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A study of strain-rate effect and fiber reinforcement effect on dynamic behavior of steel fiber-reinforced concrete

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HIGHLIGHTS

- SFRC of a large range of fiber content are compressively tested using SHPB facility.
- Wave-shaper technique is investigated and adopted through the experiment.
- Strain-rate effect and fiber reinforcement effect of SFRC are studied thoroughly.
- Mechanisms underlying the two effects and their coupling effect are investigated.

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ABSTRACT

This paper presents an experimental study on uniaxial mechanical properties of steel fiber-reinforced concrete (SFRC) subjected to high strain-rate compressive loading. SFRC specimens of 6 different steel fiber volume fractions (0.0%, 0.75%, 1.5%, 3.0%, 4.5% and 6.0%) are fabricated and tested using a 75-mm-diameter split Hopkinson pressure bar (SHPB). Wave-shapers are investigated to ensure that two basic assumptions of SHPB hold true and that constant strain-rate is maintained within SFRC specimens. Based on acquired dynamic stress–strain relations, dynamic strength increase factor, fiber reinforcement factor, critical strain, and energy absorption are studied versus both strain-rate and fiber volume fraction. That provides an insight into strain-rate effect and fiber reinforcement effect on dynamic behavior of plain concrete and SFRC. The mechanisms underlying strain-rate effect and fiber reinforcement effect are discussed.

1. Introduction

Steel fiber-reinforce concrete (SFRC), concrete with extra addition of steel fiber, is of widespread engineering applications because of its stronger strength, ductility, and toughness than plain concrete [1]. When SFRC structures are subjected to impact loading, investigation of dynamic characteristics of SFRC become significant. Because strain-rate and fiber volume fraction both have great effects on dynamic behavior of SFRC, and the two effects are coupled in SFRC. A better understanding of dynamic characteristics of SFRC also help to design SFRC structures with strong resistance to penetration and explosion.

Over the past several decades, various experimental investigations were performed on SFRC to explore its dynamic behavior. Lok and Xiao [2] investigated SFRC panels with fiber volume fraction up to 1.5% exposed to air blast loading, found that the failure pattern of SFRC panel is deeply influenced by fiber volume fraction. Marar et al. [3] found a logarithmic relation between toughness energy and impact energy for SFRC with fiber volume fraction up to 2.0% using drop weight. Lok et al. [4,5] studied dynamic compressive strength and toughness of SFRC with fiber volume fraction up to 0.6% using a split Hopkinson pressure bar (SHPB). In these studies, SHPB technology used on SFRC was investigated and tapered striker bars were adopted to overcome problems existing in routine SHPB facility. Liu [6] studied dynamic behavior of SFRC with fiber volume fraction up to 6% using SHPB. A cease of the increase of strength with respect to fiber volume fraction was observed at fiber volume fraction 5.0%.

Most studies cited above studied SFRC of fiber volume fraction up to 2.0%, because high fiber fraction gives rise to fiber-caking, material inhomogeneity, and void increase. Only a very few studies tested SFRC of V_f higher than 3.0% [6], concluding that the increase

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in strength with respect to V_f ceased at about $V_f = 5.0\%$. That is contrary to results from the present study, probably because the inferior quality of SFRC specimens with higher V_f. In the present investigation, the above problems are solved by adopting special compositing method and super plasticizer to improve the workability of SFRC mortar.

Among the methods adopted in SRFC dynamic compressive experiments, such as drop weight [3,7] and air blast [2], SHPB [4,5] could obtain the main part of stress–strain curve at essentially the same strain-rate in the range from $10\,\mathrm{s}^{-1}$ to $10^3\,\mathrm{s}^{-1}$, which is of special importance in protective engineering. However, for SHPB technology used on concrete-like materials, special consideration must be given to one-dimensional wave assumption, stress uniformness assumption and constant strain-rate maintenance [4]. In the present investigation, wave-shapers are investigated to ensure the reliability of experimental data based on a good understanding of the mechanism underlying SHPB technology.

The aim of the experimental study is to provide a better understanding of stain-rate effect and fiber volume fraction effect on dynamic behavior of SFRC. To achieve this aim, a series of SHPB tests on SFRC are performed. Through the experimental data, strain-rate effect and fiber reinforcement effect on the characteristic properties of SFRC are identified. These properties include dynamic strength increase factor, fiber reinforcement factor, critical strain and energy absorption. The mechanisms underlying both strain-rate effect and fiber-reinforcement effect are discussed using damage mechanics.

2. Experimental procedure

2.1. Preparation of SFRC specimens

Secondary compositing method [8] was used to mix SFRC. This method comprises two phases. Firstly, fibers, part of cement, part of sand and part of water were mixed into fiber mortar, while the other matrix materials were mixed into plain concrete mortar. Secondly the fiber mortar and the plain concrete mortar were mixed into SFRC mortar. 15 cm cubes were casted with the SFRC mortar, and then wet-cured for 30 days. Cylinders of 70-mm -diameter were cored from these cubes. These cylinders were divided into cylindrical specimens of 35-mm -length and 70-mm -diameter for dynamic compression tests. The two ends of specimens were ground plane, smooth, and parallel, in order to ensure contact of pressure-bar/specimen interfaces and reduce friction effects. Six types of specimens were used throughout experiment, with steel fiber volume fractions $V_f = 0.0\%$, 0.75%, 1.5%, 3.0%, 4.5% and 6.0%, respectively. For each fiber volume fraction, thirty specimens were fabricated. In addition, cylindrical specimens of 100 - mm -length and 50 - mm -diameter were fabricated for quasi-static tests. Table 1 summarizes detailed mix proportions and quasi-static strengths for each fiber volume fraction.

A number of factors have been considered to determine the size of SFRC specimens. On one hand, in order to represent the actual behavior of SFRC, specimens must be large enough to contain sufficient material. The diameter and length of specimens must be greater than triple the maximum size of ingredients. In the present study, the maximum size of aggregate and the length of steel fibers are both 10 mm, therefore the diameter and length of specimens are at least 30 mm. On the other hand, specimens must be as short as possible in order to reduce inertia effects and ensure that stress within specimens becomes uniform more quickly. Furthermore, when the length to diameter ratio of specimens is equal to 0.5, inertia effects minimize [9]. Given these above discussions and the 75 mm diameter of pressure bars, it was determined to adopt 70 mm diameter by 35 mm long specimens for SHPB tests.

2.2. SHPB technique for testing SFRC

Stress–strain curves of SFRC specimens at high strain-rates were obtained with a 75-mm-diameter split Hopkinson pressure bar (SHPB) [10]. This facility is shown schematically in Fig. 1. Vaseline is applied evenly over the two ends of specimen to reduce friction effects. Then the specimen is placed in-between incident and transmitter bars with pressure-bar/specimen interfaces closely in contact.

Strike bar impacts onto incident bar, and produces incident pulse ε_i, which propagates along incident bar, and is reflected and transmitted at the incident-bar\specimen interface. The reflected part is denoted by ε_r. Transmitted wave propagates further, and is reflected and transmitted at the specimen\transmitter-bar interface. Transmitted pulse propagates along transmitter bar and is ε_t

Incident bar and transmitter bar must be longer than twice of striker bar to ensure that all incident, reflected, and transmitted pulses can be recorded by the two strain gages, respectively. According to one-dimensional wave theory and Hooke's law [11], strain-rate, strain, and stress histories of specimen can be derived from three pulses, as follows

$$\dot{\varepsilon}(t) = \frac{C_0}{L_s}[\varepsilon_i(t) - \varepsilon_r(t) - \varepsilon_t(t)] \tag{1}$$

$$\varepsilon(t) = \frac{C_0}{L_s}\int_0^t [\varepsilon_i(t) - \varepsilon_r(t) - \varepsilon_t(t)]\mathrm{d}t \tag{2}$$

$$\sigma(t) = \frac{EA}{2A_s}[\varepsilon_i(t) + \varepsilon_r(t) + \varepsilon_t(t)] \tag{3}$$

where $\dot{\varepsilon}(t)$, $\varepsilon(t)$, and $\sigma(t) =$ strain-rate, strain, and stress histories of the specimen, respectively; C_0, A, and $E =$ wave velocity, cross-sectional area, and Young's modulus of pressure bars, respectively; and L_s and A_s = length and cross-sectional area of the specimen, respectively.

There are two basic assumptions underlying SHPB technique: a) stress and strain within specimens remain uniform throughout the test; and b) waves propagate along pressure bars following one-dimensional wave theory. Lok [4] examined the two assumptions for SHPB tests on SFRC in detail. According to his study, stress and strain within specimens cannot become uniform prior to peak stress, unless the rising edge of incident pulse is longer than 60 μs. And differences between waveforms recorded from actual tests and that deduced from one-dimensional wave theory are negligible only if the bar-diameter\wave-length ratio (d/L) is less than 0.2. Because actual incident pulse consists of Fourier components of a wide range of frequencies, the amount of the high-frequency components of incident pulse must decrease to reduce the error caused by one-dimensional wave assumption. Regular SHPB facility produces an approximate rectangular incident pulse, which possesses an extremely short rising edge and a considerable amount of high-frequency components, as shown in Fig. 2 (a) and (b).

There are two solutions to these problems. One method is to use a linear tapered striker bar to produce a half-sine incident pulse with a long rising edge [5,12]. This method is costly because a specific type of material requires a specially designed striker bar. The other method is to place a compressible wave-shaper at the center of strike-end of incident bar [13,14]. Wave-shaper can be made of rubber, brass, or red copper, which are relatively cheap.

After some trial tests, brass wave-shapers of 20-mm diameter were adopted in the present study. Incident waves produced by regular SHPB facility and SHPB facility with brass wave-shaper