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Fatigue life prediction method of concrete based on energy dissipation

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HIGHLIGHTS

- A novel concrete fatigue life prediction method is proposed.
- The method is based on the energy dissipation.
- The critical dissipated energy is concerned only with the mechanical property of concrete.

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ABSTRACT

The fatigue test is conducted, and from which the evaluation law of the energy dissipation is revealed and analyzed. In the second stage of the fatigue test with invariable cyclic, the energy dissipation within each cycle stay constant, and has an exponential relationship with the stress level; the critical dissipated energy is concerned only with the mechanical property of the material, but immune to the testing load. The process of energy dissipation is discussed, and a novel fatigue life prediction method of concrete based on the energy dissipation is proposed. The life prediction of concrete is compared with experimental results, and the proposed prediction method is validated.

1. Introduction

Fatigue fracture is one of the most common failure modes for concrete structures, and mostly occurs in concrete structures under cyclic loading, such as crane beam, pavement, bridges, etc. The fatigue strength and fatigue life are the essential problems for such structures. Basically there are three approaches to research the fatigue failure mechanism of concrete at present, the phenomenological method, the fracture mechanics and the continuum damage mechanics.

The phenomenological method makes use of the concrete fatigue life data under different stress levels from lots of fatigue tests, and at last generates representative empirical formulae by regression analysis (S-N curve). The concluded laws from the phenomenological method is simple and reliable, so this method currently becomes the main bases for fatigue designing of concrete structures. While now it suffers from the discreteness of concrete property, and that the failure mechanism is unconcerned.

The fracture mechanics identifies the failure state of the specimen by the crack propagation, and the crack initiation and propagation depend on the stress intensity factor, which is related to the crack length and the stress state. The crack propagation is related to the variation of stress state through the Paris formula, and thus the criterion to identify the fatigue failure is formed [1,2].

There are two important approaches to investigate the fatigue damage mechanics, including the continuum damage theory and the energy method. The continuum damage theory based on continuum mechanics and the irreversible thermodynamic, selects some damage variable to characterize the damage of materials, and then establishes the corresponding damage evolution equation and constitutive equation [3,4]. The energy method based on mechanism of material damage, analyzes the energy dissipation variation in the process of fatigue loading, and then obtains the damage evolution law of materials and the fatigue life prediction method according to the trend of the energy dissipation [5,6].

In this paper, we investigate the fatigue life of concrete by use of the energy method. We conduct lots of concrete fatigue tests, and analyze the energy dissipation of concrete in the loading process. The evolution laws of energy dissipation are put forward on the basis of the test results, and a novel fatigue life prediction method of concrete is proposed based on these laws.

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2. Energy parameters for fatigue process

2.1. Energy analysis of fatigue process

Concrete is a kind of brittle material, and is always exchanging energy with the environment throughout the loading process [7]. When loading, the test machine does work on the specimen, part of the mechanical energy dissipates as heat, and the other energy is stored in the specimen as the internal energy. Regarding the test machine and specimen as a dissipative system, the amount of dissipated energy of the system is equal to the decrement of work capacity, as the dissipation systems theory. The elastic deformation is recoverable, thus all the energy except the elastic strain energy, are the dissipated energy of the system, such as the plastic strain energy, the fracture energy and the heat energy.

The total dissipated energy of the system can be divided into two parts, one is the heat energy mainly dissipated by convection, conduction and radiation, and the other is the dissipated energy due to material damage:

$$E_T = E_D + E_H \tag{1}$$

where E_T is the total dissipated energy, E_D is the energy dissipation due to material damage, and E_H is the dissipated energy as heat.

The usual energy dissipation due to damage includes the plastic strain energy, the energy in the process of defect formation and crack propagation, etc. The corresponding physical quantities have been designed as the governing damage variable respectively, to characterize the degree of material damage. Because the energy dissipation due to material damage is affected by all the damage factors, thus the change of the material property could be represented by its evolution process. As is shown in experiments [8] that the heat energy dissipation of concrete in the fatigue loading process maintains constant generally, and the trend of energy dissipation due to damage is almost same as that of the total energy dissipation. So the total dissipated energy can be represented by the energy dissipation due to damage, both of which are called the energy dissipation in this paper.

2.2. Dissipated energy

According to the definition of the energy dissipation, the dissipated energy within single-cycle is equal to the work decrement of the dissipative system in the process of loading and unloading, and could be represented by the area of the hysteresis curve in the stress-strain relation:

$$W_{\mathrm{d}} = \oint \sigma d\varepsilon \tag{2}$$

Owing to the additivity of energy, accumulated dissipated energy is defined as the sum of all the single-cycle energy dissipation from the beginning of loading to the current N time:

$$W_{\mathrm{d}} = \sum_{\mathrm{i}=1}^{\mathrm{N}} w_{\mathrm{d}}^{\mathrm{i}} \tag{3}$$

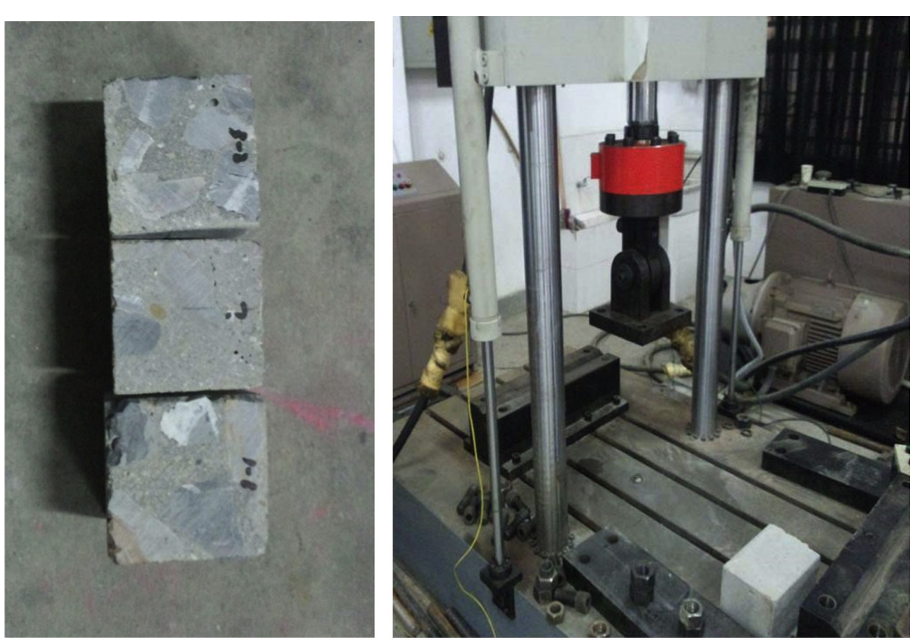
Carpenter [9,10] believes that the materials damage could only be caused by the change of energy dissipation, so they proposed the rate of dissipated energy change, which means the fluctuation of energy dissipation between two neighboring cycles, and is calculated as:

$$\mathrm{RDEC} = \left(w_{\mathrm{d}}^{\mathrm{i}+1} - w_{\mathrm{d}}^{\mathrm{i}}\right)/w_{\mathrm{d}}^{\mathrm{i}} \tag{4}$$

3. Fatigue test

The size of the concrete specimen used in the fatigue test is 100 mm × 100 mm × 100 mm as shown in Fig. 1(a), and the strength grade is C25. In the preparation of the concrete, the sand is used as fine aggregate, the gravel is used as coarse aggregate, the tap water is used as the mixing water, and the ordinary Portland cement is used. The proportion of the component is cement: water: sand: gravel = 367: 180: 649: 1204.

The fatigue test is performed on the SDS300 universal test machine, by loading under stress control, as shown in Fig. 1(b). In order to obtain the single-cycle energy dissipation under different stress level w_{d}, the multi stage and variable amplitude loading mode is employed. The load increases progressively, and it cycles



(a) (b)

Fig. 1. (a) The concrete specimen and (b) the test machine of the fatigue test.