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Deformation of concrete under high-cycle fatigue loads in uniaxial and eccentric compression

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HIGHLIGHTS

- Uniaxial and eccentric compressive fatigue tests were conducted on concrete.
- Elastic modulus showed negligible decrease with fatigue load cycles.
- Strains and curvatures continuously accumulated under fatigue load cycles.
- Deformation prediction model proposed for concrete under high-cycle fatigue loads.
- Effects of fatigue on long-term deformations of concrete structures were studied.

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ABSTRACT

This paper studies the deformation evolution of concrete under high-cycle fatigue loads. First, uniaxial and eccentric compressive fatigue loads were exerted on prism concrete specimens to observe the mechanical properties of concrete under fatigue loading. Fatigue tests showed that elastic modulus does not always decrease, but strains always increase as loading cycles accumulate. Moreover, strains on the cross-section of each eccentrically fatigued specimen always maintain linear distributions. Based on these experimental findings, a simplified constitutive model for concrete under high-cycle fatigue loads was adopted; hence, a fatigue deformation prediction model was developed to analyze the strain and stress distributions on a cross-section under both cyclic axial forces and bending moments. The proposed model demonstrated its validity by predicting fatigue deformations in good agreement with experimental results. Finally, based on the new prediction model, a case study was conducted, which found that fatigue could pose a big influence on the long-term deformation of concrete bridges.

1. Introduction

Concrete bridges have been widely constructed in China along with the rapid development of highway and high-speed railway networks. To meet the huge requirements of faster long distance transportation systems, higher speed limits are becoming more and more common in both highway and rail transportation. Conceivably, these concrete bridges must bear more fatigue load cycles than in the past given the same service lifetime period. These concrete bridges are constructed based on rigorous requirements designed to resist deformation. A reliable concrete transportation infrastructure is needed to keep goods and traffic moving without construction detours and delays. Thus, the effect of fatigue creep on long-term deformation in concrete bridges has drawn significant attention.

Many researchers have investigated the fatigue creep behavior of concrete and proposed various approximate empirical formulas [1–8] and theoretical models [9], among which some were even mutually contradictory. Generally accepted theories of fatigue creep were lacking until 2014 when Bazant and Hubler established a fatigue creep model, which they described as being “anchored in the microstructure and would allow extrapolation to 100-year lifetime” [10]. They created that model by first assuming that microcracks of concrete under fatigue loading propagated in the forms of tensile cracks or compressive crushing bands as shown in Fig. 1. Although very good agreement was achieved between their model calculations and experimental results, their assumption necessitates an experimental basis to make the fatigue creep model more convincing. In fact, based on Bazant and Hubler’s

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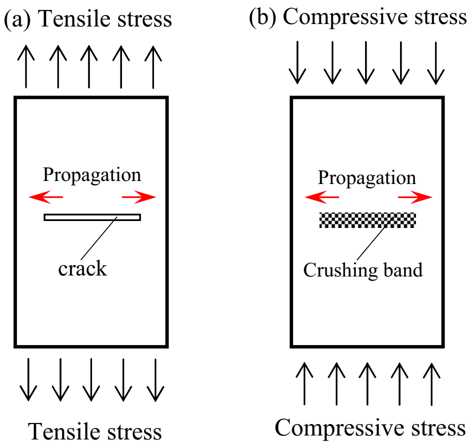

Fig. 1. Propagation of microcracks of concrete under fatigue: (a) tensile crack and (b) compressive crushing band.

derivations, propagation of Mode-I-type tensile cracks (Fig. 1a) or compressive crushing bands (Fig. 1b) will yield zero creep strain in the horizontal direction, i.e., perpendicular to the stress direction. However, Taliercio and Gobbi [11–13] found that creep strains perpendicular to the loading direction do exist in concrete specimens under fatigue loads with the maximum load level higher than 0.8. On the other hand, high-cycle fatigue tests, which are designed to observe the concrete creep strains perpendicular to the loading directions with maximum load levels lower than 0.8, remain lacking.

Moreover, in previous experimental studies [1–8], exclusive concerns were focused on fatigue of concrete under uniform fatigue stresses. However, a more realistic approach to concrete bridge structures is to consider concrete girders or piers response to both axial forces and bending moments which always generate stress gradients in each cross-section. While these bridges are subjected to fatigue loads, the cross-sections of the girders or piers usually undergo stress redistributions. Consequently, fatigue tests on concrete with both axial forces and bending moments are also needed in addition to those on concrete with only uniaxial forces if we want to gain a full understanding of fatigue creep of concrete and its structural influences.

In this paper, both uniaxial and eccentric compressive fatigue tests were conducted on prism concrete specimens to observe mechanical properties of concrete under high-cycle fatigue loads. The experimental findings support the assumption by validating its inference made by Bazant and Hubler [10] mentioned above. Moreover, a constitutive model for concrete under high-cycle fatigue loads was adopted and hence a prediction model was established to calculate deformations of concrete sections under both cyclic axial forces and bending moments. The proposed deformation prediction model was validated by comparing model predictions with experimental results. Finally, based on the proposed fatigue deformation prediction model, a case study was conducted to observe the effects of fatigue loads on the long-term deformation of concrete bridges.

2. Experimental program

2.1. Materials and specimens

A total of 24 prism concrete specimens were cast in this experiment. These included 10 axially-loaded and 14 eccentrically-loaded specimens (labeled UC and EL, respectively), which measured 100 × 100 × 300 mm. The mix proportion of concrete is shown in Table 1. Ordinary Portland cement (OPC) was used as the cementing material. Granite gravel with particle sizes ranging from 5 to 16 mm and natural river sand were used as coarse and fine aggregates, respectively. The tested apparent densities of cement clinkers, coarse, and fine aggregates were 3077, 2628, and 2604 kg/m^3, respectively. All specimens were cured in the curing room for 28 days, at 20 ± 2 °C with a relative humidity of 95%. After that, they were moved out of the curing room and stored in an airtight chamber into which a basin of oversaturated calcium hydroxide ($Ca(OH)_2$) solution was put to absorb CO_2 in the atmosphere, avoiding possible natural carbonation of concrete. Once a specimen was about to undergo loading tests, including static and fatigue ones, the specimen would be moved out of this chamber.

2.2. Uniaxial and eccentric compressive fatigue tests

EL specimens were loaded with an identical eccentricity of 20 mm to generate both tensile and compressive stresses in the cross-section of each specimen. UC1-4 and EL1-4 specimens were subjected to axial and eccentric static loads, respectively, till failure. The average failure loads, i.e., 364.2 and 265 kN, were reputed as nominal failure loads (P_u) for UC and EL specimens, respectively. Three different fatigue load levels, i.e., the minimum and maximum load levels (P_{min}/P_u and P_{max}/P_u) for specimens were designed, as shown in Table 2. For UC specimens, the maximum load level was designed as a constant, i.e., 67.2%, and the minimum load level was controlled at 5%, 25%, or 45%, respectively. For EL specimens, the minimum load level was kept as constant as 10%, and the maximum load level was controlled at 60%, 70% or 80%. Different load ranges were chosen for concentrically and eccentrically loaded specimens to endow fatigue tests with diverse loading parameters. Through multiplying the nominal failure loads with the load levels each specimen was expected to undergo, the lower and upper load values for each specimen were determined. With the lower and upper load values, fatigue loads were thus exerted on each prism specimen with a sinusoidal waveform at a loading frequency of 10 Hz, through an MTS test set, as illustrated by Figs. 2 and 3 for UC and EL specimens, respectively. Fig. 4 shows that the input and applied load signals were very close to each other, which demonstrated the capability of this test set to exert sinusoidal fatigue loads on these concrete specimens at a loading frequency of 10 Hz. Meanwhile, two couples of 80-mm long strain gages were set on two opposite surfaces of each UC specimen, within the central 100-mm zone, to measure the vertical (compressive) and the horizontal (tensile) strains. Five couples of the same type strain gages were set at five positions on two opposite surfaces of each EL specimen to measure the strain distribution on the mid cross-section of each specimen, as shown in Fig. 3. Synchronously, fatigue loads were also measured by a force transducer. Moreover, two different loading cycles, i.e., 1.5 and 2.5 million, were designed for UC specimens under each expected stress level range. Two different loading cycles, i.e., 1 and 2 million, were designed for EL specimens under each anticipated load level range. As an exception, EL7 was loaded to 500,000 cycles in order to include a case with a relatively small number of loading cycles. Once the number of expected load cycles was reached, fatigue loads were unloaded to zero; in the meantime, realistic residual strains were measured by strain gages.

3. Fatigue test results and discussion

3.1. Stress-strain curves

Fig. 5 shows typical stress-strain relationships of concrete under uniaxial compressive fatigue loading. It seems that