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Fatigue deformation behavior and fiber failure mechanism of ultra-high toughness cementitious composites in compression

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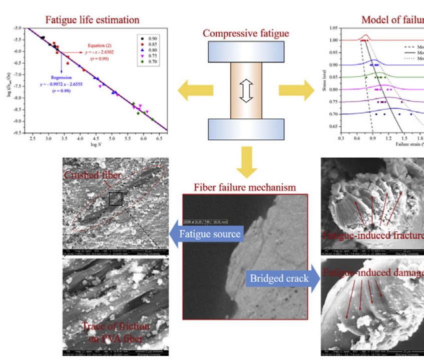
HIGHLIGHTS

- Stress level has little influence on secondary strain rate of strain-normalized cycle curve.
- Fatigue failure strain is larger than monotonic envelope and it increases as stress level decreases.
- Three fatigue-induced fiber failure modes are found, namely crushed failure, ruptured failure, and pull-out failure with damage.

GRAPHICAL ABSTRACT



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ABSTRACT

Ultra-high toughness cementitious composites (UHTCCs) belong to a family of fiber-reinforced cementitious composites with strain-hardening behavior under tension. Such composites have potential application in structures sustaining fatigue loads. In this paper, the compressive fatigue deformation behavior of UHTCC under various stress levels S ($S = 0.90$, 0.85, 0.80, 0.75, 0.70 and 0.65) was investigated. It is found that the stress level has little influence on the cyclic creep curve of UHTCC, while the fatigue failure strain increases as the stress level decreases. The failure strains at different stress levels obey the two-parameter Weibull distribution, and a probabilistic model is proposed to consider the effect of stress level on the fatigue failure strain. Using X-ray computed tomography and a scanning electron microscope, three fatigue-induced failure modes of polyvinyl alcohol fibers in UHTCC are found and the possibility for further improvement of the compressive fatigue performance is discussed.

1. Introduction

Ultra-high toughness cementitious composites (UHTCCs) belong to a family of fiber-reinforced cementitious composites with a tensile strain-hardening capacity of several percent [1]. These materials are also known as engineered cementitious composites (ECCs) [2], and strain-hardening cementitious composites (SHCCs) [3]. UHTCC was designed with micromechanical principles [4], and the use of this material

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has been explored worldwide over the past two decades. It is found that this material shows high ductility [5–10] and has potential use to improve the performance of concrete structures [11–19].

For safe practical applications of UHTCC, it is important to thoroughly evaluate the mechanical performance of this novel material under fatigue loading. Recent studies mainly focused on the flexure and tensile fatigue behavior of UHTCC, such as the flexure fatigue properties and fiber failure characteristics [20–24]. It has been found that UHTCC shows a higher fatigue life compared to plain concrete, polymer cement mortar, and steel fiber-reinforced concrete (SFRC) [20–22]. The tensile property of UHTCC under monotonic and cyclic loads has been studied in [25–27]. Based on the tension and tension–compression fatigue test results in [27], the fatigue behavior of UHTCC is superior to that of ordinary concrete, and several strategies (e.g., the use of high-modulus fibers) were suggested to improve the fatigue resistance of UHTCC. Furthermore, the micromechanics-based investigation of fatigue deterioration of UHTCC and polyvinyl alcohol (PVA) fiber was carried out to understand the micro-mechanism of the fatigue performance under flexure and tensile loading [28–30]. Huang et al. [31] proposed a novel model based on the three-parameter Weibull function to describe the three-stage fatigue deformation behavior of plain and fiber-reinforced concrete, which was validated via comparison of its results with previously reported results of compressive, tensile, and flexural fatigue tests. Recently, the fatigue response of reinforced concrete beams strengthened by carbon-fiber-reinforced polymer (CFRP) was experimentally investigated [32,33]. Charalambidi et al. [34] proposed an analytical model for predicting the fatigue life of FRP strengthened reinforced concrete beams.

A knowledge on the compressive fatigue performance of UHTCC is crucial for specific applications (e.g., airport runway and highway pavements), and fatigue damage of components is affected by both flexural and compressive cyclic loadings. Thus, the fatigue behavior of UHTCC in compression was recently investigated by the authors in [35,36]. The results showed that UHTCC has a higher compressive fatigue life compared to plain concrete and SFRC at the same stress level, and a fatigue-damaged PVA fiber with crushed end was observed and reported for the first time [35]. The effect of loading frequency on the fatigue behavior of UHTCC was investigated in [36]. For the compressive fatigue behavior of cementitious materials, the stress level S (i.e., the ratio of the maximum fatigue stress σ_f to the static compressive strength σ_0) is one of the determining factors in structural design. A solid knowledge of compressive fatigue properties of UHTCC under various stress levels is obviously necessary for its practical application in modern infrastructure. However, to date, only few studies investigated the influence of stress level on the fatigue deformation behavior of UHTCC. There is also a necessity for analytical methods to predict the fatigue life and deformation of UHTCC for the reliable application of this material. Additionally, a knowledge of the fiber failure mechanism under compressive fatigue is required for further material optimization.

In this study, the fatigue deformation behavior under various stress levels (S = 0.90, 0.85, 0.80, 0.75, 0.70 and 0.65), including the three-stage cyclic creep curve, secondary strain rate, and fatigue failure strain, is particularly analyzed. Based on the initial distribution of static failure strain of UHTCC, a probabilistic model of fatigue failure strain considering the effect of stress level is proposed for a reliable application of this material. The surface morphology and interior features of the fatigue failure specimen are investigated using an X-ray computed tomography (XCT) test. Three fatigue-induced failure modes of PVA fibers are found around the fatigue source region and the corresponding failure mechanism is revealed. Finally, relevant conclusions are drawn.

2. Experimental programs

In this experiment, cementitious binders, fine silica sand, water, superplasticizer, and polyvinyl alcohol (PVA) fiber were used to produce UHTCC. The cementitious binders included ordinary Portland cement and fly ash. The proportion of the UHTCC matrix was cementitious binders: water: fine sand = 1: 0.24: 0.6 [9] [35]. The ratio of the superplasticizer to the cementitious binders is 0.14% (by weight). The maximum aggregate size of the silica sand is 300 μm. The PVA fiber was KURALON K-II REC15 type (specifications provided in Table 1) and the fibers in the matrix were 2% of UHTCC volume. The mixing process of UHTCC was as follows: 1) mixing the cementitious binders and fine sand for 2 min, 2) adding water and mixing for 2 min, 3) adding the superplasticizer and mixing for 5 min, and 4) adding the PVA fibers and mixing for 5 min. Two batches of UHTCC cylinder specimens (Series I and II) were prepared with the same mix. The dimensions of the specimens were 70 mm in diameter × 140 mm in height. The specimens were cured for 28 days and laid in ambient environment for three months before testing. In the previous study, it was found that the increase of the compressive strength of UHTCC was very small after 90 days [37]. This is one of the reason why the specimens were tested after three months in this study. However, the cementitious material may be susceptible to cyclic creep. In the following work, the influence of this factor will be further considered and investigated.

The 1000 kN INSTRON system was used in the monotonic and fatigue tests. Generally, the compressive strain can be measured by compressometer at the central part of the specimen. However, UHTCC would show a microcracking behavior during the compressive test. Extensive cracking may lead to disturbances at the contact points of the compressometer and it may not reflect the actual deformation in the fatigue test [38]. Thus, the displacement between two load platens was measured in our test; this method was also applied in previous studies on compressive fatigue behavior [36,39–41]. The test setup of this study is presented in Fig. 1(a).

The static compressive strengths of Series I and II (displacement control = 0.20 mm/min) are 43.08 MPa and 38.22 MPa, respectively. The loading of compressive fatigue test is presented in Fig. 1(b). The experimental program was designed for the comparison of the results in this study to the ones in previous study [39]. The loading frequency was kept at 4 Hz for all the fatigue tests to avoid the frequency effect on the fatigue life and deformation, and the minimum stress level was 0.1. The fatigue test was carried out under load control with a sinusoidal waveform. Six stress levels were considered in this investigation and the corresponding fatigue lives are listed in Table 2. After the fatigue test, the XCT test was used to reveal the internal damage of the fatigue failure specimens. The selected pieces for the static and fatigue failure surface of the specimens were analyzed using a scanning electron microscope (SEM).

One-half of the fatigue failure specimen (S = 0.80) was scanned and the corresponding 3D attenuation contrast image was computationally reconstructed by CT Pro. VG Studio. The XCT test was carried out at the Institute of Advanced Engineering Structures and Materials, Zhejiang University, China. The X-ray projections were acquired with an exposure time of 500 ms at an accelerating voltage of 200 kV and 100 μA beam current using a tungsten target. The stage was rotated through 360°, resulting in 3000 projections collected on a Perkin Elmer 2000 × 2000 pixel amorphous silicon flat panel detector, and the effective pixel size was 49.0 μm. It must be pointed out that the resolution of XCT is limited to approximately 1000–2000 times of the object cross-section diameter and a higher resolution requires smaller

Table 1
Properties of PVA fiber.

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