments. Test results show that the fatigue life increases with the increasing of the applied loading frequency, while decreases with the increasing of stress level. The stiffness degradation shows a typical three-stage process with the number of fatigue cycles. A new damage model considering the effect of the applied loading frequency and stress level is proposed based on the stiffness degradation and the secondary strain rate during low-cycle fatigue tests. Also, a fatigue model is proposed herein to characterize the deformation and damage behavior of concrete under cyclic tension. The calculated fatigue lives of concrete are compared with experimental data and show good fitting results.

1. Introduction

Concrete is a widely used material that is typically used in situations in which it is required to withstand a large number of cycles of repeated loading during its service life. Fatigue behavior of plain concrete, in particular, is an important parameter in the design of concrete pavement for roads, air fields, and heavy-duty industrial yards. From 1960s research efforts began to be devoted to concrete structures subjected to earthquakes [1,2]. These structures may receive several cycles to several thousand cycles of seismic loading. The term "low-cycle fatigue" refers generally to this range of loading. For convenience, Hsu [3] defined "low-cycle fatigue" as the approximate range from 1 cycle to 1000 cycles, and "high cycle fatigue" as the approximate range from 1000 to 10,000,000 cycles.

A review of the literatures shows that several investigators have carried out laboratory fatigue experiments to explore the effect of many parameters on fatigue behavior of plain concrete [4–6]. These studies adopted a relationship between the stress level S (the ratio of the maximum loading stress to the ultimate strength), the stress ratio R (the ratio of the maximum loading stress to the minimum loading stress), and the number of loading repetitions N_f, which causes fatigue failure. The relationship between fatigue life and stress level established is known as $S \sim N_f$ curve.

Graf and Brenner [7] was the first to investigate the loading frequency effect on fatigue behavior of concrete, their results showed that the fatigue behavior remained unchanged when the frequency was in the range from 4.5 Hz to 7.5 Hz, and the fatigue life decreased

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when the frequency was lower than 0.16 Hz. Mordock [8] suggested that the effect of loading frequency on fatigue life of concrete was significant when the stress level was larger than 0.75. Zhang et al. [9] investigated the loading frequency effects on compressive fatigue behavior of concrete, and proposed a predictive formula for fatigue life of concrete considering frequency. Medeiros et al. [10] studied the loading effect on fatigue behavior of plain and fiber reinforced concrete. Their results showed that the effect of frequency on the fatigue characteristic of plain concrete was significant, and the addition of fiber into concrete reinforced the fatigue behavior of concrete under low loading frequency.

Tensile behavior of concrete has significant influence on the formation of cracks which in turn affect the overall stiffness of concrete structures [11]. Although the influence of tensile properties on the overall behavior of concrete structures has been acknowledged for a long time, the fatigue characteristic of concrete in tension has not been studied in much detail. Most of the studies on fatigue performance of concrete have been under compressive loading. The fatigue response of concrete in direct tension has received little attention until now, mainly because of the experimental difficulties involved [12,13].

Test data of the low cycle behavior of concrete in direct tension is rather limited. In this paper, to investigate the effect of loading frequency on the low cycle fatigue performance of plain concrete in direct tension, several series of cyclic tension tests at different frequencies were carried out. Especially the behavior before the initiation of macroscopic fatigue cracks in concrete, such as irreversible strain accumulation and strain range variation with the number of fatigue cycles through experiments. Also, a fatigue model is proposed herein to characterize the deformation and damage behavior of plain concrete under cyclic tension.

2. Experimental program

2.1. Preparation of concrete test specimens

The concrete specimens with the same mix proportion were used in the tests. The mix proportion by weight of concrete used in this paper is shown in Table 1. The concrete were poured in polyvinyl chloride (PVC) molds. The dimensions of the PVC models were diameter of 73 mm and height of 250 mm. The specimens were cured in water for 90 days after 2 days in PVC molds. Before testing, two ends of the specimen were cut by the double knife rock cutting machine. This method can ensure two ends of the specimen were parallel to each other and perpendicular to the longitudinal axis. The dimensions of the cut specimen were diameter of 73 mm and height of 146 mm. The steel discs were pasted on the two ends of cylinder specimen by the structural adhesive. Thus the specimen and the steel discs become an integral. Besides the specimen and the test machine were connected together by the spherical joint system. The spherical joint can also automatically adjust the specimen position to reduce the eccentricity. An anchor rod in the spherical joint system was connected with the fixture of testing machine, as shown in Fig. 1.

2.2. Test procedure

The low cycle fatigue tests were carried out through MTS 810 machine (servo hydraulic control). The loading capacity of the testing system is 250 kN. The deformation of concrete in cyclic tension was measured by the average value of two extensometers. These two extensometers were fixed on the two opposite sides of the concrete specimen. The gauge length of the extensometer is 130 mm. The strain of the specimen was determined by the average value of the two extensometers divided by the gauge length. The frequency of data acquisition of fatigue test was 200 Hz. Three maximum load levels calculated according to the stress levels of 0.85, 0.90 and 0.95 were adopted in this investigation. The minimum load during one fatigue test was 0.2 kN (near-zero). The loading frequencies for one stress level are 1/4, 1 and 4 Hz, respectively. Note that load control was used during these tests. At least four concrete specimens were repeated for one fatigue test condition. The failure concrete specimens after low cycle fatigue tests are shown in Fig. 2.

Table 1
Concrete mix proportions by weight.

Constituent (kg/m^3)					w/c
Water	Cement	Sand	Aggregate	Water Reducer	
205	410	668	1089	2.05	0.50

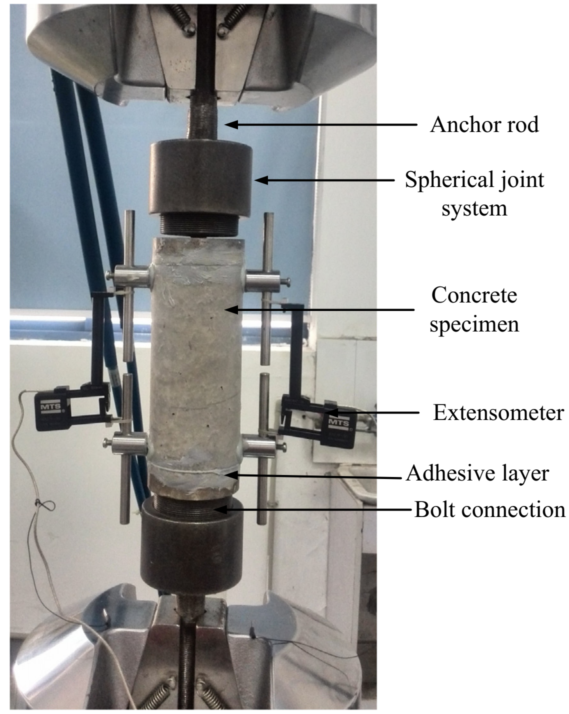

Fig. 1. Experimental set-up for cyclic tension test of concrete.

3. Test results and discussion

3.1. Fatigue life

According to Medeiros [10], the repetition numbers of cycles to failure can be called as fatigue life N_f. The test results for fatigue life of concrete under cyclic tension are shown in Fig. 3. It can be found from Fig. 3 that the test data exhibits obvious discrete characteristics. The statistical characteristics of fatigue life of concrete in compression and flexure have been investigated by Singh and Kaushik [14] and Bajaj et al. [15]. In this paper, the average value for test data under one loading regime is adopted for analyzing and discussion.

It can be found from Fig. 3 that the effect of stress level and loading frequency on fatigue life of concrete in direct tension is significant. Generally, the fatigue life decreased with the increasing of stress level, while the fatigue life of concrete increased with the increasing of loading frequency. The stress level effect on fatigue life of concrete can be ascribed as the damage accumulation rate. The higher stress level results in a higher damage in per unit cycle.