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The Mechanical Property of Steel Reinforced Concrete under Compressive Impact Loading Investigated with the SHPB Experiments

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Abstract-In this paper, high velocity impact test of SFRHSC was conducted with SHPB experimental technique four series mixture of SFRHSC were used: C100V4, C100V3, C100V2, C100V0.And the steel fiber volume fraction (v_f) were 0, 2%, 3% and 4% respectively. The primary objective of this research is to enhance the understanding of the response of SFRHSC to high strain rate impact. The anticipated results of the study are determination of dynamic material properties and failure mechanisms of SFRHSC. The crack characteristics of steel fiber reinforced and plain concrete are investigated in the SHPB test. Analyzed the relation between the character on the Crack Surface of Concrete and material properties and the impact pressure. Also the multiracial characteristics are given on the Crack Surface of Concrete. The crack distributions of steel fiber reinforced concrete are investigated. The crack resistance effects of fiber are analyzed from the degree of closeness and uniformity.

Keywords- *SHPB; bar; concrete; multifractal*

I. INTRODUCTION

Ultra-high performance cementitious composite is a type of building material with very high strength and durability. With high strength and ductility, it is suitable for bridge decks, thin shell structures, nuclear power plants and defensive facilities that may experience impact loads [1－4]. But the higher strength the concrete is, the higher brittle it is. So it necessary to add the steel fiber to the high strength to increase its mechanical property.Also,To better design and analyze these structures, High strength concrete (HSC) becomes more common in practice, however, the higher the strength of HSC, the higher the material brittleness. Therefore, it is important to enhance the ductility of HSC, and one possible direction is to use steel fibers reinforced, named steel fiber reinforced high strength concrete (SFRHSC). The static behavior of SFRHSC have been more researched, while the dynamic behavior of SFRHSC were researched less, and the later are very important to properly design and analysis of structures to resist dynamic loads such as earthquakes, accidental impacts or explosions. The early experimental data of concrete under impact loading were almost obtained with pendulum test, drop weight tests [1], however, there are more gaps among different results from different researchers [2-6]. Of course, one of the factors is the heterogeneous nature of concrete, but the mainly reason due to the possible imprecision of those loading and measuring devices. A great number of tests have been conducted to find the effect of strain rate on the dynamic strength of concretes. A few methods, such as direct impact test, Split Hopkinson Pressure Bar (SHPB) test, plate impact test and the Light Gas Gun test, are commonly used to determine the dynamic material properties [1-5].The split Hopkinson pressure bar (SHPB) is an effective method to obtain the dynamic stress－strain curves of materials.

II. THE EXPERIMENTS

A. Materials preparation

The strength grade of cement is P·II 52.5 according to the relevant China standard. The maximum particle size of natural sand is 2.5 mm with a fineness modulus of 2.6. The equivalent diameter, length and tensile strength of the steel fiber are 0.2 mm, 13 mm and 1800 MPa respectively. The mix proportion is adopted C100 by the China standard.The volumetric steel fiber concentration 0, 2%, 3% and 4% are used which called C100V0,C100V2,C100V3, and C100V4,.Specimens have the diameter 40mm and 20mm length. 1．2 The design of the experiments. The volume fraction (v_f) of steel fibers is varied from 0%, 1-4%, the matric is designed with C100. The specimens are circular cylinders 40 mm in diameter. Specimens with same length (20mm) are used. The strain rates

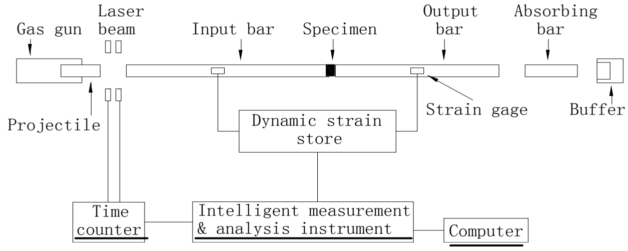


Fig 1 The SHPB set up

achieved ranged from 30 to 100s^{-1}.The Split Hopkinson Pressure Bar(SHPB) is somehow a universal experimental technique in the study of the constitutive law of materials at high strain rates. A typical SHPB set-up is outlined in Fig.1.It is composed of the long incident bar and transmission bar with a short specimen between them. The technique is based on the theory of one-dimensional wave propagation in an elastic bar. The striker bar, propelled by the pressurized gas, impacts against the input bar. The impact develops a compressive longitudinal incident wave $\varepsilon_i(t)$ .Once it arrives at the bar specimen interface, a reflected wave $\varepsilon_r(t)$ is developed in the input bar, whereas a transmitted wave $\varepsilon_t(t)$ is developed in the output bar. Specifically, the stress and strain histories are, respectively,

$$\sigma_s(t) = \frac{EA}{A_s}(\varepsilon_t(t)) = \frac{EA}{A_s}[\varepsilon_i(t) + \varepsilon_r(t)] \qquad (1)$$

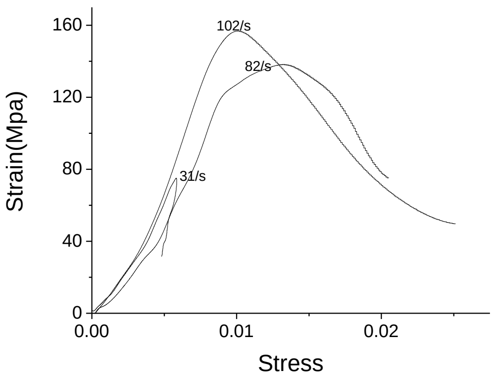
$$\dot{\varepsilon}_s(t) = \frac{2c_0}{L}[\varepsilon_i(t) - \varepsilon_t(t)] = -\frac{2c_0}{L}(\varepsilon_r(t)) \qquad (2)$$

$$\varepsilon_s(t) = -\frac{2c_0}{L}\int_0^t \varepsilon_r(t)dt = \frac{2c_0}{L}\int_0^t [\varepsilon_i(t) - \varepsilon_t(t)]dt \qquad (3)$$

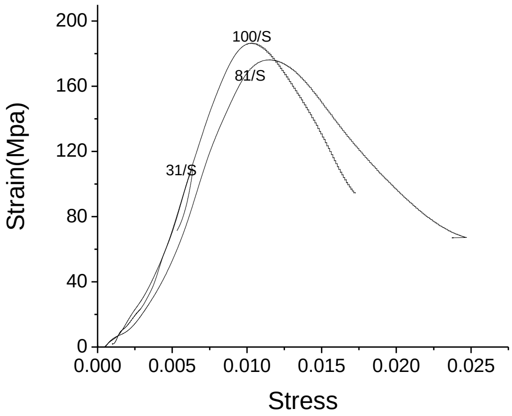
Where E, A, and C0 denote the Young's modulus, cross-sectional wave speed of the bars.Fig2 shows the stress and strain rate histories obtained from the reflected and transmitted histories.

B. Analysis of the tests

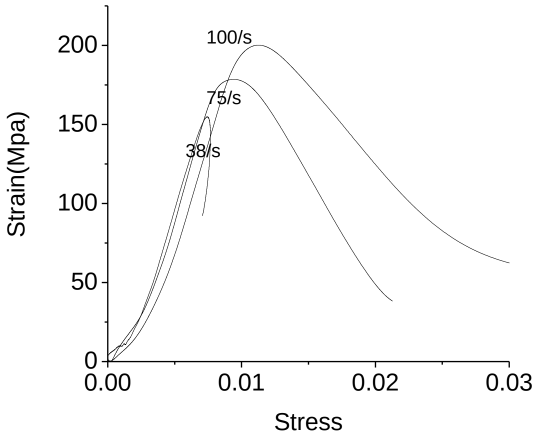
Similar to static or quasi-static state, steel fiber also play an important role in strengthening and toughening of SFRHSC at high strain rate. As shown in Fig 3, when the strain rates increase about 60/s to 100~105/s, the compressive strength for four series of concrete raise, and the magnitude of the raise is in the order C100V4> C100V3 > C100V2>C100V0, which illustrates that the strain rate hardening effect becomes stronger with the incorporation of steel fibers. SFRHSC exhibits relatively excellent ductility at high strain rate. As shown in Fig 2, the descending portions of the stress-strain curves of the SFRHSC are much flatter than those of the matrix concrete. Experiment results shows that the SFRHSC specimen damaged relatively contrast to matrix concrete specimen at different strain rate. Where C100V4 > C100V3 >



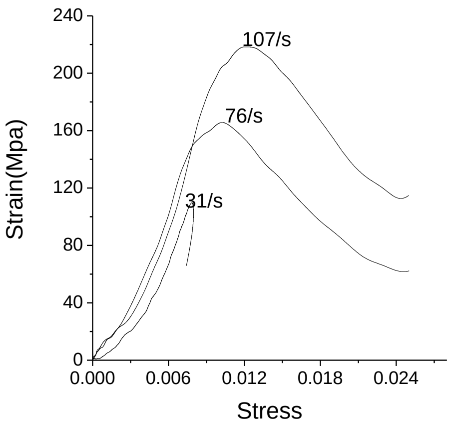
(a) C100V0



(b) C100V2



(c) C100V3



(d) C100V4

Fig. 2 (a), (b), (c) and (d): Stress-strain curves of three series of concrete

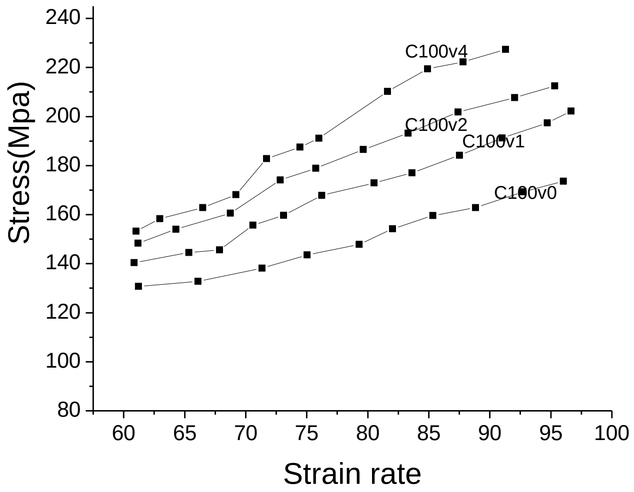
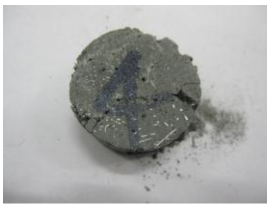


Fig 3. The strength-strain rate relation curves of four series of concrete


(a) (b)




(c) (d)

Fig. 4 The typical crack of the different concrete

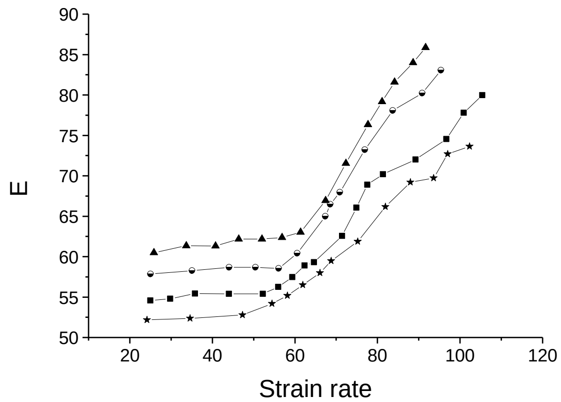


Fig 5 The E-strain rate relation curves of four series of concrete

C100V2>C100V0.Four series of concrete specimens damaged are shown in Fig 4, the matrix concrete specimen was crush up completely, but the SFRHSC specimens remained their integrity. The studies have shown that concrete has a sensitivity threshold [18].When the strain rate is smaller than the threshold value, the elasticity modulus changes little with the strain rate increasing. On the contrary, when the strain rate is larger than the threshold value, the elasticity modulus changes rapidly with the strain rate increasing. It can be seen from the experiments that the sensitivity threshold appears at the time the macro crack become to occur in the surface of the specimen. It can be deduced it is the time that the microfissure of the specimen become destabilization and connection each other. So it is significative to study the dissipation of energy and fractal characteristics etc. at this moment (Fig5).

III. THE FRACTAL CHARACTERISTICS OF THE STRAIN RATE SENSITIVITY THRESHOLD

Before you begin to format your paper, first write and save the content as a separate text file. Keep your text and graphic files separate until after the text has been formatted and styled. Do not use hard tabs, and limit use of hard returns to only one return at the end of a paragraph. Do not add any kind of pagination anywhere in the paper. Do not number text heads-the template will do that for you.

Finally, complete content and organizational editing before formatting. Please take note of the following items when proofreading spelling and grammar:

The steel fiber reinforced concrete on the strain rate sensitivity threshold in SHPB experiments have the following image (Fig.4(d)). The Morphological comparison of concrete damage converted to the black-white bitmap of concrete (Fig.6).

The fractal method is used to study the fractal characteristics of the concretes in SHPB experiments. The fractal dimension can be evaluated from the rate of growth of number N, necessary to cover the entire surface, as the size d of the elementary prisms decreases. The following equation holds:

$$D = \lim_{d \to 0} \frac{\log N}{\log(1/d)}$$

From a practical point, the fractal dimension (D) can be evaluated from the slope of the regression line in the bi-logarithmic diagram logN vs.logd(Fig7).

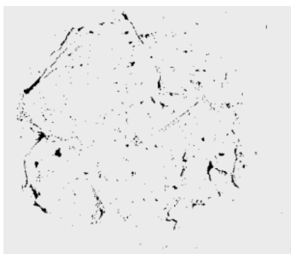


Fig.6 Black-white bitmap of concrete

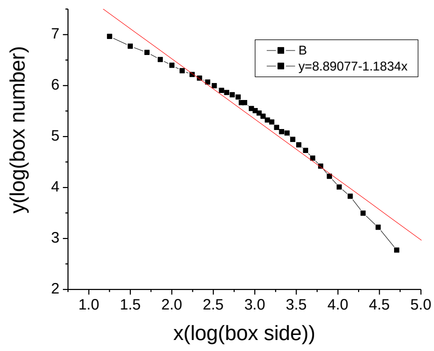


Fig.7 The box dimension of the fitting curves for the test concrete

The multifractal method [15] is used to study the fractal characteristics of the concretes in SHPB experiments (fig6). Grid of each pixel (i, j) calculated belonging to the crack, which divided by the total grids of the pixels $\sum n_{ij}$. The probability of each square p_{ij} can be obtained.

$$p_{ij} = \frac{n_{ij}}{\sum n_{ij}}$$

Suppose N is the number of singular existence interval box, $f(\alpha)$ is defined as a singularity α of the grid geometry of the Hausdorff dimension,

$$N(\alpha) \propto \alpha^{-f(\alpha)}$$

From the multifractal method,

$$\begin{cases} \alpha(q) = \dfrac{\mathrm{d}\,\tau(q)}{\mathrm{d}\,q} \\ f(\alpha(q)) = \alpha(q)q - \tau(q) \end{cases} \qquad (4)$$

Where $\chi_q(\varepsilon)$ is the partition function, $\tau(q)$ is the quality index.

As an example, The image calculated by the log-log curves(fig8).It can be seen from the calculated results basically remain a straight line, which indicating that the scale-free and the concrete surface crack with multi-fractal characteristics. It can be seen from the calculation, when q take the absolute value of 10 pm, the calculation has been stable(fig9).

As an example, the $f - \alpha$ curves (fig10) are obtained with the same chamber pressure(fig6(c),(d)).

It can be seen that:1 For the same kinds of concrete at different chamber pressure, the pressure increase, $f(\alpha)_{\max}$ are also on the rise, that the proportion of cracks in concrete on the rise.

$\Delta\alpha$ increasing with the increasing of the pressure which indicated the more uniform distribution of crack the more smaller of the pressure .

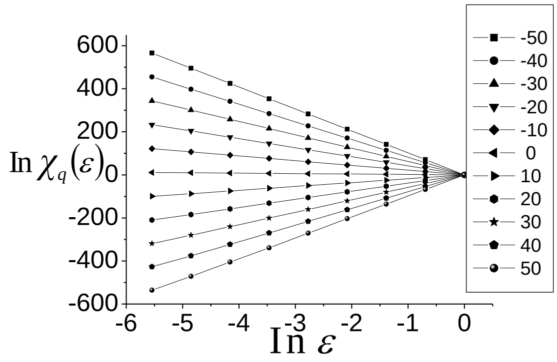


Fig.8 In $\chi_q(\varepsilon)$ ~ In ε curves

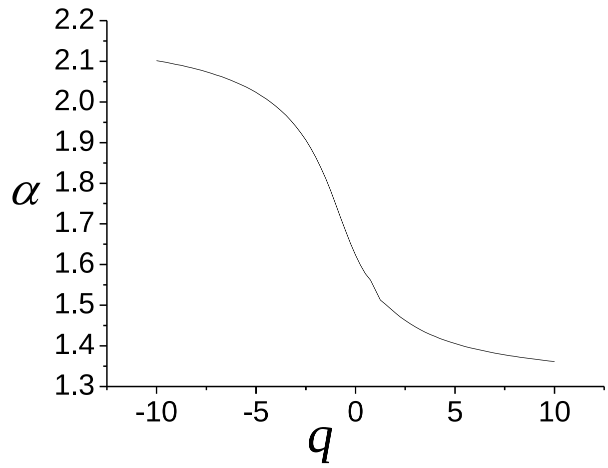


Fig.9 $\alpha \sim q$ curves

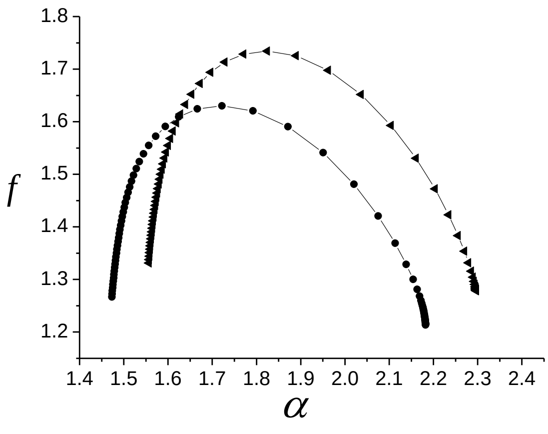


Fig.10 Concrete multifractal spectrum curves

IV. THE RELATIONSHIP BETWEEN THE DAMAGE FACTOR AND THE FRACTAL

Jiang-xiong Li[17] also applied the dimensional analysis of SHPB mechanism and obtained the following relationship between the strain rate and the dimension.

$$\dot{\varepsilon} = A + B * D \quad (5)$$

Where A，B are the constants. A，B are different when the v_f of the concretes are different.

Homoplastically,for the multifratal characteristics, the relationship between the strain rate and the dimension can be expressed as,

$$\dot{\varepsilon} = A + B * ((1-C) * F * \Delta\alpha + C * f(\alpha)_{\max}) \quad (6)$$

The stress can be described as,

$$\sigma = \sigma(\varepsilon, \dot{\varepsilon}, d) \quad (7)$$

Where σ is the stress, ε is the strain, $\dot{\varepsilon}$ is the strain rate, d is the damage factor which can be described as,

$$d = 1 - \exp(\frac{\varepsilon}{F})^m \quad (8)$$

where

$$m = (1 + av_f)(1 + b\ln\dot{\varepsilon}) \quad (9)$$

$$F = (1 + kv_f)(1 + n\ln\dot{\varepsilon}) \quad (10)$$

Where a,k,b,n are the constants.

The σ in SHPB experiment can be expressed as,

$$\sigma = (1-D)\varepsilon = E_0\varepsilon\exp(\frac{\varepsilon}{F})^m \quad (11)$$

The constants M, F can be obtained by fitting the experimental curves(fig2).The relationship between the damage factor and the fractal dimension have been set up.

V. CONCLUSIONS

1 SFRHSC is rate sensitivity material, and the critical strain rate is existence. When the strain rate lower than the critical strain rate, the dynamic compressive strengths of SFRHSC lower than their static compressive strengths, and increase slowly with the increase of the strain rate, and SFRHSC exhibits significant strain rate hardening effect, namely, strength increase after the strain rate higher than the critical strain rate.

2 Steel fibers play an important role in strengthening and toughening of SFRHSC at high strain rate. The strain rate hardening effect becomes stronger with the incorporation of steel fibers, and the magnitude of the compressive strength raise is in the order when the strain rates increase after the critical strain rate.

3 The differences of multi-fractal spectrum to the maximum, minimum probability of a subset of dimension can be used to count the most of the surface of the concrete cracks and the smallest proportion.

4 This study is based on fractal surface crack of concrete research. In fact, when the impact velocity is large ,the concrete is usually the overall damage, even crushed. The study the impact of surface fractal surface crack is often impossible to carry out, It is need to study the three-dimensional fractal.

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