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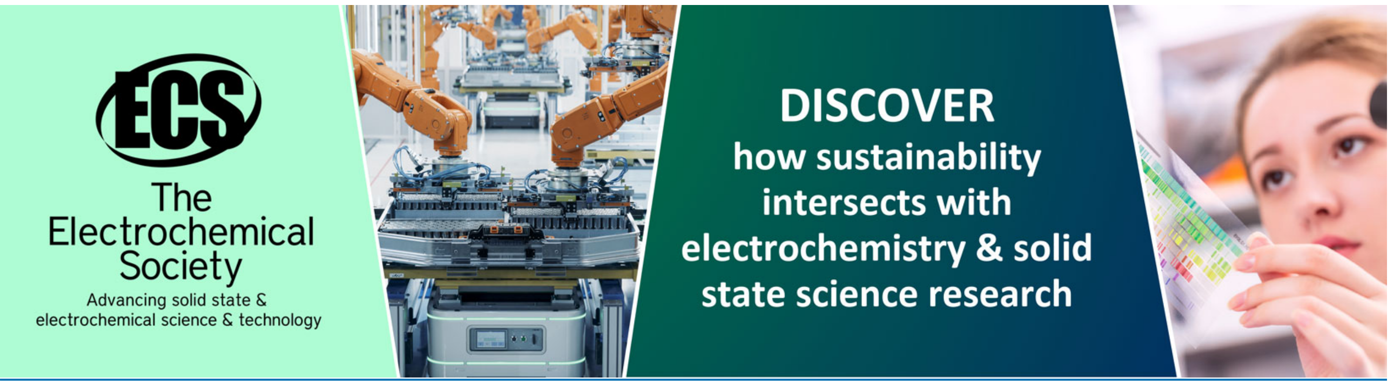

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Uniaxial Tensile Test and Numerical Simulation of Hybrid Fiber Reinforced Concrete

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Abstract: According to the reinforcement principle of hybrid fiber, steel fiber and PVA fiber were used to prepare hybrid fiber reinforced concrete (HyFRC) with compression strength of 120 MPa (SPHFC120). The tensile properties of SPHFC120 were studied by uniaxial tensile test, and the uniaxial tensile constitutive equation was established according to the stress-strain curve. An efficient and applicable three-dimensional mesoscale model to simulate HyFRC was developed. It consists of two components involving concrete matrix and fibers, and the bond between concrete matrix and fibers was considered indirectly by defining the fiber constitutive model. The model was validated with uniaxial tensile test. Then parametric studies were conducted to investigate the effect of fibers content on the tensile performance of HyFRC. The results show that PVA fibers obviously improve the tensile strength, peak tensile strain and tensile toughness of steel fiber reinforced concrete.

1. Introduction

Fiber reinforced concrete (FRC) is one of the effective methods to improve the performance of concrete. The research on FRC has been developed rapidly due to its excellent properties such as high strength, excellent durability and superior toughness. Hybrid fiber reinforced concrete (HyFRC) mixes two or more fibers of different sizes or types to reinforced concrete. Reasonable mix proportion design makes hybrid fibers show a positive hybrid effect, and it can perform better than single FRC, which has attracted more attention [1].

Researchers have prepared a variety of HyFRC, such as hybrid steel fiber[2], Steel-Polypropylene fiber[3], Steel-Polyvinyl alcohol fiber[4], and have conducted a comprehensive study on their compressive and flexural tensile properties, but little research on tensile properties. At present, the problem is that high performance leads to poor economy. In addition, in order to obtain high performance, more stringent curing conditions are adopted. This will lead to the later engineering application is difficult to operate.

In this paper, a group of HyFRC with high comprehensive properties was prepared by using the curing conditions of ordinary concrete on the basis of cost control. Its compressive strength is 120 MPa according to the laboratory standard compression test, recorded as SPHFC120. The axial tensile properties of SPHFC 120 were studied in this paper. The uniaxial tensile constitutive equation was established according to the stress-strain curve, and the three-dimensional numerical simulation was carried out.

2. Uniaxial tensile test and constitutive equation of SPHFC 120

2.1 Experimental phenomena and results

According to Code of GB / T31387-2015 [5], the TYA-2000 electro-hydraulic pressure testing machine was used to conduct the 100 mm cube compression test at the loading rate of 12 ~ 14 KN /s; the dumbbell shaped specimen and fixture were used to conduct uniaxial tensile test at the loading rate of 0.1 mm / min on the 100kN microcomputer controlled electronic universal testing machine (CMT5105). The loading device and failure mode of SPHFC specimen under uniaxial tension are shown in Figure1.

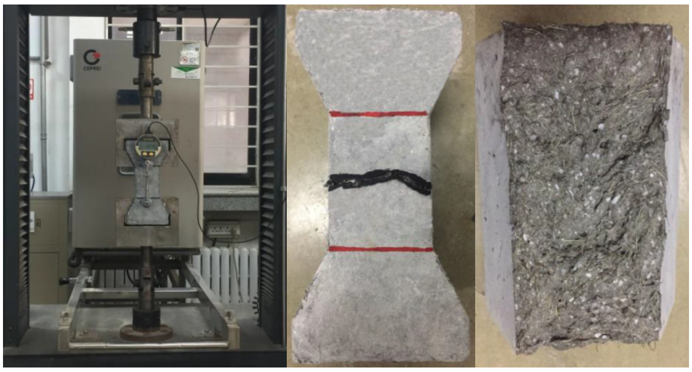


Figure 1. Loading device for the uniaxial tensile test and failure modes of SPHFC under uniaxial tension

The test results of SPHFC cube's compressive and uniaxial tensile properties are shown in Table 1.

Table 1. Test results

No.	Density / （kg/m^3）	Compressive strength /MPa	Tensile strength /MPa	Peak strain
1	2485	148.5	7.76	0.1950
2	2501	150.4	7.75	0.2038
3	2466	144.8	6.97	0.1481

It can be seen from the figure that the through crack of SPHFC specimen under uniaxial tension is curve type, and there are many small cracks near the main crack, and the cross section is uneven. Compared with the flat crack and smooth section of plain concrete specimen during uniaxial tensile, this failure pattern reflects from the side that the addition of steel fiber and PVA fiber significantly improves the tensile toughness of concrete.

The uniaxial tensile stress-strain curves of SPHFC 120 are shown in Figure 2. In the uniaxial tensile stress-strain curves of SPHFC 120, a yield plateau appears near the peak load, and then the load decreases slowly.

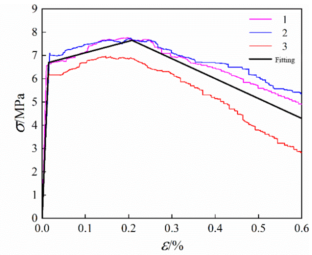


Figure 2. Stress-strain curves of SPHFC 120 under uniaxial tension and fitting curve

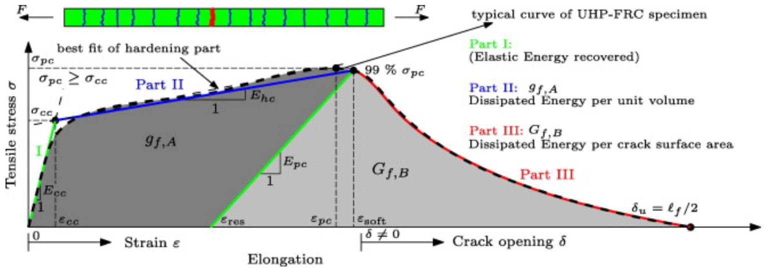


Figure 3. Stress-strain and Idealized Modeling Method of Typical Ultra-high Performance Fiber Reinforced Concrete [6]

2.2 Uniaxial tensile constitutive equations

As the most basic constitutive relation of concrete materials, the tensile constitutive relationship of concrete is of great significance in describing the tensile properties and nonlinear analysis of concrete. It is difficult to describe the tensile properties of SPHFC only by tensile strength. The tensile constitutive equation reflecting the stress-strain relationship should be established for the structural design and analysis of SPHFC.

Refer to Figure 3 Stress-strain and Idealized modeling method of ultra-high performance fiber reinforced concrete[6], the axial tensile full stress-strain curve of SPHFC 120 is divided into three linear parts: (1) elastic stage, i.e. the range from initial tension to initial crack point; (2) hardening stage, that is, the range from initial crack point to softening point; (3) softening stage, that is, the softening point to the failure range of the specimen.

The following is a three segment linear fitting based on the average stress-strain curve of SPHFC120, as shown in Figure 2,get the fitting formula (1).

$$\sigma = \begin{cases} 44634.33016\varepsilon\,, 0 \leq \varepsilon \leq 0.00015 \\ 6.62058 + 497.11025\varepsilon\,, 0.00015 \leq \varepsilon \leq 0.00208 \\ 9.43385 - 854.88023\varepsilon\,, \varepsilon \geq 0.00208 \end{cases} \quad (1)$$

3. Generation and validation of three-dimensional random mesoscale model

3.1 Generation of model

In this simulation, the steel fiber and PVA fiber are regarded as three-dimensional random and uniform distribution in the concrete matrix, the position and angle of steel fiber and PVA fiber are random. The random function Rand in MATLAB is used to generate three groups of random variables (N_0 (x_0, y_0, z_0) in three-dimensional space, the angle between the projection of fibers on XY plane and X-axis, and the angle between the projection of fibers on YZ plane and Z-axis). Through Excel and AutoCAD, the 3D random fiber distribution model made by Matlab is imported into ABAQUS, and an instance of fiber component is established.

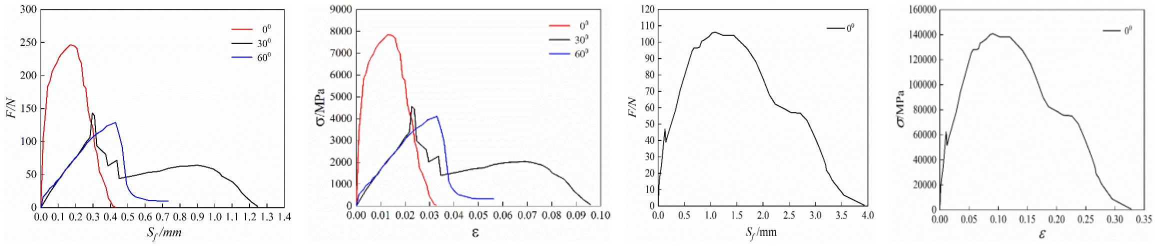
3.2 Validation of model

In the finite element simulation, the fiber load slip relationship obtained from the pull-out test of a single fiber is transformed into the stress-strain relationship of fiber tension, and the bond between fiber and concrete matrix is indirectly considered through the conversion. The corresponding conversion expression (2) [7]:

$$\left.\begin{aligned} \sigma_f &= \frac{4F}{\pi D^2} \\ \varepsilon_f &= \frac{S_f}{L_f} \end{aligned}\right\} \quad (2)$$

Where S_f is the slip distance of the fiber, D is the diameter of the fiber, L_f is the length of the fiber, and F is the drawing load of the fiber.

Many fibers are unlikely to get the load slip curve for each inclination fiber, and the angle of the fiber and the direction of force is greater than 75 degrees when the role is very small. Therefore, the contribution of 0-15 degrees, 15-45 degrees and 45-75 degrees steel fibers is replaced by the included angles of 0 degrees, 30 degrees and 60 degrees between the steel fibers and the tensile direction, without considering the effect of 75-90 degrees [8]. The domestic PVA fiber has poor dispersibility, and only considers the contribution of the fiber at an angle of 0 degrees between the fiber and the force direction. The constitutive relationship between steel fiber and PVA fiber is shown in Figure 4.



(a) (b) (c) (d)

Figure 4. Constitutive relation of steel fiber and PVA fiber[9,10]:(a)Load slip curves of steel fiber;(b) Stress-strain curves of steel fiber;(c) Load slip curve of PVA fiber; (d) Stress-strain curve of PVA fiber

The damage plastic model of concrete corresponding to the compressive strength grade of plain concrete (C80) corresponding to SPHFC is adopted in this paper. The matrix of SPHFC is modelled by means of linear (8 nodes) 3D solid elements and regarded as a homogeneous entity. To simplify modeling calculations, fibers are viewed as straight round and linear truss units are used.

The experimental and simulation tensile stress-strain curves are shown in Figure 5. The SPHFC120 uniaxial tensile stress-strain curve obtained by Abaqus simulation loading is in good agreement with the test. With this model, the uniaxial tensile properties of SPHFC can be well simulated. However, it can also be seen that the simulation results still have shortcomings compared with the experimental values. The main manifestations are that compared with the experiments, the simulation value of the rising section reaches a higher stress value and the simulated value of the falling section decreases more gently. The main reason for this difference is that the steel fibers and PVA fibers in the simulated specimens are evenly distributed, the effective fiber grid has a very high degree of overlap, and there is no initial defect inside the specimen caused by fiber clumping.

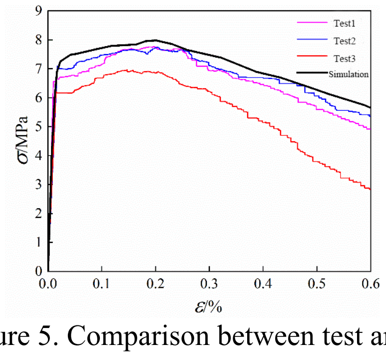


Figure 5. Comparison between test and Simulation of stress-strain curves of SPHFC120 under uniaxial tension

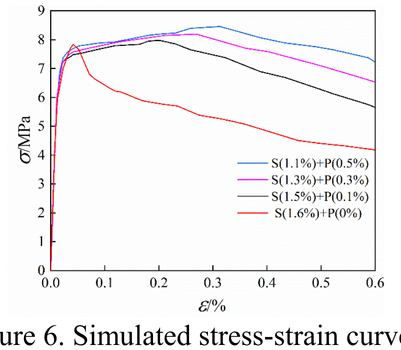


Figure 6. Simulated stress-strain curves of different fiber combinations under uniaxial tension

4. Numerical analysis

In order to better understand the influence of different fiber content combination on the tensile properties of SPHFC, the proportion of steel fiber and PVA fiber was changed in this paper when the total fiber content was 1.6%. The specific parameters and results are shown in Table 2, and the stress-strain curves of four groups of specimens are shown in Figure 6.

It can be seen from table 3 that when the total content of two kinds of fibers is 1.6%, the peak tensile stress and tensile strain of concrete increase with the increase of PVA fiber content, and reach the maximum value when 1.1% steel fiber is combined with 0.5% PVA fiber, which is increased by 7.9% and 647.8% respectively compared with pure steel fiber concrete. From Figure6, it can be seen that when the total content of two kinds of fibers is 1.6%, the initial crack stress of concrete increases with the increase of PVA fiber, and the decline section of stress-strain curves are also slower than that of pure steel fiber. After mixing steel fiber and PVA fiber, the tensile strength, peak tensile strain and tensile toughness of concrete are higher than those of pure steel fiber concrete, which indicates that the tensile properties of SPHFC are better than that of pure steel fiber concrete under the same volume content.

Table 2. Simulation results of combined uniaxial tension with different fiber contents

Steel fiber content /%	1.1	1.3	1.5	1.6
PVA fiber content /%	0.5	0.3	0.1	0
Peak stress /MPa	8.46	8.19	7.98	7.84
Peak strain /%	0.3126	0.2694	0.2011	0.0418

5. Conclusion

(1) The tensile stress-strain curve of SPHFC120 has a yield plateau before reaching the peak load. The whole process can be divided into three stages: elastic stage, strain hardening stage and crack growth softening stage.

(2) According to the stress-strain and idealized modeling method of ultra-high performance fiber reinforced concrete, the full stress-strain curve of SPHFC120 under uniaxial tension is divided into three linear parts, and the uniaxial tensile constitutive equation of SPHFC120 is obtained by three segment fitting, which reflects the development trend of tensile stress-strain curve of SPHFC120.

(3) From the perspective of micromechanics, a three-dimensional fiber random distribution model is obtained by using MATLAB, and the bond slip between fiber and matrix is considered in an equivalent substitution way for numerical simulation verification and parameter analysis. The simulation results are consistent with the experimental phenomena. After steel fiber and PVA fiber are mixed, the tensile strength, peak tensile strain and tensile toughness of concrete are higher than that of pure steel Fiber concrete.

Acknowledgments

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References

[1] Ahmed S F U, Maalej M . Tensile strain hardening behaviour of hybrid steel-polyethylene fibre reinforced cementitious composites[J]. Construction & Building Materials, 2009, 23(1):96-106.
[2] Yu Jing, Lei Shiman, Liang Xingwen, Liu Xiaojun, Li Lin. Mix design method of a new type of hybrid steel fiber reinforced self compacting concrete [J]. Journal of Building Materials, 2017,20 (04): 611-615 + 629
[3] Xu Lihua, Mei Guodong, Huang Le, Lu WeiMiao. Research on axial tensile stress-strain relationship of steel polypropylene hybrid fiber concrete [J]. China Civil Engineering Journal, 2014,47 (07): 35-45
[4] Yu Jing, Zhai Tiantian, Liang Xingwen, sun Xiaoji. Study on fluidity and mechanical properties of steel PVA fiber reinforced concrete [J]. Journal of Building Materials, 2018,21 (03): 402-407

[5] GB/T 31387-2015, Reactive powder concrete [S].
[6] Wille K , El-Tawil S , Naaman A E . Properties of Strain Hardening Ultra High Performance Fiber Reinforced Concrete (UHP-FRC) under Direct Tensile Loading[J]. Cement and Concrete Composites, 2014, 48(2):53-66.
[7] Qing Longbang, Su Yimeng, Yu Kelai, Mu Ru, Wang Miao. Meso numerical modeling method of SFRC and analysis of influence of fiber orientation on fracture properties [J]. Journal of Materials Science and Engineering, 2019,37 (03): 480-486
[8] Vítor M.C.F. Cunha.Steel Fibre Reinforced Self-Compacting Concrete (from Micro-Mechanics to Composite Behaviour)[D].Portugal:University of Minho ,2010.
[9] Yu J , Meng L , Leung C K Y . Pull-out Response of Single Steel Fiber Embedded in PVA Fiber Reinforced Cementitious Matrix[C]. International Conference on Fracture Mechanics of Concrete & Concrete Structures. 2016.
[10] Carl Redon,Victor C. Li,Cynthia Wu,Hideki Hoshiro,Tadashi Saito,Atsuhisa Ogawa. Measuring and Modifying Interface Properties of PVA Fibers in ECC Matrix[J]. Journal of Materials in Civil Engineering,2001,13(6).