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Investigations on the FPZ evolution of concrete after sustained loading by means of the DIC technique

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HIGHLIGHTS

- FPZ becomes much greater before forming full FPZ and much smaller after that under sustained loading.
- Boundary effect on FPZ evolution decreases with the increase of sustained load level.
- Crack propagates subjected to the initial cracking load during the creep test.
- A method using clip gauges to test crack propagation length and opening displacement is proposed.

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ABSTRACT

The three-point bending (TPB) specimens were first subjected to two levels of sustained loading, i.e., 30% peak load and the initial cracking load over 115 days. Then, they were moved out from the loading frames and tested under TPB loading until failure. The digital image correlation (DIC) technique was utilized to investigate the fracture process in concrete after sustained loading. According to the variations of the crack opening displacement from the experimental observations, the crack propagation lengths and the crack widths with respect to different loading points were derived, which provides the information on the evolution of the fracture process zone (FPZ) in concrete after sustained loading. The results indicated that, compared with the tested results from the aging specimens in the static TPB tests, the low sustained loading did not show obvious effects on the FPZ evolution. However, under the high sustained loading, the crack initiated during the loading duration, resulting in a longer critical crack propagation length. In addition, the decrease in the FPZ length for the specimens under the high sustained loading is more significant at the post-peak load stage, resulting in the increase in brittleness of concrete. Finally, a test method for determining the crack propagation length using clip gauges was proposed, which is more convenient in lab. The crack propagation lengths tested using clip gauges fairly well agreed with those by means of the DIC and verified the proposed measure method in this study.

1. Introduction

In practical engineering, most concrete structures operate subjected to sustained loading, such as gravity dams, protecting shells in nuclear power stations, cooling towers in thermal power plants, etc. Under sustained loading, the creep behavior of concrete has a significant effect on the load-carrying capacity and durability of the structures, which is associated with the sustained load levels and duration. Generally, it is considered that the linear creep takes place due to viscoelasticity of concrete under low load levels [1], while the structures present the non-linear creep behavior caused by the couple of crack growth and viscoelasticity of concrete under high load levels [2]. Considering that some structures still can be in service under sustained loading without the occurrence of failure, the fracture properties including the fracture toughness, the evolution of the fracture process zone (FPZ), after the sustained loading should be paid more attention to so that the crack propagation process and the load-carrying capacity can be predicted more precisely.

For quasi-brittle materials, such as concrete, there exists a FPZ ahead of the crack, which features strain softening and strain localization behavior [3]. Both the crack propagation length and the

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opening displacement in the FPZ are essential for characterizing the nonlinear behavior of concrete. The FPZ evolution has been widely investigated through many experimental and numerical studies. These studies indicate that the variations of the FPZ length will experience three stages with the crack propagation in concrete. In the first stage, the FPZ length increases linearly with the new crack formation. In the second stage, the FPZ length keeps a plateau due to the development of stress-free zone at the crack ending [4,5]. In the final stage, the FPZ length decreases rapidly when a crack approaches the top surface of a specimen [6–8], which can be explained by the boundary effect [6,9,10]. According to the experimental results, the maximum FPZ length of concrete increases with the increase of the specimen height, and decreases with the increase of the notched crack length-to-depth ratio (a_0/D) [11]. The same conclusion was drawn by Dong et al. [5] in the numerical analysis on the FPZ evolution by introducing the initial fracture toughness-based criterion. In addition, it also has been founded in their study, that the maximum FPZ length is not equal to the full FPZ length if the ligament is long enough, i.e. the FPZ length may keep increasing even after the FPZ fully is formed. The above-mentioned phenomenon is the evolution of FPZ under a static loading condition. Regarding the FPZ variations under the sustained loading, many studied have been conducted on its evolution during creep process in concrete. Salilba et al. [12,13] carried out the TPB creep tests at 85% peak load over a duration of four months. Then, in the followed standard TPB tests, the acoustic emission (AE) technique was used to assess the width of the FPZ. The decrease in the FPZ width was observed based on the amplitude distribution of the AE hits in the post-peak load stage. Omar et al. [14] investigated the damage development for the TPB specimens under 80% peak loading during the creep process. Meanwhile, by introducing the size effect model to analyze the characteristic length of the FPZ, they found that the fracture energy and the FPZ decreased for the TPB specimens after the creep tests. These studies provided the valuable information to assess the effects of sustained loading on the fracture properties and the FPZ evolution in concrete. However, the quantitative analyses on the FPZ variations with respect to the different loading stages after creep process have been less reported. Particularly, the crack propagation length caused by the sustained load in the creep stage and its effects on the FPZ evolution in the followed fracture process are not clarified clearly. In addition, the agreement of the FPZ evolution in various fracture stages is more convincing for verifying a numerical method when a comparison is made between the experimental and predicted results. Therefore, for the purpose of an in-depth insight into the fracture mechanism of concrete specimens after sustained loading, it is significant to investigate the FPZ evolution under different sustained loading levels.

The digital image correlation (DIC) is an optical technique used to visualize the surface displacement fields of a specimen. Through making a comparison of the digital images of specimen surfaces before and after deformations, the displacements of the regular grid points on the specimen surface can be obtained, so that the FPZ the evolution during fracture process can be derived through introducing a tensile softening constitutive law between the cracking opening displacement (w) and the cohesive stress (σ). So far, the DIC technique has been successfully used for investigating crack propagations in various conditions, including strengthened reinforced concrete specimens under fatigue loading [15], the mode I and mixed mode I-II fractures in cementitious materials [11,16–18] the fracture properties at concrete-concrete and rock-concrete interfaces [19,20]. The results of the above researches have demonstrated the availability of the DIC technique in the measurement of the crack propagation of concrete.

In this study, the DIC technique was employed to investigate the FPZ evolution after sustained loading. First, basic creep tests were conducted on the TPB specimens at 30% of the peak load and also at the initial cracking load for 115 days. Thereafter, these specimens were unloaded from the creep frames and then subjected to TPB loading immediately until failure. The crack opening displacements at various loading stages were obtained using the DIC technique and compared with the ones in the static standard TPB tests. Based on the experimental results, the FPZ evolution during fracture process and the effects of the formed cracks in the creep stage on the crack propagation were discussed. It is expected that the experimental results presented in this study can lead to a better understanding of the effects of sustained loading on the fracture process in concrete. In addition, it may be helpful to verify the developed numerical and theoretical methods for analyzing the fracture process after a creep stage by providing experimental evidence of the FPZ evolution and the crack opening displacements.

2. Experimental program

2.1. Specimen preparation and experimental set-up

The basic creep tests on the TPB concrete specimens were carried out firstly in this study. The dimensions of the TPB specimens were 500 mm × 100 mm × 100 mm (length × width × depth) with a 30 mm-long pre-notch. The mix proportions of the concrete were 1:0.60: 2.01:3.74 (cement:water:sand:aggregate) by weight and the maximum coarse aggregate size was 10 mm. The specimens were demoulded 24 h after casting and then moved into the standard curing room with 23 °C and 90% relative humidity for three months to avoid the effects of autogenous shrinkage at early age and the increase of strength on the results of creep tests. The mechanical properties of concrete, including the elastic modulus E, the splitting strength f_t, and the uniaxial compressive strength f_c at the ages of 28 and 90 days are listed in Table 1. In order to calibrate the applied load in the creep tests, three TPB specimens were tested to obtain the peak load P_{max}, and the mean value of P_{max} was determined as 3.81 kN at the age of 90 days. In addition, three specimens were cast at the same time and kept under the same curing conditions without loading, named as the "aging specimens".

After 90 days of curing, the basic creep tests were carried out under TPB loading by means of the designed steel loading frames, with the experimental set-up illustrated in Fig. 1. A load cell was connected onto a bolt and the load was applied by turning the bolt. The data acquisition system with a digital display was employed to record the real-time load. The creep tests were performed inside an environmental chamber with 23 °C and 60% relative humidity. To ensure only the basic creep to be measured in the experiment, double-layer aluminium tape was used to seal all surfaces of the specimens to prevent the moisture dissipation. Meanwhile, the low and high loading levels, i.e. 30%P_{max} and the initial cracking load, were applied in the creep tests, respectively. Accordingly, the specimens subjected to 30%P_{max} and the initial cracking load are denoted as Specimens C-30 and C-ini, respectively.

In the case of 30%P_{max}, the bolt was turned until the load level of 1.14 kN, i.e. 30% × 3.81 kN, was reached. By contrast, in the case of the initial cracking loading, four strain gauges were symmetrically pasted on both sides of the specimen surfaces, 5 mm away from

Table 1
Mechanical properties of concrete.

Mechanical property	E (GPa)	f_t (MPa)	f_c (MPa)
28 days	32.86	2.20	37.2
90 days	36.35	2.53	46.3