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Experimental investigation on the stress-strain behavior of steel fiber reinforced concrete subjected to uniaxial cyclic compression

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HIGHLIGHTS

- The effects of steel fibers on the cyclic stress-strain behavior of concrete specimens were investigated.
- Significant improvements in plastic strain accumulation and elastic stiffness degradation of SFRC specimens were observed.
- Damage process and failure mechanism of SFRC were analyzed based on acoustic emission parameters analysis.
- As analytical formulation for damage evolution law of SFRC was developed.

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ABSTRACT

The behavior of steel fiber reinforced concrete (SFRC) under cyclic loading plays an important role in prediction of SFRC structural response. This paper deals with the stress-strain behavior and damage evolution of SFRC under uniaxial cyclic compression. A total of 36 specimens are tested for different fiber volume fractions and aspect ratios. Acoustic emission (AE) technique is used to characterize the damage progression and reveal the failure mechanism of SFRC during the whole loading process. The results show that slight strength degradation for SFRC specimens under cyclic loading is observed in comparison with monotonic loading cases. The increase in volume fraction of steel fiber can lead to a remarkable decrease in the plastic strain accumulation as well as an increase in the elastic stiffness ratio, while the effect of fiber aspect ratio is undiscernable. In addition, it is indicated from the AE parameters analysis that the total AE activities of SFRC specimens are higher than that of plain concrete specimen and become greater with an increase in the fiber volume fraction, while the opposite is true for increasing the fiber aspect ratio. Meanwhile, as substantiated by AE, the failure of SFRC mainly demonstrates a shear cracking mode that is induced by fiber pull-out and fiber sliding events, the amount of which is proportional to both fiber volume fraction and aspect ratio. Finally, based on the test results of stiffness degradation, an analytical formulation for the damage evolution law of SFRC is developed and the prediction yields a close estimation of SFRC damage progression.

1. Introduction

Over decades, steel fiber reinforced concrete (SFRC) has been experiencing rapid development and gaining wide application in practical engineering field, such as tunnel linings, pavements, overlays and repairs [1–3]. When the fibers are uniformly dispersed and randomly oriented in the concrete matrix, a multidirectional constrained system is formed, as a consequence, significant improvement in the mechanical properties in terms of strength, stiffness and post-peak ductility can be achieved [4–9].

To date, considerable efforts have been made to investigate the mechanical behavior of plain concrete and confined concrete under cyclic loading conditions [10–20]. Predictive equations for constitutive relation and damage evolution have also been well established [21–26]. In those models, various cyclic parameters in terms of strain, strength, elastic stiffness, dissipated energy etc. are used to identify the damage index. Alternatively, some others have succeeded in the incorporation of fracture energy and damage-plastic concept for the damage modeling [27,28]. Those research outcomes have led to a great success in prediction of concrete cyclic loading responses and serve as a base for nonlinear analysis of concrete structural performance. Thereafter, using the plain concrete model as a foundation, similar approaches are attempted to describe the response of SFRC. Currently, extensive

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experiments concerned on the mechanical properties of SFRC have been carried out and various formulations for constitutive modeling of SFRC have been proposed [4–8,29–31], which are mostly applicable for monotonic case. Of the limited tests for SFRC under cyclic loading, the study conducted by Otter and Naaman [29] is worth quoting. They claimed that the SFRC behaves similarly as plain concrete, except for the envelope that is greatly influenced by the fibers. Moreover, it is noted that the existing constitutive models are found to be obtained through phenomenological methods with the model parameters lacking of physical meaning, and the damage evolution and damage mechanism of SFRC remain to be further elucidated.

In an attempt to reveal the underlying damage mechanism of SFRC, extensive researches on the AE behavior of SFRC structures have been conducted [32–33,34]. As a kind of nondestructive testing method, AE technique that uses the elastic waves resulting from crack initiation and propagation in a material, is a very useful method for in-situ monitoring of the dynamic process of crack growth in a concrete specimen [35–38]. In concrete members, the amplitude distribution of the acquired AE signals is very sensitive to microcracking, and inherent mechanism such as matrix cracking and fiber pull-out can be distinguished by the average frequency of the corresponding signals [39,40]. Furthermore, it has been previously observed that steel fibers can influence the failure mode and shear cracks dominate the SFRC failure by AE signals' analysis, which has been verified by other researchers [40–42]. However, more attention has been paid to the AE behavior of concrete members at structural scale, the AE responses of SFRC at material level can rarely be found.

The purpose of this paper is to study the stress-strain behavior and damage evolution of SFRC under uniaxial cyclic compression, which is of great importance for civil engineering design and concrete structural response analysis. The influences of fiber volume fraction and aspect ratio on the cyclic stress-strain response were studied. The damage evolution with respect to macro elastic stiffness degradation and AE activities was investigated. In addition, together with the observations of failure pattern at macro scale, the failure mechanism of SFRC was analyzed based on the AE parametric analysis in terms of RA value and average frequency at meso-scale.

2. Experimental program and setup

2.1. Materials and specimens preparation

The prism specimens with a dimension of 150 mm × 150 mm × 300 mm were employed in this study. The plain concrete mixtures are specified as a 28-day cubic compressive strength of 40 MPa. The mixture design of plain concrete can be found in Table 1. Ordinary Portland cement type P.O 42.5 was used as the binder for the mixtures. Crushed granitic rocks with the size between 5 and 20 mm were used as the coarse aggregates. Normal river sands with fineness modulus of 2.7 were used as the fine aggregates. A highly efficient water reducer with a reducing rate of about 20% was adopted in the mixture design in order to obtain good workability. All these mix proportions are designed according to the code JGJ 55-2011 [43].

Due to the advantages of deformed fiber in crack bridging and arresting effect [44–46], corrugated steel fibers were used in this study. The major material properties are shown in Table 2. According to the recommendation of previous studies [2,6], the recommended SF volume fraction is between 0.5% and 2.0% and aspect ratio ranges from 30 to 80. In this work, the volume fractions of SF were selected as 1.0%, 1.5% and 2.0% and the aspect ratios of 30, 60 and 80 were used.

All the specimens were fabricated following the specification in CSCE 38:2004 [47]. After uniformly mixing, the fresh concrete was very carefully cast into plastic forms and slowly vibrated at a vibrating table. After 24 h, the specimens were demoulded and stored in a standard curing room with a constant temperature of 20 °C and humidity of 95% until 28-day strength was achieved. In addition, for each case, six cubes having 150 mm side length were prepared for compressive strength (f_{cu}) and splitting tensile strength (f_{st}) tests. The average test results are listed in Table 3.

2.2. Test set-up

The uniaxial compressive experiments were performed on a universal electro-hydraulic servo rock testing machine-INSTRON-1346 shown in Fig. 1a. It has a 2000-kN load capacity. One linear variable displacement transducer (1#LVDT) with a maximal range of 5 mm was used to measure the vertical displacement, and the lateral displacement was monitored by 2#, 3#LVDT during the loading process. In this loading system, the axial load and displacements were automatically recorded in a computer. The test setup (loading equipment) and details of instrumentations are schematically shown in Fig. 1b.

Acoustic emission (AE) signals were obtained through a PCI-2 AE acquisition system produced by the American Physical Acoustics Corporation. The sensor type is Nano30, with the operating frequency range of 100–400 kHz. The amplitude distribution covers the range 0–100 dB. The parameters of the acquisition system are listed in Table 4. The AE sensors were mounted through the following steps: 1) coating the couple agent-Vaseline on the AE sensors surface; 2) sticking sensors to the specimen surface by plastic tape; 3) checking the coupling effect between sensors and specimen by the pencil lead break (PLB) test. In this work, two sensors (1#, 2#) symmetrically distributed on the sample were performed, as shown in Fig. 1.

2.3. Loading scheme

Both monotonic and cyclic loading scenarios were performed in this study. At the beginning of each test, a pre-loading of approximate 10 percent of the ultimate compressive strength was applied in order to stabilize the testing system. For the monotonic loading case, a displacement control method with a speed of 0.005 mm/s was used. The loading process was terminated until the concrete specimens collapsed into failure. For the cyclic loading case, all the specimens were tested following the loading scheme shown in Fig. 2, which adopted a hierarchical loading method with a controlled displacement. In the pre-peak region (stageⅠ), the displacement increment in each step was 0.15 mm with a speed of 0.01 mm/s. In the post-peak region (stageⅡ), the displacement increment was then set to 0.3 mm. Moreover, the unloading process was load controlled with a speed of 10kN/s. The test was terminated once a displacement limited value of 4.2 mm was reached.

Table 1
Designed concrete mixture proportions (kg/m^3).

Cement	Sand	Gravel	Water	Super plasticizer	Water cement ratio
417	724	1086	175	2.1	0.42