DIRECT TENSILE CONSTITUTIVE LAW OF ULTRA-HIGH PERFORMANCE CONCRETE WITHOUT THERMAL CURING

Li-Ping Geng(1), Jun-Yuan Guo(2), Guo-Ping Liu(3), Jun-Yan Wang(1)

(1) Key Laboratory of Advanced Civil Engineering Materials, Tongji University, Ministry of Education, Shanghai 201804, China.

(2) College of civil engineering, Tongji University, Shanghai 201804, China.

(3) Shanghai Royang Innovative Material Technologies Co., Ltd

ABSTRACT

In this study, three types of direct tensile constitutive law of ultra-high performance concrete (UHPC) were investigated according to French Association Civil Engineering（AFGC）Recommendations. They were high strain-hardening UHPC, low strain-hardening UHPC, and strain-softening UHPC, respectively. The axial tensile stress-strain curves of UHPC were measured by experiment. The constitutive law of low strain-hardening and strain-softening UHPC obey stress-cracking width (σ-f(w)) while high strain-hardening UHPC follows stress-strain (σ-f(ε)) due to the large number of very fine and very dense cracks, once the matrix strength reached. Three types of simplified constitutive law under ultimate limit states and serviceability limit states were established for application in construction.

Keywords: High strain-hardening UHPC; Low strain-hardening UHPC; Strain-softening UHPC; Serviceability limit states; Ultimate limit states

1. INTRODUCTION

Ultra-high performance concrete (UHPC) is a cementitious composite material, generally consisting of cement, quartz sand, silica fume and fibers [1]. Between the years of 1990 and 1995, UHPC was first investigated by Bouygues in the name of Reactive Powder Concrete (RPC) [2]. Next, in 1997 the first world's engineering structure made by RPC namely the Sherbrooke pedestrian bridge was built by Ductal ® in Sherbrooke, Quebec, Canada [3]. The additional of fiber is able to increase the UHPC strengths and durability [4].

This paper mainly describes three types of axial tensile constitutive law of UHPC to provide information for ultra-high performance concrete structure design. According to the AFGC Recommendation, UHPC axial tensile constitutive law can be divided into three types, namely high strain-hardening fiber reinforced concrete, low strain-hardening fiber reinforced concrete and strain-softening fiber reinforced concrete [5]. Stress hardening can occur when the post-cracking resistance is higher than that of the matrix [5]. Or else softening can occur when the post-cracking resistance remains lower than the resistance of the matrix [5]. Low strain-hardening and strain-softening fiber reinforced concrete obey stress-cracking width ((w)) law, but high strain-hardening fiber reinforced concrete may not, because of the large number of very fine and very dense cracks). Once the elastic strength is reached, fine, very dense micro-cracks develop, which can be treated as strain.

2. EXPERIMENTAL PROGRAM

2.1 Materials and specimens

The UHPC materials used in this study were commercial products named TENACAL® provided by Shanghai Royang Innovative Material Technologies Co., Ltd. There were three types of UHPC, named high strain-hardening UHPC, low strain-hardening UHPC and strain-softening UHPC respectively. For each mixture, nine specimens with dimension shown in Fig.1 were cast for direct tensile test. The specimens were demolded at 24 hours and then cured in the water at a temperature of 20 oC for 28 days.

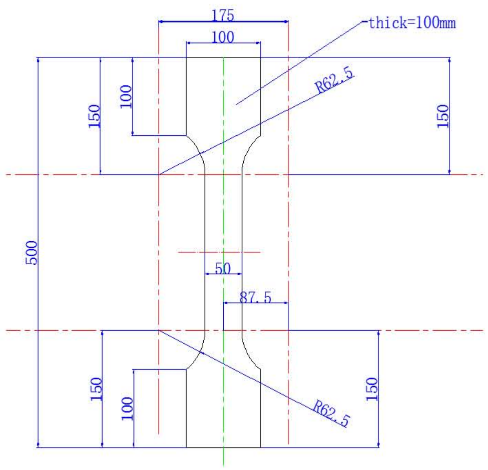

Fig.1.Specimen dimension

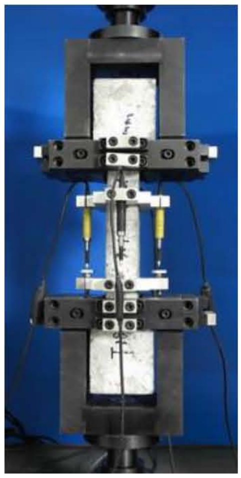

Fig.2. Test apparatus

2.2 Test apparatus and methods

Direct tensile test was conducted on a 30 t electric servo universal testing machine. Tensile sample period of each upper and lower surface had a rectangular metal frame, which was used to fix the four linear variable displacement meter (an LVDT) in order to measure the axial tensile deformation. Four LVDTs deformation signal acquisition were automatically transferred to the universal testing machine control system. Figure 2 shows the experimental equipment. Visual cracking width was observed by the crack width measuring instrument. The test of loading speed was 0.06 mm/min and the gauge length was 150 mm. The whole experiment was controlled in about 1h until the specimen was failure.

3. TEST RESULTS AND ANALYSIS

3.1 Tensile behaviors of high strain-hardening UHPC

The stress - strain curve of high strain-hardening UHPC is shown in Fig. 3[6]. The curve can be divided into three parts: ① linear elastic rising period with tensile stress (σ) linearly increase;② Strain hardening period with multi-point cracking development;③strain softening period with local critical cracks extend quickly.

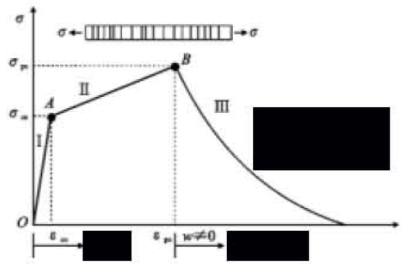

Fig.3. The constitutive law of high strain-hardening UHPC [6]

Fig.4 shows 9 axial tensile stress-strain curves of high strain-hardening UHPC. The characteristic parameters of high strain-hardening UHPC are illustrated in Table 1. Linear elastic curve and strain hardening curve were fitted to a straight line. The intersection of the horizontal axis was the linear elastic strain limit , while the corresponding linear elastic limit stress was determined. The peak stress was approximated to limit stress and the corresponding was limit strain.

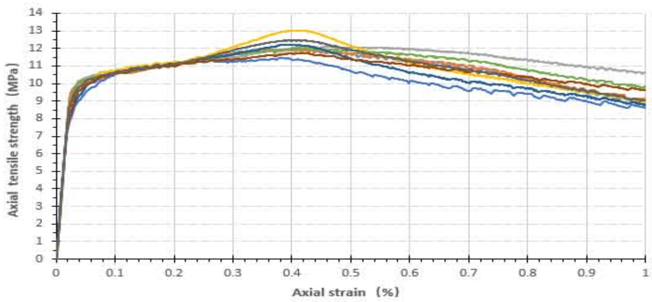

Fig.4. Strain - stress curves of high strain-hardening UHPC

Fig. 5 illustrates the average stress-strain curve and standard deviations of nine tensile specimens of high strain-hardening UHPC. Combining the results in Fig.4 with Table 1, the scatter of linear elastic and strain hardening segment of high strain-hardening UHPC was marginal. Linear elastic segment of nine samples coincide substantially. The post-cracking peak remained higher than. It was not difficult to observe that the first crack of UHPC appears when the strain is about 250 με. The stress reached the peak 12.11 MPa when strain was approximately 4000 με. At this time, the steel fibers were gradually pulled out. As shown in Table 1, average linear elastic stress and strain of nine tensile specimens were 8.78MPa and 0.025%, respectively. While the standard deviations were only 0.482 MPa and 0.0011%, respectively. It indicated the scatter of high strain hardening UHPC linear elastic segment was marginal. For high strain-hardening UHPC, the strain-stress curve approximated straight line in early loading experiment, with the increase of stress, the slope of stress-strain curve became deviated. A large number of very fine and very dense cracks began to produce with Zi Zi Zi tearing sound. Stress deviation from linear elastic limit stress continued to rise when the matrix first crack. Steel fibers were gradually pulled out, with multiple micro cracks. When the stress reached the peak, the main crack began to expand. After the test, damaged specimens remained good integrity.

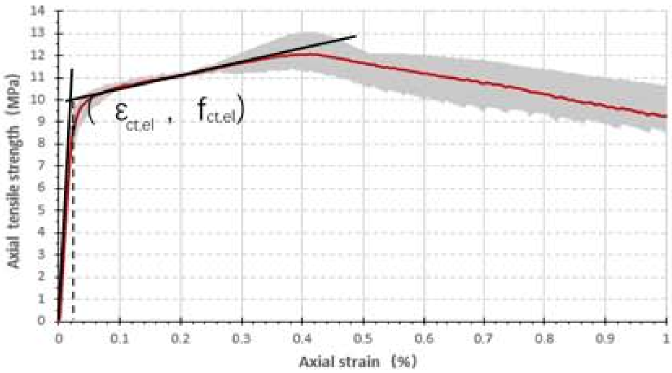

Fig.5. Average axial tensile stress - strain curve of high strain-hardening UHPC and the standard deviation chart

Table 1 Characteristic parameters of axial tensile curve for high strain-hardening UHPC

Specimen number	(%)	(MPa)	(%)	(MPa)
1	0.023	9.30	0.370	11.95
2	0.023	9.16	0.378	11.95
3	0.025	9.47	0.418	12.14
4	0.025	8.41	0.404	13.01
5	0.026	8.13	0.384	11.46
6	0.025	8.98	0.426	12.03
7	0.025	8.23	0.388	12.21
8	0.027	8.52	0.426	11.74
9	0.024	8.85	0.394	12.46
Average	0.025	8.78	0.399	12.11
Deviation	0.0011	0.482	0.021	0.442
Standard	0.023	8.00	0.36	11.38

3.2 Tensile behaviors of low strain- hardening UHPC

Fig.6 is the direct tensile mean stress-strain curve of low strain-hardening UHPC. Like strain-stress curve of high strain-hardening UHPC, the scatter of linear elastic period of low strain-hardening UHPC stress-strain curve was marginal. The linear elastic limit stress is about 8.5MPa,is about 0.02%. The limit stress and strain is about 9.5MPa,0.04%, respectively. Stress had a slight rise when stress was higher than the linear elastic limit stress, but dropped rapidly. Because the cracking width was very small, the width by crack width measuring instrument was not easy to measure. According to AFGC recommendation, the allowable crack width of low strain hardening UHPC is 0.3 mm when it reaches limit stress [5]. Fig.6 indicates the strain was about 0.48% and the residual tensile strength was about 7.8 MPa when the crack width was

0.3mm. The crack width was less than 0.1 mm when comes to , obviously, the crack width was in a safe range.

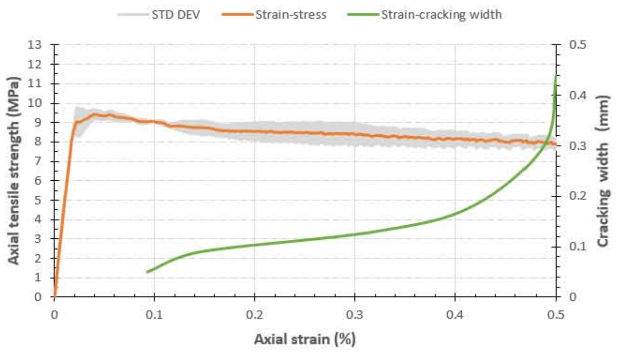

Fig.6. Average axial tensile stress-strain curve of low strain-hardening UHPC and strain - cracking width curve

The average constitutive law of this kind of UHPC is strain-hardening. However, in terms of characteristic law, and taking the fiber alignment and dispersion into account, its constitutive law is strain-softening. This type of constitutive law corresponds to most of the UHPC currently on the market [5]. For stress-strain curve of low strain hardening UHPC, once the stress reached the linear elastic limit, first crack occurred in matrix. As the test continued, the crack was expanded, stress was slow down. Most of the steel fibers were pulled out until the crack width increased to a certain degree. Specimens lost tensile bearing capacity, unlike the strain hardening specimens which had multiple micro-cracks. Only one crack could be observed, and the position was uncertain. Some were in the specimen gage length, and some appeared out of the specimen gage length. Once the linear elastic stress limit was reached, the crack formed quickly and there was only a single crack. As the trial continued, the crack continued to expand. Therefore, stress-strain or stress-cracking width constitutive law could be used.

3.3 Tensile behaviors of strain-softening UHPC

Fig.7 is stress-strain curve and strain-cracking width curve of strain-softening UHPC. The and were 7.2MPa and , respectively. Cracking width was within the scope of the security. But the limit stress and strain were same to.When the crack width extended to 0.3 mm, the strain and residual tensile stress were about 0.09% and 6.8 MPa, respectively, which were lower than those of the low strain-hardening UHPC. For strain-softening UHPC, once the tensile strength of matrix was reached, crack expanded quickly.

4. CONSTITUTIVE LAW

4.1 Strain-softening or low strain hardening constitutive law

Apparent ductility in tension is obtained by exerting tensile stress on the fibers followed by gradual slipping of their anchorage in the cement matrix [5]. The following parts present simplified tensile laws [5]. These constitutive laws can be replaced with more realistic laws resulting from tests [5]. Fig.8 and Fig.9 are simplified stress-strain constitutive law of low strain-hardening UHPC or strain-softening UHPC in serviceability limit state and in ultimate limit state. Table 2 and Table 3 show the characteristic parameters of low strain-hardening

UHPC,strain softening UHPC,respectively. AFGC Recommendation advises that , in serviceability limit state.

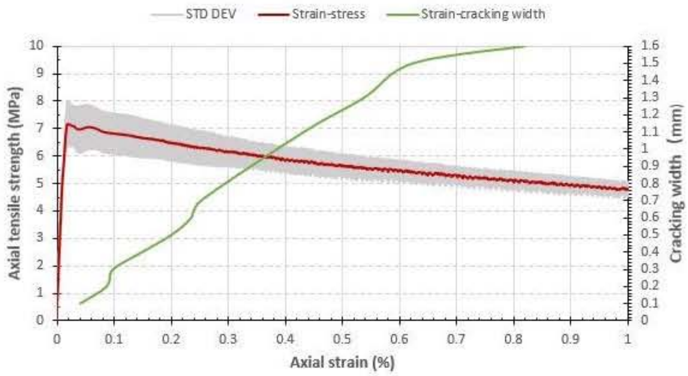

Fig.7. Average axial tensile stress-strain curve of strain-softening UHPC and strain - cracking width curve

Table 2 The characteristic parameters of low strain-hardening UHPC

Low strain-hardening UHPC	SLS law				K			
		8.57	0.0186	9.43	1.25	7.54	0.659	
	ULS law							
		8.57	1.05	9.43	8.16	0.0175	7.18	0.852

: Characteristic limit of elasticity under tension
: Characteristic maximal post-cracking stress
: Elastic tensile strain at SLS
: Elastic tensile strain at ULS
: SLS e quivalent strain corresponding to the local peak in post-cracking phase or to acrack width equal to 0.3 mm if there is no peak
: ULS e quivalent strain corresponding to the local peak in post-cracking phase or to acrack width equal to 0.3 mm if there is no peak
K: Fibre orientation factor
: Partial safety factor

Table 3 The characteristic parameters of strain-softening UHPC

Strain softening UHPC	SLS law				K			
		7.16	0.02	7.16	1.25	5.73	0.455	
	ULS law							
		7.16	1.05	7.16	6.82	0.0155	5.46	0.581

In the case of strain-softening or low strain-hardening behavior, the curve is obtained by partially truncating the real curve. If a maximum local value is observed, the plateau is formed by clipping the curve corresponding to the law to correspond to the maximum local value as indicated in Fig.10. The stress was 7.8 MPa for low strain-hardening UHPC, while 6.8 MPa for strain softening UHPC.

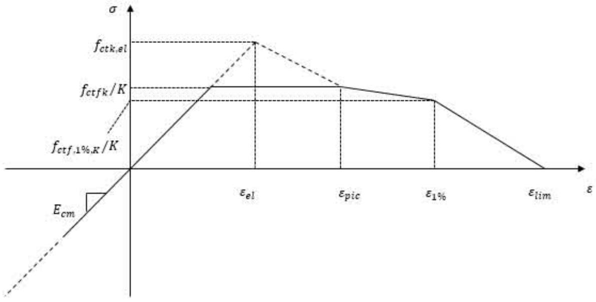

Fig.8. Simplified stress-strain constitutive law of low strain-hardening UHPC or strain-softening UHPC in serviceability limit state [5]

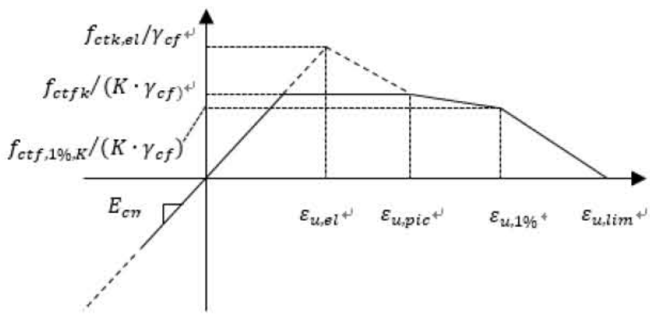

Fig.9. Simplified stress-strain constitutive law of low strain-hardening UHPC or strain-softening UHPC in ultimate limit state [5]

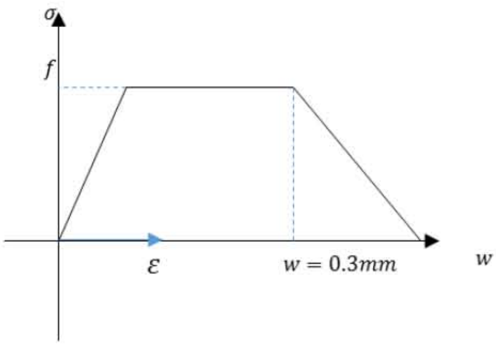

Fig.10. Simplified strain-softening or low strain-hardening constitutive law

4.2 Strain-hardening constitutive law

Fig.11 and Fig.12 are simplified stress-strain constitutive law of high strain-hardening UHPC in serviceability limit state and in ultimate limit state. Table 4 is the Characteristic parameters of high strain-hardening UHPC. , in serviceability limit state.While AFGC recommendation suggests that ,.So the constitutive law of high strain-hardening UHPC in room temperature curing meets the AFGC recommendation.The situation applied to ultimate limit state.

Table 4 The characteristic parameters of high strain-hardening UHPC

High strain-hardening UHPC	SLS				K			
	law	8.78	0.025	12.11	1	12.11	0.399	
	ULS						(MPa)	
	law	8.78	1.05	12.11	8.36	0.022	11.53	0.28

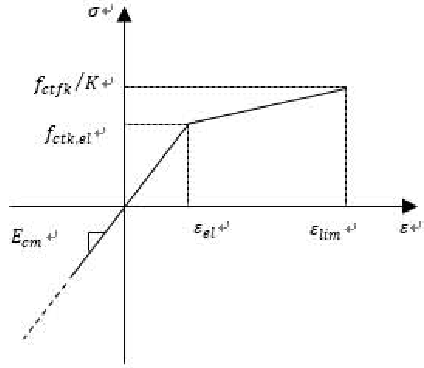

Fig.11. Simplified high strain-hardening constitutive law in serviceability limit state [5]

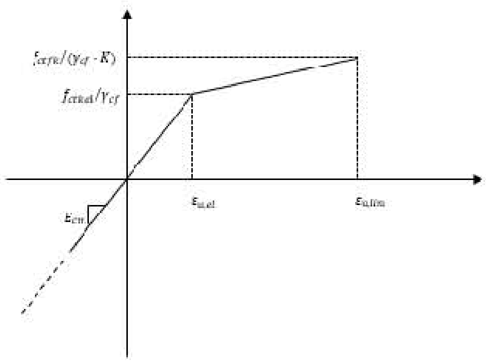

Fig.12. Simplified high strain-hardening constitutive law in ultimate limit state [5]

5. CONCLUSION

- (1) The scatter of room temperature curing UHPC at elastic stage in direct tensile test is marginal. After axial tensile UHPC specimen cracking, the steel fiber anchoring in cement based material began to bear stress. Low strain-hardening and strain-softening UHPC had only a single crack, and the high strain-hardening UHPC had multiple cracks. With the increase of crack width, steel fibers were gradually pulled out, bearing capacity of the specimens also gradually decreased.
- (2) Low strain-hardening and strain-softening UHPC constitutive law can be characterized by stress-strain () or stress-cracking width (). For low strain-hardening UHPC, the and were about 8.57 MPa and , respectively. When the crack width extended to 0.3mm, the strain and residual tensile stress were about 0.48% and 7.8 MPa, respectively. While for strain softening UHPC, the and were about 7.16 MPa

and ,respectively. When the crack width extended to 0.3mm, the strain and residual tensile stress of strain softening were about 0.09%，6.8MPa.

- (3) For high strain-hardening UHPC, ，, andwere 8.78 MPa,12.11 MPa,0.025%, and 0.399%, respectively.
- (4) Simplified stress-strain () or stress-cracking width () constitutive law in serviceability limit state and ultimate limit state provide significantly information for the design and application of UHPC.

REFERENCE

[1] Makita T, Brühwiler E. Tensile fatigue behaviour of Ultra-High Performance Fibre Reinforced Concrete combined with steel rebars (R-UHPFRC) [J]. Electronics Letters, 1990, 26(21):1746-1748.
[2] Richard, P., Cheyrezy, M., Composition of Reactive Powder Concretes, Cement and Concrete Research, Vol. 25, No. 7, 1995, pp. 1501-1511.
[3] Blais P.Y., Couture, M., Precast, Prestressed Pedestrian Bridge: World's First Reactive Powder Concrete Structure, PCI Journal, 1999.
[4] Kusumawardaningsih Y, Fehling E, Ismail M, et al. Tensile Strength Behavior of UHPC and UHPFRC[J]. Procedia Engineering, 2015, 125:1081-1086.
[5] Toutlemonde F, Resplendino J. 47. Ultra High Performance Concrete: New AFGC Recommendations[M]// Designing and Building with UHPFRC. John Wiley & Sons, Inc. 2013:713-722.
[6] Wille K, Dong J K, Naaman A E. Strain-hardening UHP-FRC with low fiber contents[J]. Materials & Structures, 2011, 44(3):583-598.