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Compressive fatigue damage and failure mechanism of fiber reinforced cementitious material with high ductility

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ABSTRACT

The fiber reinforced cementitious material with high ductility has potential use in particular environments and structures that undergo repeated or fatigue loads. In this study, a series of monotonic and fatigue tests were performed to investigate the compressive fatigue behavior of this material. It is found that the fatigue life of this material is higher than that of plain concrete and steel fiber reinforced concrete under the same stress level. In addition, the failure deformation of fiber reinforced cementitious material with high ductility under fatigue load was larger than the monotonic envelope, while the envelope coincides with the monotonic loading curve for concrete or fiber reinforced concrete. The failure surface and damage process were investigated and a new failure mode of polyvinyl alcohol fiber with crushed end was discovered. The fatigue failure surface could be divided into three regions, including fatigue source region, transition region and crack extension region.

1. Introduction

Fiber reinforced concrete is made by adding fibers into concrete matrix to improve its ductility. With fiber reinforced concrete widely applied in modern complicated structures, which is subjected to repetitive cyclic loads (e.g. automobile traffic, wind action and sea waves), the fatigue behavior of this material is also getting more and more attention. Numerous experiments have been conducted to study the fatigue behavior of fiber reinforced concrete [1–8]. Fiber reinforced cementitious material with high ductility is a kind of cementitious material reinforced by random distributed short fibers, which is also referred to as engineered cementitious composites (ECC) [9], strain hardening cementitious composites (SHCC) [10], polyvinyl alcohol (PVA) fiber reinforced cementitious composites (PVA-FRCC) [11], or ultra-high toughness cementitious composites (UHTCC) [12], and its use has been explored throughout the world. This material was proposed by Li and Leung and was designed with micromechanical principles [13]. UHTCC possesses the following characteristics: it is reinforced with short fibers with the corresponding volume fraction lower than 2.5%; the hardened composite exhibits significant pseudo strain-hardening and multiple-cracking behaviors with tensile strain capability above 3%; and it can keep the crack width below 100 μm even when the tensile strain achieves its maximum value [12]. This material has potential use in complicated environments and structures that are subjected to repeated or fatigue loads, such as airport runway, highway pavements, bridge decks and offshore platform, due to its high ductility [12,14–16] and durability [17–20]. To apply ultra-high toughness cementitious composites in practice, the investigation of fatigue behavior of this material is needed.

Several studies have been carried out focusing on fatigue behavior of UHTCC in the past decade. Fatigue failure characteristics and fiber bridging characteristics of UHTCC under flexure were investigated and it was found that UHTCC exhibited significantly higher fatigue life and more ductility than concrete, polymer cement mortar and steel fiber reinforced concrete [21–25]. In addition, flexural fatigue behavior of concrete beam with UHTCC layer [26–28] and the tensile failure property of UHTCC under monotonic and cyclic tensile loads [29,30] has been studied. Based on the fatigue test results in [27], while the use of UHTCC layer can increase the strength of concrete beam, its improvement on fatigue performance is even more effective and concrete beam with UHTCC layer could sustain fatigue loading at a larger deflection without failure. Up to now, the existing study is mainly focused on the behavior of UHTCC under flexural fatigue and cyclic tensile loads, while there is limited study on the compressive fatigue properties of UHTCC. Considering that the fatigue behavior of UHTCC under compression is crucial for its application in certain conditions (e.g. airport runway and road pavements) and fatigue damage of structural components are affected by both the flexural and compressive cyclic loading, the available work is rather limited and a better understanding of the compressive fatigue behavior is required.

Thus, in order to investigate the fatigue behavior of UHTCC under compression, a series of monotonic and fatigue tests were performed.

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Table 1
Properties of PVA fiber.

Tensile strength (MPa)	Diameter (μm)	Fiber length (mm)	Young's modulus (GPa)	Elongation (%)
1600	40	12	40	6

This paper focuses on the evaluation of failure process of UHTCC, including fatigue life, deformation pattern and failure mode of fibers on the failure plane. Emphasis will be placed on analysis of the damage process of this material under monotonic and fatigue loads. Finally, relevant conclusions are drawn, which could be used as a reference for a wider application of UHTCC in structures.

2. Experimental program

2.1. Specimen preparation

In this experiment, UHTCC was produced using cementitious binders, fine silica sand, water, superplasticizer and PVA fiber [12]. The binders were composed of ordinary Portland cement and fly ash. The PVA fiber was KURALON K-II REC15 type with corresponding properties given in Table 1 and fibers added to the mix were 2% of the total composite volume. Two series of UHTCC cylinder specimens (Series I and II) with the same mix were prepared, the dimensions of which were 70 mm (diameter) × 140 mm (height). The specimens were demolded 72 h after they were cast and were cured for 28 days. Then, the specimens were laid in common environment for 3 months before monotonic and fatigue test.

2.2. Testing method

The compressive and fatigue test were performed in a 1000 kN INSTRON testing system. The displacement between two load platens was measured. For monotonic tests, displacement control was adopted with a constant rate of 0.20 mm/min. The average static compressive strength of Series I was 43.08 MPa (6 specimens), while that of Series II was 38.22 MPa (10 specimens). The average elastic modulus was 15 GPa measured by strain gauges during the static test. It needs to be pointed out that, although the elastic modulus of UHTCC is lower than that of concrete, this material could be applied to partially replace concrete at some crucial locations of structures to take the advantage of both materials. For fatigue tests, a constant amplitude fatigue load was used. The tests were carried out under load control with a sinusoidal waveform of 4 Hz. Six different stress levels were considered. Those maximum stress levels were 0.90, 0.85, 0.80, 0.75, 0.70 and 0.65, respectively, of the static compressive strength of UHTCC, shown in Table 2. Note that Series I was used in the fatigue tests under the stress level of 0.90, 0.80, 0.70 and 0.65, and Series II was used for the remaining stress levels. The ratio between the minimum fatigue loads to the maximum fatigue load ($R = P_{min}/P_{max}$) was kept at 0.1. The fatigue test commenced with a ramp to the maximum load at a rate of 8 kN/s followed by a sine waveform fatigue loading.

After specimen failure, the crushed pieces on the failure surface of specimens were selected for scanning electronic microscope (SEM) tests and Energy-dispersive X-ray spectroscopy (EDS) was utilized for the elemental analysis, as well as point analysis from the sample surface.

Table 2
Fatigue load and specimen numbers of the test.

Stress levels	Specimen series	Static compressive strength (MPa)	Maximum fatigue stress (MPa)	Specimen numbers
0.90	I	43.08	38.76	6
0.85	II	38.22	32.50	6
0.80	I	43.08	34.47	6
0.75	II	38.22	28.68	6
0.70	I	43.08	30.16	6
0.65	I	43.08	28.00	2

Table 3
Test result for fatigue life of UHTCC at various stress levels.

Specimen No.	Stress levels					
	0.90	0.85	0.80	0.75	0.70	0.65
1	620	1500	9520	42,524	484,135	2,000,000*
2	700	1869	28,394	149,691	679,756	2,000,000*
3	1100	1928	35,908	497,273	1,054,123	/
4	1572	4052	55,629	718,343	1,906,379	/
5	1586	4115	108,081	792,262	2,000,000*	/
6	1900	13,019	131,442	1,295,229	/	/

Note: * represents the fatigue failure did not happen when load cycles reached two million.

3. Results and discussion

3.1. Fatigue life and distribution

The fatigue lives for each fatigue stress level are summarized in Table 3, which were obtained from the above experiment study. Note that specimens that did not fail at two million cycles are considered as run-outs. Since the fatigue life distribution of plain and fiber reinforced concrete was found previously to follow the Weibull distribution in [7,8, 31–33] and the flexural fatigue life of UHTCC follows this distribution as well [25], in this paper, the verification of Weibull distribution will be attempted for compressive fatigue of UHTCC.

For fatigue life, the Weibull cumulative distribution function $P_f(N)$ could be written as follows with the location parameter or minimum value considered as zero [31–33].

$$P_f(N) = 1 - \exp\left[-\left(\frac{N}{N_a}\right)^{\alpha}\right] \quad (1)$$

where α is the shape parameter; N_a is the scale parameter; N is the fatigue life.

Taking twice natural logarithm for both sides of Eq. (1) gives

$$\ln \ \ln \frac{1}{1-P_f(N)} = \alpha \ln \ N - \alpha \ln \ N_a \quad (2)$$

Setting $Y = \ln \ln (1/(1 - P_f(N)))$, $X = \ln N$, $\beta = \alpha \ln u$, we can get

$$Y = \alpha X - \beta \quad (3)$$

The graphical method could be employed to estimate the distribution parameters and it could be found from Eq. (3) that the fatigue lives follow Weibull distribution when the relationship between Y and X is linear (the correlation coefficient r is close to one). Also, when a failure probability p is given, the corresponding fatigue life N at certain stress level S could be calculated.

According to the probability theory of Weibull distribution, the failure probability p corresponding to the tested failure life N can be

Table 4
The results of Weibull distribution parameters and regression analysis.

Stress levels	α	β	r	N_a
0.90	1.9054	13.8900	0.9661	1465
0.85	1.0249	8.7558	0.8941	5131
0.80	0.9429	10.5593	0.9891	73,039
0.75	0.6979	9.4061	0.9722	713,344
0.70	1.3936	19.5555	0.9769	1,242,160