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Fatigue Life Analysis of Engineered Fiber Reinforced Cementitious Composite

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ABSTRACT

As a new type of building material, Engineered Fiber Reinforced Cementitious Composite have attracted the attention of many scholars in civil engineering. They have super toughness, quasi strain hardening, and multi joint cracking characteristics. Due to the excellent characteristics of ECC, this material has been widely developed in the United States, Japan, and Europe, and has been successfully applied in multiple practical project engineering. Materials should meet fatigue reliability requirements before being put into use. Due to the large variability of fatigue life, in order to meet engineering needs, probability statistics should be used to analyze their fatigue characteristics. Compared to other continuity probability distribution models, the Weibull distribution model can better describe the fatigue life characteristics of ECC materials. Domestic and foreign scholars have conducted corresponding research on the fatigue life of ECC materials, all of which have confirmed that the fatigue performance of ECC materials is significantly better than that of ordinary concrete, and its fatigue life follows a Weibull distribution. This article will apply Weibull probability density function to derive the fatigue life of ECC materials, in preparation for subsequent experiments.

KEYWORDS

ECC; Fatigue life; Fatigue performance; Weibull distribution

1. INTRODUCTION

Buildings are often subjected to fatigue loads during their service life, such as wind loads, earthquake loads, etc, which can cause premature structural failure.

Nowadays, concrete materials are developing towards lightweight and high-strength direction, and are evolving from single materials to composite products, allowing the various properties of materials to be designed according to needs and improving the functional use of materials. In order to improve and enhance the ductility and strength of concrete materials, scholars have been striving to explore. Due to the fact that the interface between coarse aggregate and cement mortar is the weakest link in concrete, the Li VC team at the University of Michigan in the United States has developed a high ductility fiber-reinforced cement-based composite (ECC) material in recent years [1]. ECC materials have attracted the attention of scholars since their inception, and extensive research has found that ECC has good ductility, crack resistance, impact resistance, and other properties, it can greatly improve the safety and durability of engineering, and is therefore widely used in bridge engineering [2], seismic support [3], and repair engineering [4].

To meet the engineering requirements, materials must meet the fatigue reliability requirements. Hu et al. [5] conducted fatigue tests on ECC cube specimens under different lateral pressure levels, unified the S-N formula for ECC under different lateral pressures, verified the Weibull distribution, and plotted the p-S-N curve. The results showed that the fatigue life of ECC follows the Weibull distribution, and compared with ordinary concrete and fiber-reinforced concrete, it has better compressive fatigue performance. Its advantages become more significant with the increase of maximum stress level; Li et al. [6] studied the fatigue performance of UHTCC cylindrical specimens under compression conditions and found that the fatigue life of UHTCC follows a Weibull distribution, and at the same stress level, the fatigue performance of UHTCC is better than that of plain concrete and steel fiber reinforced concrete; Huo Haifeng et al. [7] investigated the tensile fatigue performance and damage mechanism of concave I-shaped ECC specimens by axial tensile cyclic loading. The results showed that the fatigue life of ECC specimens follows a two parameter Weibull distribution, and the axial tensile strain develops similarly with displacement and follows a three-stage development; Li Qinghua et al. [8] conducted uniaxial compression fatigue performance tests on UHTCC cylindrical specimens to investigate their fatigue life and failure mode. The study found that UHTCC material follows three-stage deformation, similar to plain concrete and steel fiber reinforced concrete, but has stronger deformation ability and fatigue life follows Weibull distribution; Luo Lu et al. [9] conducted three-point bending fatigue tests on UHTCC specimens with unilateral incisions, established two fatigue damage propagation models, and found that they were in good agreement with the results.

Matsumoto et al. [10] conducted cyclic tensile compression tests on SHFRCC dumbbell shaped specimens prepared with two different mix ratios (ordinary conventional aggregate and lightweight aggregate) to investigate the evolution process of fiber bridging tensile stress attenuation under cyclic tensile compression loading, and analyzed the effect of cycle times on the decrease of SHFRCC tensile stress. Yun H D et al. [11] conducted uniaxial cyclic tensile tests on cylindrical specimens of SHCC (d=100mm, h=200mm) to investigate the effects of different fiber types (PVA fiber, PE fiber) and freeze-thaw cycles on the cyclic tensile properties of SHCC materials. The experimental results indicate that the stress-strain curve envelope of SHCC specimens under cyclic tensile loading is similar in shape to the stress-strain curve under monotonic loading. As shown in Figure 1-8, with the increase of freeze-thaw cycles, the cyclic tensile strength of SHCC gradually increases, while its ultimate tensile strain under cyclic tension decreases.

2. THE WEIBULL PROBABILITY DENSITY FUNCTION

In mathematical statistics, one of the most important theoretical frequency distributions is the normal distribution, but due to the fact that the N value of the normal distribution has a probability of being less than 0, it is not reasonable to use it in statistical fatigue life. In recent years, the Weibull distribution has also been widely used both at home and abroad. The advantage of the Weibull probability density function lies in the fact that there is a minimum safe life, i.e., a 100% reliable safety life. Using the Weibull distribution theory, the safety life or minimum safe life given in the extremely high reliability range is still fairly consistent with actual conditions. The Weibull probability density function [12] is expressed as:

$$f(N)=\frac{b_0}{N_a-N_0}\left[\frac{N-N_0}{N_a-N_0}\right]\exp\left[-\left(\frac{N-N_0}{N_a-N_0}\right)^{b_0}\right],\quad (N_0<N<\infty) \tag{1}$$

The Weibull cumulative distribution function of fatigue life is:

$$F(N)=1-\exp\left[-\left(\frac{N-N_0}{N_a-N_0}\right)^{b_0}\right],\quad (N_0<N<\infty) \tag{2}$$

In the equation, F(N) is failure probability, N_0 is minimum lifespan parameter, N_a is characteristic lifespan parameters, b is Weibull shape parameter.

The Weibull probability density function is shown in Figure 1.

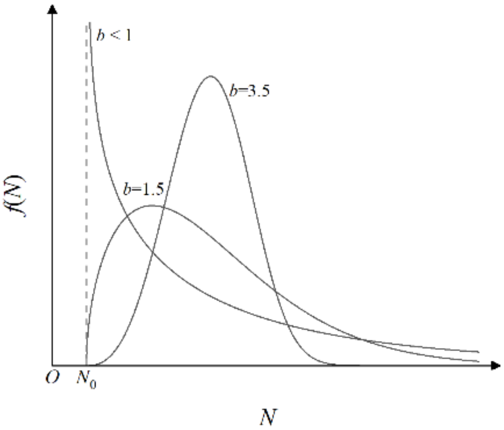

Figure 1. The Weibull probability density function

For ease of analysis, the three parameter Weibull function can be transformed into a two parameter Weibull function. By taking the logarithm of the two ends of the equation and simplifying it, we can obtain:

$$\lg\lg\frac{1}{p} = b_0 \lg N + c \tag{3}$$

In the equation, p=1- F(N), c and e are constants.

Using the mean rank method [13] to estimate the failure probability, the survival probability of the i-th sample point is:

$$p = 1 - F(x_i) = 1 - \frac{i}{n'+1}, \quad (i = 1, 2....n') \tag{4}$$

Substitute the data of the experimental sample points into equation 3 and perform linear fitting on each data point. If the fitting results have good correlation, then the parameter follows a Weibull distribution.

3. S-N CURVE ,P-S-N CURVE WITH FAILURE PROBABILITY AND FATIGUE STRENGTH

3.1. S-N curve

The fatigue loading mode is divided into two stages: the initial linear loading stage and the formal fatigue loading stage (Figure 2). The initial linear loading stage is a stable loading from 0 to the average fatigue load Pm, which takes about 15 seconds. Then, the formal fatigue loading stage is carried out, and the maximum fatigue load Pmax and minimum fatigue load Pmin are determined according to the stress level and stress ratio under different working conditions. The stress amplitude will change with the change of stress level and stress ratio. A sine wave cyclic load with a specified frequency f is maintained for loading. During the fatigue loading period, longitudinal residual strain is collected after complete unloading. The test is stopped if the specimen does not reach 2 million cycles of failure or exceeds 2 million cycles of failure. The test data is recorded.

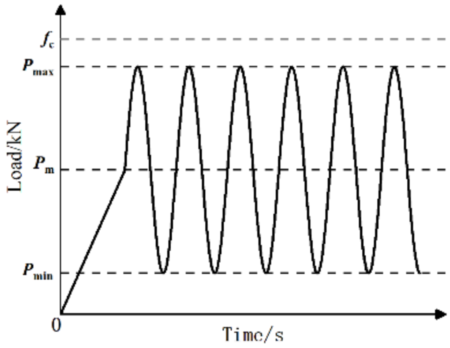

Figure 2. Schematic diagram of fatigue loading pattern

As is well known, fatigue life significantly increases with the decrease of maximum stress level. To effectively analyze the impact of stress levels on fatigue life, it is necessary to establish an effective model to analyze both, such as the Basquin formula [14]:

$$S^m N = C \tag{5}$$

In the equation, m and C are both undetermined coefficients. By taking the logarithm of the two ends of the equation and simplifying it, we can obtain:

$$\lg S = a - b \lg N \tag{6}$$

It can be observed that there is a linear relationship between the independent variable and the dependent variable. By fitting the experimental results to the data, an S-N curve can be obtained, which can be further analyzed.

3.2. P-S-N curve

According to the experimentally fitted S-N curve, its reliability is about 50%. In engineering applications, the S-N curve with failure probability, namely the P-S-N curve, is generally used. The equivalent fatigue life under a specified probability can be calculated using the following equation:

$$\overline{N} = N_a \left| \ln\left[1 - F(N)\right] \right|^{\frac{1}{b}} \tag{7}$$

Draw the S-N curve based on the equivalent fatigue life under different probability scenarios, and the resulting curve is the P-S-N curve.

3.3. Fatigue Strength

The drawing of the S-N curve based on the equivalent fatigue life under different probability conditions yields the P-S-N curve. Fatigue strength is an important indicator of material fatigue performance and also an important parameter for the design of engineering structures or components. The fatigue strength of materials is usually determined by the relationship curve between maximum stress level and fatigue life (S-N). Considering engineering practicality, the uniaxial compression fatigue ultimate strength of ECC under different stress ratios and loading frequencies should be determined according to the S-N curve equation with a failure probability of 0.5. The maximum stress level corresponding to the fatigue life is the uniaxial compression fatigue strength of ECC.

4. CONCLUSION

Concrete, as a common building material, has been optimized and improved to a certain extent since its initial use, but there are still many shortcomings in practical applications. The main defects of concrete are brittle failure under extreme loads and insufficient durability. In this context, ECC material is a fiber-reinforced cement-based composite material with high ductility, toughness, and fine crack characteristics. Cement based materials that exhibit strain hardening characteristics and multi crack cracking under direct tensile and bending loads have good ductility and ability to control micro crack width. ECC material is a type of material with high ductility, toughness, and fine cracks High performance materials with seam characteristics, due to their stable state during cracking.Under stress, multiple subtle cracks appear. ECC materials have higher tensile ductility compared to concrete, and their tensile (strain) hardening behavior and energy dissipation are superior to ordinary concrete. ECC material has a high ductility of 3%~7%.

Due to the excellent characteristics of ECC, this material has been widely developed in the United States, Japan, and Europe, and has been successfully applied in multiple practical project engineering. Materials should meet fatigue reliability requirements before being put into use. Due to the large variability of fatigue life, in order to meet engineering needs, probability statistics should be used to analyze their fatigue characteristics. Compared to other continuity probability distribution models, the Weibull distribution model can better describe the fatigue life characteristics of ECC materials. Domestic and foreign scholars have conducted corresponding research on the fatigue life of ECC materials, all of which have confirmed that the fatigue performance of ECC materials is significantly better than that of ordinary concrete, and its fatigue life follows a Weibull distribution.

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