International Journal of Fatigue 96 (2017) 261–269

Contents lists available at ScienceDirect

International Journal of Fatigue

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

Experimental study and analytical modeling on hysteresis behavior of plain concrete in uniaxial cyclic tension

Xudong Chen [a,*], Yebo Huang [a], Chen Chen [a], Jun Lu [b], Xiangqian Fan [b]

[a] *College of Civil and Transportation Engineering, Hohai University, Nanjing 210098, PR China*
[b] *Department of Materials and Structural Engineering, Nanjing Hydraulic Research Institute, 210024, PR China*

ARTICLE INFO

Article history:
Received 21 October 2016
Received in revised form 21 November 2016
Accepted 1 December 2016
Available online 2 December 2016

Keywords:
Plain concrete
Uniaxial cyclic tension
Hysteresis
Dynamic elastic modulus
P-M model

ABSTRACT

The hysteresis phenomenon can be observed in concrete when it is subjected to the cyclic load. The uniaxial tensile cycling tests with different frequencies and loading regimes were carried on the concrete by using the electric-hydraulic servo-controlled material testing system (MTS 322). The objective of this paper is to investigate the hysteresis phenomenon of concrete stress-strain curve, the axial energy consumption per unit volume, dynamic elastic modulus, damping ratio, and the effect of the cyclic number and loading frequency on these mechanical characteristics. The Preisach-Mayergoyz (P-M) model has also been used to analyze the hysteresis loops of concrete. It was concluded that the hysteresis loops curve move towards the direction of the axial strain with the number of cycle increasing. With the increasing of cycle number, the axial energy consumption per unit volume decreases rapidly and then the decrease rate tends to be stable. With the increasing of cyclic frequency, the value of dynamic elastic modulus decrease. Under the same loading frequency, the value of dynamic elastic modulus and damping ratio decrease as the number of cycle increases. The P-M model is appropriate for modeling the experimental hysteresis loop and energy consumption of concrete.

1. Introduction

The hysteresis phenomenon is a common nonlinear response in concrete [1–4]. Under the uniaxial cyclic load, the stress-strain curve of concrete shows the feature of nonlinearity, hysteresis, energy dissipation [5,6]. Under cyclic loading, the axial irreversible deformation of concrete can be divided into three phases which are initial deformation, steady deformation and accelerated deformation [7,8]. The accumulation of three phases of deformation leads to the concrete failure [9–12]. It is worthwhile to note that when the maximum of the cyclic load is lower than a value, no matter how many times the load is circulated, the concrete won't failure [13–15].

At present, two theories or models are available to explain the hysteresis [16]. One is analyzing the hysteresis from the microcosmic mechanism of concrete. The other one is explaining from the macroscopic view or the nonlinear elastic wave equation. The early microcosmic explanation about hysteresis holds that there is friction and sliding between cracks and in boundary of the grains. Tutuncu et al. [17,18] thought there was grain contact adhesion and stick-slip sliding. These microcosmic mechanism theories are of great significance of learning the period of hysteresis and attenuation, but these theories cannot explain some observational facts very well. On the other hand, the pragmatic macroscopic phenomenological model also got a development. The typical models are Endochronic theory [19] and Preisach-Mayergoyz model [20]. Besides, there is also the thermal attenuation reactivated wave theory [21] and Scaled memory theory in the macroscopic models [22]. Each model has its own advantages. For example, some models can imitate several experimental phenomena and show the linear elasticity of the material at small strain. McCall and Guyer [23] got the quasi-static stress-strain state equation by using the assumption of hysteretic meso-scopic elastic units and the Preisach—Mayergoyz (P-M) model. They also applied it to the motion equation of nonlinear elastic wave propagation.

In this paper, the uniaxial tensile cycling tests were conducted on the plain concrete. The hysteresis phenomenon of concrete, including the axial energy consumption per unit volume, dynamic elastic modulus, damping ratio, and the effect of the number of cycles and loading frequency on these behavior have been studied. The P-M model has also been used to simulate the experimental stress-strain curve of concrete, and the quantitative relationship between the model parameters and loading frequency was discussed.

---

[*] Corresponding author.
E-mail address: cxdong1985@hotmail.com (X. Chen).

http://dx.doi.org/10.1016/j.ijfatigue.2016.12.002
0142-1123/© 2016 Elsevier Ltd. All rights reserved.

2. Experiment program

2.1. Test specimen

Cylindrical concrete specimens were prepared for the uniaxial tensile and compressive tests. The dimensions of the specimens were diameter of 72 mm and height of 148 mm. And also, three 150 mm × 150 mm × 150 mm cubic specimens are also prepared to test the standard cubic compressive strength. The type of cement used in this experiment was ordinary Portland cement. Water reducer was added to obtain good fluidity. The fine aggregate was river sand with particle size distribution fitting with the ASTM C33 (2004). The maximum grain diameter of coarse aggregate was 20 mm. Tap water in the laboratory was used. The proportions of the mixture are shown in Table 1.

The specimens were cured in water for 90 days after 3 days in polyvinyl chloride (PVC) models. Two cylindrical discs are pasted with the ends of the specimen by the structural adhesive. The other sides of the discs are connected to the tester by spherical hinges and screws. The spherical hinges can reduce the eccentricity. The tester stretches the irons and then the force is exerted on the specimen through the irons. Three extensometers are bonded to the mid-length of the specimen for recording the axial deformation (shown as Fig. 1).

2.2. Test method

The uniaxial tensile tests including monotonic and cyclic tests are performed on an electric-hydraulic servo-controlled material testing system (MTS 322). Strain-controlled monotonic tensile test is conducted on concrete specimen to measure the static tensile strength and initial elastic modulus of concrete, and the strain rate is 1με/s. In cyclic tensile test, two loading regimes and four frequencies of 0.05, 0.1, 0.5, 2 Hz have been used. In the first cyclic load regime, the static stress is 1.72 MPa, the dynamic stress is 1.60 MPa and the number of cycles is 30. In the second one, the static stress is 2.21 MPa, the dynamic stress is 1.23 MPa and the number of cycles is 30. Sinusoidal waveform is used in the cyclic test. Combining two effects-cyclic frequencies and loading regimes, there are 8 groups and three specimens in each group are tested. Detailed description of the test setup can be seen in the previous papers by the authors [24–27]. Besides, standard cubic compressive test and uniaxial compressive test are performed on concrete to obtain the static compressive strength of concrete used in this test.

3. Test result analysis

3.1. Static mechanical behavior

From static tests on concrete, the following data can be obtained as follows: the 150 mm × 150 mm × 150 mm cubic compressive strength of the concrete is 54.4 MPa. Uniaxial compressive strength of cylindrical concrete is 20.75 MPa. Monotonic tensile stress-strain curve is shown in Fig. 2. The static uniaxial tensile strength and elastic modulus extracted from the tensile stress-strain curve are respectively 3.7 MPa and 35 GPa.

Table 1
Mix proportion for concrete.

Mass of concrete ingredients (kg/m^3)						*w*/*c*
Water	Cement	Sand	Aggregate	Fly ash	Water reducer	
205	328	668	1089	82	2.05	0.50

Note: 1.0 kg = 2.2046 lb; 1.0 m = 3.281 ft.

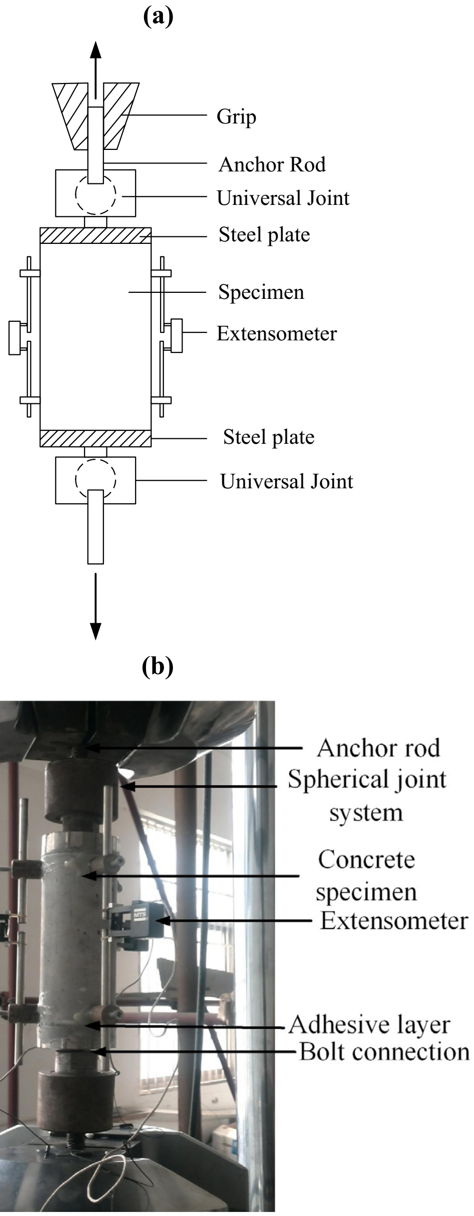

Fig. 1. Cyclic tensile test setup: (a) schematic description of tensile tests and (b) experimental setup.

3.2. Cyclic stress-stain curve

Concrete is a non-ideal elastic body. As a result, the stress-time curve and the strain-time curve of concrete are not completely matched. It means that phases of these two kinds of curves are out of synchronization. Fig. 3 shows the stress-time and the strain-time curve under cyclic tensile load test. In Fig. 3, it is obvious that the phase difference exists between stress and axial strain. As shown in Figs. 4 and 5, determined by phase difference in one certain cycle, the stress curve and the strain curve form a hysteresis loop. One specimen in each group was selected as the feature one, Fig. 4 shows the dynamic stress-strain curves of concrete specimens under various loading regimes. Fig. 5 shows the dynamic stress-strain curves corresponding to the 16th cycle of these 8 concrete specimens. As Figs. 4 and 5 shown, the hysteresis loops is like leaf with pointed tip. It means that, when the cycle load turning, the elastic deformation responds rapidly and the plastic deformation is quite small, which makes curve not smooth or like ellipse [28].