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The study on steel fiber reinforced concrete under dynamic compression by damage mechanics method

Wang Jianhua[1,2], Lou Jun[2] and Yang Haiping[2]

[1]School of Water Conservancy and Hydropower Engineering, Hohai University, Nanjing, China
[2]Zhejiang Tongji Vocational College of Science and Technology, Hangzhou, China

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ABSTRACT

Generally, steel fiber reinforced concrete (SFRC) during the few past decades has been found to possess many excellent dynamic performances such as high resistance to explosion and penetration, which has now attained acknowledgment in numerous engineering applications since it has several advantages. The randomly distributed short fibers can be utilized to improve the physical properties of reinforced concrete structures due to the resistance from crack initiation to crack propagation. Most of the steel fiber reinforced concrete research just to solve a specific problem, and little information available concerning the structure performance degradation of SFRC in certain circumstances. In current paper, a formulation to model the mechanical behavior of high performance fiber reinforced cement composites with arbitrarily oriented short fibers. The formulation can be considered as a two scale approach, in which the macroscopic model, at the structural level, takes into account the microstructural phenomenon associated with the fiber-matrix interface bond/slip process. Based on ANASYS software platform, the numerical study on SFRC durability by damage mechanics method is carried out. Furthermore, waveforms from dynamic compression and dynamic stress-strain curves for SFRC under different strain rate will be analyzed. Numerical results can provide some reliable basis for SFRC durability design.

Keywords: SFRC; Dynamic Compression; Damage Mechanics; Strain Rate; ANSYS

INTRODUCTION

During recent years, steel fiber reinforced concrete (SFRC) has gradually advanced from a new, rather unproven material to one which has now attained acknowledgment in numerous engineering applications. Lately it has become more frequent to substitute steel reinforcement because adding fibers can overcome the brittleness of the concrete by improving the post-cracking behavior and enhancing ductility. Therefore, the applications of SFRC have been varied and widespread due to its various advantages, for example tunnel linings, slabs, and airport pavements (S. Tokgoz et.al, 2012; R.S. Olivito et.al, 2010).

In particular, concrete is a unique composite material that is porous and highly heterogeneous. It is brittle in resisting tensile stresses, but the addition of discontinuous fibers leads to a dramatic improvement in their toughness during the fracture process. The randomly distributed short fibers (see Figure 1) can be utilized to improve the physical properties of reinforced concrete structures. It is generally agreed that the fibers contribute primarily to the post-cracking response of the matrix, by providing resistance to the crack opening.

Figure 1. Steel fibers used for SFRC composite

When subjected to the corrosive media in environment, durability problem appears in SFRC in the service process. The neutralization of concrete and the steel corrosion are the main aspects in the durability of concrete structures, and the neutralization of concrete is the prerequisite for steel corrosion. The neutralization of concrete in practical projects is the result of interaction of physical, chemical and mechanical factors. Therefore, the neutralization of SFRC under multiple factors should be investigated, which is significant for the durability design and assessment and for the further investigation reinforcement corrosion and service life prediction of SFRC structures.

Fiber-reinforced concrete (FRC) is a composite material made primarily from hydraulic cements, aggregates and discrete reinforcing fibers. The behaviour of steel fiber reinforced concrete (SFRC) started to be well known in the case of a first short-term loading; the durability of their vital character in the structural applications remains still largely to be explored. The long-term behaviour of operational structures reinforced with steel fibre in the cracked mod depends on their capacity of effort taken by the fibre between the two lips of cracks. This is conditioned, on the one hand, with mechanical creep and fatigue effect, on the other hand, with corrosion of fibres.

Numerous works for evaluating mechanical properties of SFRC have been reported, it now has been well accepted that incorporation of steel fiber can significantly improve the mechanical behaviors of concrete. Yang and Zhu (2005) reported that the deicer-scaling resistance of concrete is reduced by the addition of steel fibers at the same air content, especially for the air entrained concrete. Cantin and Pigeon (1996) indicated that steel fibers have no significant influence on the deicer-scaling resistance of concrete. According to Sun et al. (2002), steel fiber could retard the performance deterioration of the concrete and improve the resistance against multidamaging under severe conditions.

From the literatures, it is obvious that most of the steel fiber reinforced concrete durability research just to solve a specific problem, and little information available concerning the structure performance degradation of SFRC under dynamic compression in certain circumstances, which is closely related to durability design and service life prediction of steel fiber reinforced concrete structure. General atmospheric environment research of SFRC durability should be around neutral model, reinforced the initial corrosion time, the protective layer rust cracking, corrosion of SFRC components bearing capacity calculation methods to expand (Z.L. Wang et.al, 2009; S.P. Singh et.al, 2003; O. Ünal et. al, 2007). However, waveforms from dynamic compression and dynamic stress-strain curves for SFRC under different strain rate needs more investigate. In this paper, a formulation to model the mechanical behavior of high performance fiber reinforced cement composites with arbitrarily oriented short fibers. The formulation can be considered as a two scale approach, in which the macroscopic model, at the structural level, takes into account the microstructural phenomenon associated with the fiber-matrix interface bond/slip process. Based on ANASYS software platform, the numerical study on SFRC under dynamic compression by damage mechanics method is carried out. Furthermore, waveforms from dynamic compression and dynamic stress-strain curves for SFRC under different strain rate will be analyzed.

1. The Theroy Method

Damage mechanics theroy in recent years has attained the unprecedented development and has received a great deal of attention. It has been widely applied to various research fields of concrete structures, such as damage analysis, the prediction of mechanical performance, the estimation of and service life.The theoretical framework of damage mechanics is developed in the mid-1970s. However, since the 1980s, the damage mechanics have been used to describe the non-linear characteristics of the concrete. The physical mechanism of the damage is the main cause of nonlinear stress-strain relationship and irreversible deformation. Therefore, many studies have suggested that the damage theory can be suitable for concrete constitutive model (N. Buratti et.al, 2011; L. Nguyen-Minh et.al, 2011).

Macroscopic mechanical properties of steel fiber reinforced concrete at the macro-level are studied based on the method of continuum mechanics. The study of solid materials in a representative volume element is usually analyzed by the voxels changecaused by the structural damage. At this level the damage variable can be definited as a spatially continuous distribution and the parameter changed by the time. Consequently the formula of damage variable can be written as the following:

$$D = 1 - \frac{\varphi}{\varphi_0}$$

in which φ and φ_0 respectively mean the material of the current and initial mechanical performance parameter, which represents the stress of the material strength, elastic modulus,mass density, or the ratio of the material within the volume fraction of the micro-defects or area fraction.

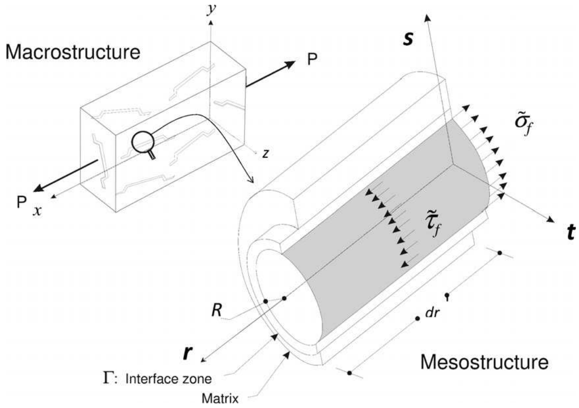


Figure 2. Idealization of the fiber matrix bond-slip mechanism at the mesoscale level

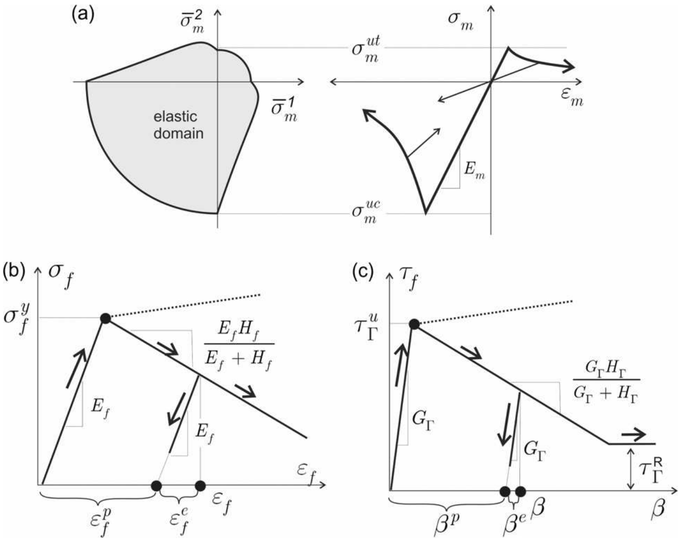


Figure 3. Constitutive model of the HPFRC components

Idealization of the fiber matrix bond-slip mechanism at the mesoscale level is shown as Figure 2. The damage mechanics study on deformable solids is researching a continuous defective distribution of concrete in order to determine the evolution of the damage continuous field variables. Its research continuum mechanical system under the ways and means can be determined. However, it is necessary to introduce mesoscopic and materials science methods in order to have better understanding of the damage causes of injury and the shape characteristics of the micro-structure. The theory methods on damage problems of steel fiber reinforced concretecan can be broadly divided into three types, namely, metal physics methods, phenomenological methods and statistical methods. A new formulation to model the mechanical behavior of high performance fiber reinforced cement composites with arbitrarily oriented short fibers is detailedly presented in the paper of J. Oliver (J. Oliver et.al, 2012).

Table 1. The values of model materical parameters

Matrix	Fiber	Interface zone
σ_m^{ut}=4.0MPa	σ_f^{y}=260MPa	τ_r^{u}=different values
E_m=21.0GPa	E_f=180 GPa	G=10^5 GPa/m
ν_m=0.2	H=170 MPa	H=0 τ=0
G_{mf}=0.1MPa	θ=0°	k=0.86%

In an attempt of overcoming these drawbacks, some researchers proposed a combination of FRP and steel reinforcements for concrete beams. From Figure 3 and Table 1, we can know constitutive model of the HPFRC components and the values of material parameters in models. By combining with these reinforcement materials and considering the minor concrete cover required for FRP, an effective reinforcement solution in terms of concrete dynamic performance is obtained by placing the FRP bars near the outer surface of the tensile zone and steel bars at an inner level of the tensile zone. Figure 4 described uniaxial stress-strain curve with damage in tension and compression. The presence of steel bars in the above mentioned hybrid reinforcement system provides a significant contribution in terms of the ductility and stiffness (J.A.O et.al, 2012). The experimental tests of this hybrid reinforcement concept, in spite of being scarce, have been utilized to confirme the potentialities of this reinforcement system.

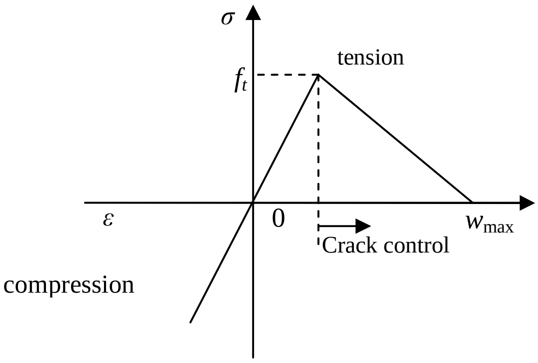


Figure 4. Uniaxial stress-strain curve with damage in compression

The basic equation of motion solved by an implicit transient dynamic analysis can be given as the following:

$$m\ddot{x}+c\dot{x}+kx=F(t)$$

where ***m*** is the mass matrix; ***c*** is the damping matrix; ***k*** is the stiffness matrix; and ***F*(*t*)** means the load vector. At any given time *t*, this equation can be regarded as a set of "static" equilibrium equations, which can also take into account inertia forces and damping forces. The Newmark or HHT method is used to solve these equations at discrete time points. The time increment Δt between successive time points is called the integration time step. For linear or nonlinear analysis, the basic demand should be satisfied as follows:

For linear problems: (i) implicit time integration is unconditionally stable for certain integration parameters. (ii) The time step will vary only to satisfy accuracy requirements.

For nonlinear problems: (i) the solution is obtained by using a series of linear approximations (Newton-Raphson method), so each time step may have many equilibrium iterations. (ii) The solution requires inversion of the nonlinear dynamic equivalent stiffness matrix. (iii) Small and iterative time steps may be required to achieve convergence. (iv)the convergent tools are provided, but convergence is not guaranteed for highly nonlinear problems.

The basic equations solved by means of an Explicit Dynamic analysis can express the conservation of mass, momentum and energy in Lagrange coordinates. These, together with a material model and a set of initial and boundary conditions, define the complete solution of the problem. For Lagrange formulations, the mesh moves and distorts with the material it models, so conservation of mass is automatically satisfied. The density at any time can be determined from the current volume of the zone and its initial mass as follows:

$$\frac{\rho_0 V_0}{V} = \frac{m}{V}$$

The partial differential equations of the conservation of momentum related with the acceleration to the stress tensor σ_{ij} can be given:

$$\rho\ddot{x} = b_x + \frac{\partial\sigma_{xx}}{\partial x} + \frac{\partial\sigma_{xy}}{\partial y} + \frac{\partial\sigma_{xz}}{\partial z}$$

$$\rho\ddot{y} = b_y + \frac{\partial\sigma_{yx}}{\partial x} + \frac{\partial\sigma_{yy}}{\partial y} + \frac{\partial\sigma_{yz}}{\partial z}$$

$$\rho\ddot{z} = b_z + \frac{\partial\sigma_{zx}}{\partial x} + \frac{\partial\sigma_{zy}}{\partial y} + \frac{\partial\sigma_{zz}}{\partial z}$$

Moreover, the conservation of energy is written as follows:

$$\dot{e} = \frac{1}{\rho}\left(\sigma_{xx}\dot{\varepsilon}_{xx} + \sigma_{yy}\dot{\varepsilon}_{yy} + \sigma_{zz}\dot{\varepsilon}_{zz} + 2\sigma_{xy}\dot{\varepsilon}_{xy} + 2\sigma_{yz}\dot{\varepsilon}_{yz} + 2\sigma_{zx}\dot{\varepsilon}_{zx}\right)$$

For each time step Δt, these equations are solved explicitly for each element in the model, based on input values at the end of the previous time step. Mass and momentum conservation must be enforced. However, in well posed explicit simulations, mass, momentum and energy should be conserved. Energy conservation is constantly monitored for feedback on the quality of the solution in order to obtain a relatively sufficient precision (as opposed to convergent tolerances in implicit transient dynamics).

2. The Analysis of Numerical Results

ANSYS software is a financial structure, fluid, electric field, magnetic field, the sound field analysis in the large general-purpose finite element analysis software. By ANSYS development, the world's largest finite element analysis software company, one that can, with most CAD software, interface, data sharing and exchange, such as Pro / Engineer, NASTRAN, Alogor, I-DEAS, AutoCAD and other modern one of the CAD tools in the product design(Z.-L. Wang et. al, 2008).

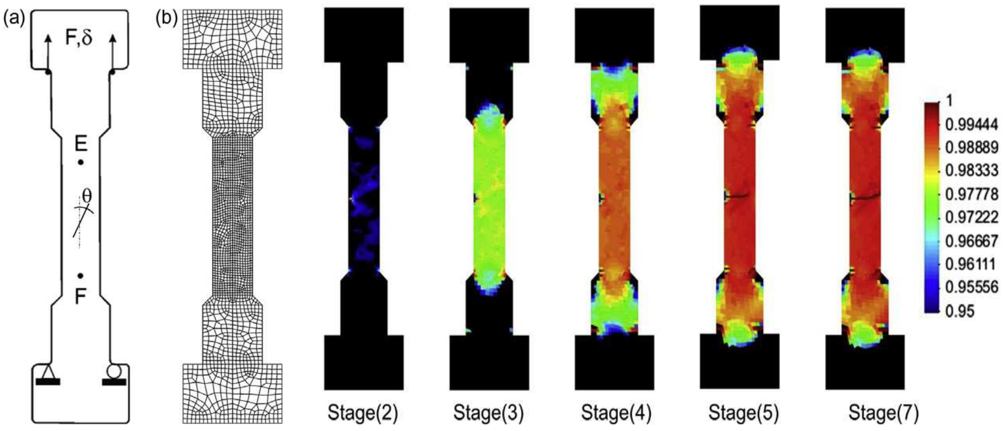


Figure 5. HPFRC dogbone shape specimen subjected to the tensile test and numerical results

3.1 Modeling on tensile of HPFRC dogbone shape

Figure 5 depicts iso-damage color maps and illustrates the evolution of the matrix damage distribution during different stages. The formulation can be considered as a two scale approach, in which the macroscopic structural model is developed by taking into account the mesostructural phenomenon associated with the fiber-matrix interface bond/slip process. This phenomenon in the macroscopic description is illustrated by a microlevel field representing the relative fiber–cement displacement. Then, the governing equations of this problem can be derived and assimilated to a specific case of the material multifield theory. The numerical results of the average stress-strain in specimens are shown in Figure 6.

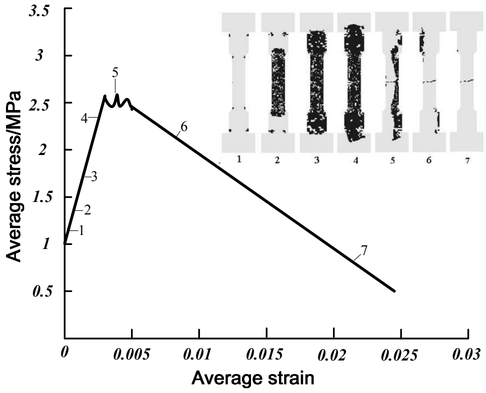


Figure 6. HPFRC dogbone shape specimen tensile test

3.2 Modeling on four-point bending beam test

Figure 7a compares the total load P versus the middle point vertical displacement response. In the Figure, we compare the experimental results, of the reinforced CSS and BSS-wire-reinforced specimens, with the numerical solution obtained for the ultimate bond strength τ_Γ^u =2.5MPa (conforming to a weak bond) and τ_Γ^u =7.5MPa (conforming to a strong bond). It can be observed that for both values of τ_Γ^u, the results closely reproduce the experimental observations for the CSS and BSS specimens.

With the present model and using several ultimate bond strengths, τ_Γ^u(= 2.5; 4.5; 5.5; 7.5Mpa) we have obtained the isodisplacement contour lines displayed in Figure 8(a) (c) (e) and (g). In these pictures, the coalescence of a number of iso-lines represents the formation of cracks. The damage distributions in the concrete are shown in Figure 8(b), (d), (f) and (h) by means of iso-color maps.

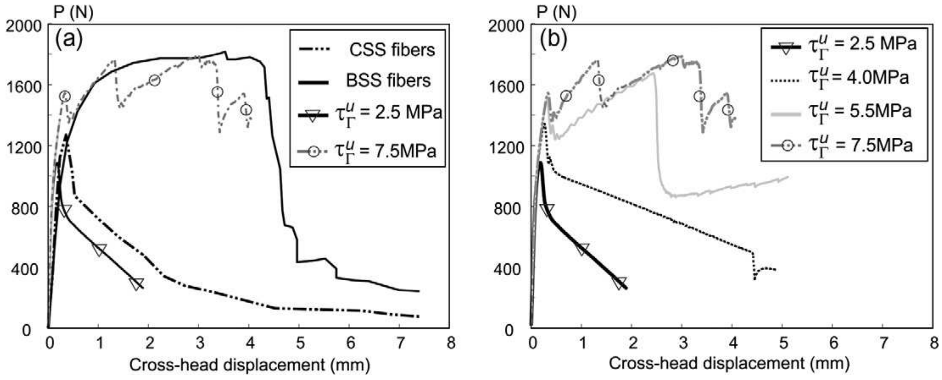


Figure 7. Four-point bending beam test. Load as a function of cross head displacement steel − wire − reinforced cement specimens

Due to the wide application of concrete structures subjected to the larger strain rate range of the load, for example, the creep strain rate is generally lower than 10^{-6}/s; corresponding structure under seismic loading strain rate of approximately 10^{-3}-10^{-2} / s; impact load of about 10^{0}-10^{1} / s under blast loading strain rate reached more than 10^{-2} / s; Several factors(the main material sensitive to the strain rate effect, the inertia effect, and mutual coupled influence between them) affect the mechanical properties of concrete materials subjected to the dynamic impact load, so that it is difficult to complete separation experiments.

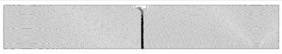
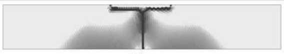
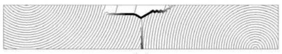
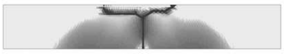
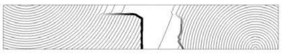
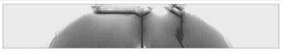
Iso-displacement curves	Damage	τ_{Γ}^{u} $[MPa]$
 (a)	 (b)	2.5
 (c)	 (d)	4.5
 (e)	 (f)	5.5
 (g)	 (h)	7.5

Figure 8. Iso-displacement curves and damage level depicting the crack patterns (CSS- and BSS-wire reinforced beam k_f =1%.)

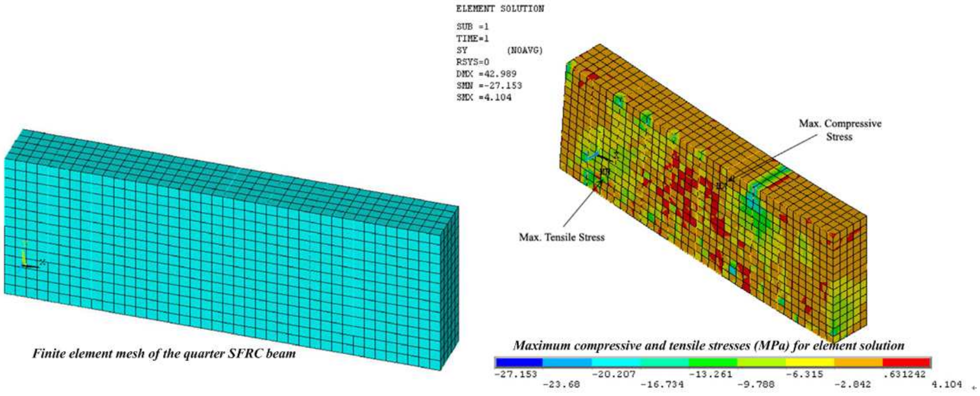


Figure 9. The numerical model based on ANSYS

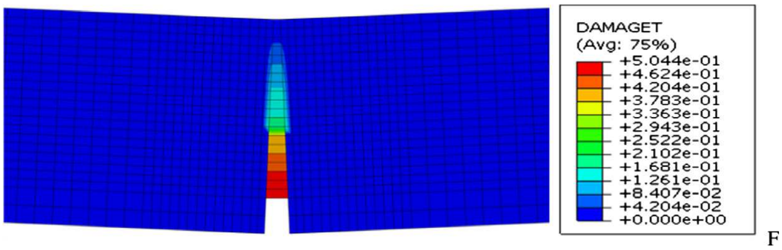
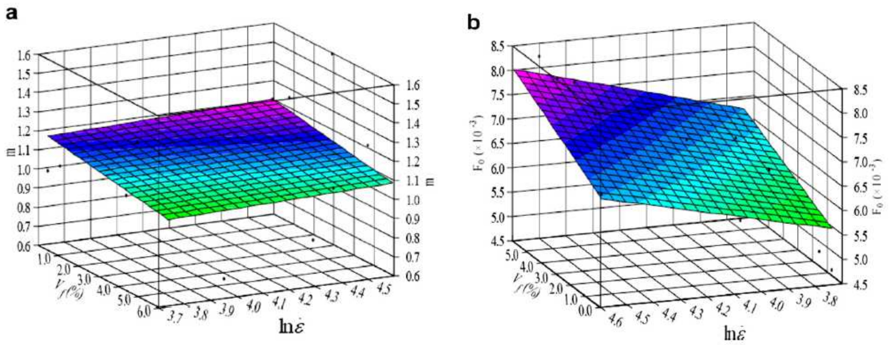


Figure 10. A deformed mesh with damage contours



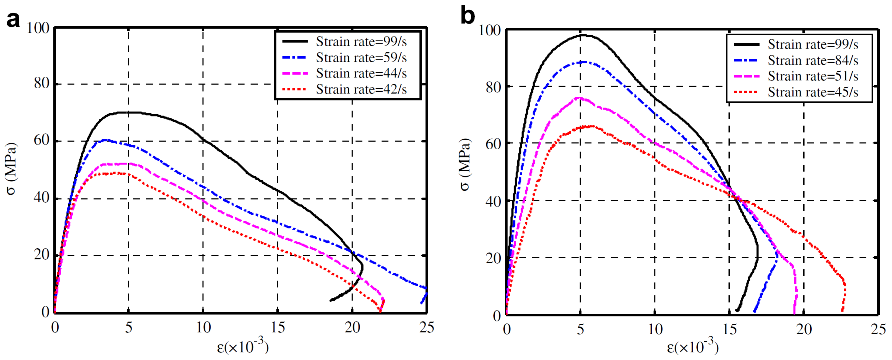


Figure 11. Dynamic stress-strain curves for SFRC under different strain rate
(a) V_f = 0.0%; (b) V_f = 3.0%;

Figure 9 is the numerical model based on ANASYS. The numerical simulation of steel fiber reinforced concrete durability was carried out by means of ANASYS. The simulated crack path for d = 30 mm displaying tensile damage contours is shown in Figure 10 as an example. Only heterogeneous models accounting for the effects of random distribution of fibres are able to simulate the scatter and thus the reliability or failure probability of UHPFRC members against external loads. The waveforms from dynamic compression test were recorded (see Figure 11). It can be noted that the impact velocity of the striker influences the destructive degree of SFRC specimen. Furthermore, in the case that the specimen was crushed under the dynamic impact of the incident bar, much of the impact energy will be absorbed by the crushed specimen.

Figure 11 shows dynamic stress-strain curves for SFRC under different stain rate. The stress–strain relationship of the SFRC specimen can be obtained by analyzing the recorded waves based on one-dimensional elastic bar-wave theory. As seen in Fig. 10, both m and F_0 show an approximately linear dependence on the volume fraction of steelfiber and the natural logarithm of strain-rate. It is noted that the relation for F_0-V_f is proportional while the relation for m-V_f is inversely-proportional. It is recognizedthat the behavior of the SFRC is significantly sensitive to the strain-rate. It is found from Figure 10 that the volume fraction of steel fiber is of great importance to the mechanical behavior of reinforced concrete. Generally, compared with normal strength concrete, the value of $\sigma$with the specimen of V_f=3.0% is improved approximately 1.25 times.

CONCLUSION

The dynamic performance of the steel fiber reinforced concrete, which is influenced by General atmosphere of the environment, corrosion of steel bars and aggressive ingress, etc., is of great significance to structure design and the prediction of service life. The conclusions in this paper can be briefly summarized as follows:

(1). The formulation that model the mechanical behavior of high performance fiber reinforced cement composites with arbitrarily oriented short fibers can be considered as a two scale approach, in which the macroscopic model, at the structural level, takes into account the microstructural phenomenon associated with the fiber-matrix interface bond/slip process.
(2). Based on ANASYS software platform, the numerical study on tensile of HPFRC dogbone shape and four-point bending beam test by damage mechanics method is carried out. It is noted that the relation for F_0-V_f is proportional while the relation for m-V_f is inversely-proportional.
(3). The numerical results of dynamic stress-strain curves suggest that the volume fraction of steel fiber is of great importance to the mechanical behavior of reinforced concrete. Generally, compared with normal strength concrete, the value of $\sigma$with the specimen of V_f=3.0% is improved approximately 1.25 times.

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