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Combined effects of steel fiber and strain rate on the biaxial compressive behavior of concrete

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HIGHLIGHTS

- Dynamic biaxial compressive experiments on SFRC were conducted.
- Combined effects of strain rate and steel fiber on dynamic strength were analyzed.
- Dynamic strength criterion of SFRC considering stress ratio was proposed.
- Model results well agreed with experiments at strain rates from 10^{-5}/s to 10^{-2}/s.

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ABSTRACT

Understanding the biaxial mechanical behavior of steel fiber reinforced concrete (SFRC) is of critical significance when the concrete structures are subjected to dynamic loading. This paper presents the results of an experimental investigation on the dynamic mechanical behavior of SFRC subjected to biaxial compressive loadings. Aiming at the combined effects of steel fiber and strain rate on strength criterion, a series of dynamic biaxial compressive experiments on 100 mm-length SFRC cubic specimens with various steel fiber contents (0%, 1%, 2%, and 3% by volume) were conducted by using a large dynamic triaxial servo-hydraulic testing apparatus. The specimens were loaded by biaxial compression with five stress ratios (i.e. 0:1, 0.25:1, 0.5:1, 0.75:1 and 1:1, respectively) at various strain rates ranging from 10^{-5}/s to 10^{-2}/s. A comprehensive dynamic biaxial strength criterion taking into account the combined effects of uniaxial strength, strain rate and stress ratio was proposed. The effect of steel fiber content and strain rate on the biaxial mechanical behavior of SFRC specimens was discussed, including the failure mode, stress-strain curve, biaxial compressive strength, dynamic strength criterion. It suggested that at given strain rate, the biaxial stress ratio is the major factor dominating the strength increment, and the incorporation of steel fiber has a remarkable enhancement on the strength for all stress ratios. Additionally, the dynamic compressive strengths of SFRC were found to increase with the increase of strain rate, while the failure pattern and dynamic ultimate strength were closely dependent on the magnitude of lateral stress exerted on the specimens. The comparison indicates that the proposed model results of dynamic strength criterion were in good agreement with the experimental data for SFRC specimens.

1. Introduction

Steel Fiber Reinforced Concrete (SFRC), which has more remarkable ductility, toughness and strength properties than plain concrete, has been of widespread application in a variety of civilian and military protective engineering structures, such as high-rise building, airport runway, safeguard structure and nuclear waste storage containment, etc. [1–3]. In reality, in addition to SFRC structures subjected to multiaxial quasi-static loads, numerous structures worldwide may suffer from dynamic loads due to recent terrorist attacks, earthquake, accidental explosions and incidental impacts [4–6]. Furthermore, comparing the failure mode between plain concrete and SFRC, one can see that steel fiber can significantly improve the dynamic performances of concrete [2–4]. Thus, understanding the response of SFRC to dynamic loading is important for the successful design and analysis of these structures.

In principle, the material behavior induced by the strain-rate dependence under dynamic loading conditions exhibits remarkable difference with that under quasi-static conditions [7–10]. The mechanical behavior of concrete has been found to be

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dependent on strain rate over a wide range of conditions. It has been well recognized that SFRC is highly sensitive to strain rate under uniaxial and multiaxial compression [11–20], tension [7,21,22], and flexure [23]. The strain rate, which is used to characterize the deformation speed of material, can be categorized into three types according to its amplitude, namely low strain rates (10^{-5}/s–10^{-2}/s), intermediate strain rates (10^{-1}/s–10^{2}/s), and high strain rates (10^{2}/s–10^{4}/s) [1,24–27]. In case of earthquake loading, the strain rate of concrete has been generally analyzed and simulated in the range of 10^{-4}/s–10^{-2}/s [28]. It is well recognized that most of structural members may be under multiaxial stress state in reality, e.g. the beam-column joints of a frame structure, especially subjected to dynamic biaxial compressive loading [19–21]. Thus, investigation of the dynamic mechanical behaviors of SFRC subjected to biaxial compressive loading under low strain rates is important to predict the structure response, and it is essential to provide valuable information for the structural design and calibration/validation of the constitutive model [3,13–17].

Over the past several decades, considerable efforts have been dedicated to investigate the influence of the volume fraction and shape of steel fibers on the dynamic mechanical behavior of SFRC, especially subjected to uniaxial compression with high stain rates [1–3,6,10–12,22–30]. For example, in the experiment performed by Wang et al. [11], the impact compression tests of SRFC specimens with the volume content of 0%, 3% and 6% ultra-short steel fibers at the strain rate up to 10^{2}/s were conducted on 74-mm-diameter split Hopkinson pressure bar (SHPB) to obtain the response of dynamic mechanical behavior. The results indicated that both the volume fraction of steel fibers and strain rate obviously exerted significant enhancing effect on the dynamic compressive strength of SFRC. Similarly, Hao and Hao [12] investigated the dynamic compressive behavior of spiral SFRC with four kinds of steel fiber content (0%, 0.5%, 1% and 1.5% by volume) at the strain rate of 50–200 s^{-1} by a series of SHPB tests. Furthermore, Lok et al. [6,29] conducted the SHPB tests to study dynamic compressive strength and toughness of SFRC with the volume fraction of steel fiber up to 0.6%. Li et al. [27] investigated the influence of steel fiber on the dynamic compressive behavior of hybrid fiber ultra-high toughness cementitious composites (UHTCC) at different strain rates ranging from 113.8 to 192.1 s^{-1}, and evaluated its dynamic behavior, including the failure patterns, dynamic compressive strength, dynamic increase factor and energy absorption ability. Overall, it can be concluded that the dynamic compressive strength exhibited increasing sensitivity to strain rate with increasing the steel fiber content, and the energy absorption was strongly dependent on the steel fiber content under high strain rates [1–3]. Meanwhile, from the low strain-rate side some observations have been made. For instance, Pan and Weng [8] reported that at a given aggregate concentration, the compressive peak stress increases with strain rate (ranging from 5×10^{-6}/s to 10^{-1}/s) whereas the peak strain generally decreases with it. Zhang et al. [5] investigated the influence of strain rate (10^{-5}/s–10^{-2}/s) on seismic responses of RC structures by means of experimental tests and numerical simulations. Generally, the compressive strength of concrete is all enhanced with the increase of strain rate.

From what is above stated so far, a large volume of literature already exists documenting the dynamic characteristic of SFRC with different steel fiber volume fractions at different strain rates, but most of them mainly focus on the dynamic behavior under uniaxial compression [2–4,6,10–12,24,27], especially at higher strain rates. However, concrete material principally works under a multiaxial stress state and frequently suffers from dynamic loading with different strain rates [31,32]. Although more and more attentions have been currently attracted to study the multiaxial behavior of concrete [15,20,33–41], surprisingly few studies have been focused on the effect of the volume fraction and type of steel fiber on the dynamic biaxial behavior of SFRC. In the present existing studies, a series of the experimental studies on dynamic biaxial compressive mechanical behavior of plain concrete have been carried out by the servo-hydraulic multiaxial testing system [42–44]. In some instances, Wang et al. [13] investigated the effect of saturation coupled with different strain rates (ranging from 10^{-5}/s to 10^{-2}/s) on the dynamic behavior of dam concrete under biaxial compression, and proposed the dynamic failure criterion to characterize both the effects of strain rate and water content on the ultimate strength of dam concrete. Shang et al. [21] performed the dynamic biaxial tensile-compressive tests of plain concrete. For the biaxial testing conducted by Yan et al. [42], over 60 cubic specimens were axially loaded in compression at various strain rates ranging from 10^{-5}/s to10^{-2}/s while two opposite side faces were applied to loading with a constant confining pressure. They found that the biaxial strength of concrete increases with strain rate at a reduced slope as the confining pressure increases. Furthermore, Quast and Curbach [44] analyzed the overlap problem of two strength enhancing effect of biaxial compressive loading and elevated strain rate by a unique biaxial SHPB testing. Generally, in the absence of experimental data, the interpreting of failure criterion involving the coupled effect of steel fiber content and strain rate for SFRC has not yet been made clear.

This paper attempts to gain insight into the dynamic mechanical behavior of SFRC under biaxial compression at the low strain rate ranging from 10^{-5}/s to 10^{-2}/s from the perspective of experimental investigation and theoretical analysis. The major objectives of this research are to: (i) provide new experimental data on the failure behavior under dynamic biaxial compressive stress state for SFRC with the strain rate ranging from 10^{-5}/s to 10^{-2}/s, and (ii) develop an analytical model of dynamic strength criterion considering the combined effect of strain rate and stress ratio in the studied range of strain rate. In this study, the dynamic biaxial compressive strength experiments on SFRC with four steel fiber contents (0%–3% by volume) at the strain rate ranging from 10^{-5}/s to 10^{-2}/s were carried out by using a large static/dynamic triaxial servo-hydraulic testing machine. For comparison purposes, plain concrete is also prepared and quasi-static experiments are conducted. The compressive stress-strain curves of SFRC with various steel fiber contents under different strain rates were experimentally obtained, and the effects of steel fiber content as well as the strain rate on the dynamic biaxial compressive properties were discussed. On the basis of the test data, the dynamic failure criterion considering steel fiber volume fraction and strain rate was proposed.

2. Experimental program

2.1. Mixture design and casting

The cubic SFRC specimens ($100 \times 100 \times 100$ mm^3) with a water-cement ratio (w/c) of 0.5 were prepared and subjected to the biaxial compressive loading. The ordinary Portland cement used in the mix was Chinese standard Graded P·O 42.5R type. The local river sand and available crushed gravel were used as the fine and coarse aggregate, respectively. The used river sand has a fineness modulus of 2.67 and apparent specific gravity of 1450 kg/m^3. Four volume fractions (υ_{SF} = 0%, 1.0%, 2.0%, 3.0%) of Dramix hooked-end steel fiber (RC65/35BN type: diameter of 0.55 mm, length of 35 mm, aspect ratio of 63.6, tensile strength of 1350 MPa) were incorporated as shown in Fig. 1. Correspondingly, the steel fiber content is set as 46.8 kg/m^3, 93.6 kg/m^3 and 140.4 kg/m^3, respectively. The details of SFRC constituents and mixture proportions are given in Table 1. The concrete mixtures were cast in metal molds and then compacted using a mechanical