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Effects of steel fiber content and shape on mechanical properties of ultra high performance concrete

Zemei Wu [a,b], Caijun Shi [a,c,*], Wen He [a], Linmei Wu [a]

[a] College of Civil Engineering, Hunan University, Changsha 410082, China
[b] Department of Civil, Architectural and Environmental Engineering, Missouri University of Science and Technology, Rolla, MO, USA
[c] State Key Laboratory for Green Building Materials, China Building Materials Academy, Beijing 100024, China

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ABSTRACT

This study investigated the effects of three shaped steel fibers (straight, corrugated, and hooked-end) with different fiber contents by volume (V_f = 0, 1%, 2%, and 3%) on mechanical properties of ultra high performance concrete (UHPC). The involved properties included flowability, compressive strength, and flexural behavior. According to the characteristics of the obtained three-point flexural load–deflection curve and the existing constitutive model of uniaxial compression, a new model for flexural load–deflection based on least square fitting was proposed. The results indicated that increased fiber content and use of deformed fibers could gradually decrease the flowability of UHPC. They also had significant effects on compressive and flexural behavior of UHPC. With incorporation of 3% straight steel fibers, its compressive and flexural strengths reached over 150 and 35 MPa at 28 d. For the concrete with 3% hooked-end and corrugated fibers, the compressive strengths at 28 d increased by 48% and 59% compared to those with the same amount of straight fiber. Steel fiber content had limited effect on the first crack strength and first crack deflection of flexural load–deflection curve of UHPC, but showed considerable effects on the peak load. The proposed model fitted well with the experimental results with correlation coefficient over 0.9.

1. Introduction

Ultra high performance concrete (UHPC) is a material made of high content of cementitious materials, fine aggregate, superplasticizer, and fiber with low water-to-cementitious materials ratio (W/CM). It has high strength (compressive strength over 150 MPa), high toughness, and high durability [1,2]. The use of fiber can provide UHPC with strain-hardening behavior in tension, and transform the brittle failure to ductile failure as well [3]. Many studies have been conducted on composition optimization, performance enhancement, costs, and energy reduction [4]. Until now, three international symposiums on UHPC have been held at Kassel University in Germany [5,6].

The flexural properties of UHPC are affected by many factors, such as fiber content, fiber and sample size, fiber blending, fiber distribution, and placing methods, etc., [7–9]. Kang et al. [10] evaluated the effects of fiber distribution on the flexural strength of steel fiber-reinforced ultra high strength concrete under two different placing directions, and found that the initial cracking and ultimate flexural strengths of UHPC placed parallel to the longitudinal direction of mold were 5.5% and 61% larger than those placed transversely. Barnett [7] studied the effects of casting methods on flexural strength by pouring three round panels in three different ways. It was found that panels poured from the center had the highest strength. Fiber blending is a promising method to improve the flexural performance of UHPFRC, which makes macro and micro fibers to play a role at two different levels. Kim et al. [11] suggested that the enhancements in modulus of rupture, deflection capacity, and energy absorption capacity of UHPC reinforced with different macro fibers were different according to the types of macro fiber as the blended amount of micro fiber increased. Dawood and Ramli [12] investigated the mechanical properties of high strength flowing concrete with 2% hybrid fiber of steel fibers, palm fibers, and synthetic fibers. It was found that with the increase of hybrid fibers content, both the first crack and the post-crack strengths increased. Although a lot of researches studied the optimal steel fiber content for mechanical properties, limited information is available about the effects of fiber shape on reinforcing and toughening characteristics of UHPC.

* Corresponding author at: College of Civil Engineering, Hunan University, Changsha 410082, China.
E-mail address: cshi@hnu.edu.cn (C. Shi).

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The objective of this research is to investigate the effects of three shaped fibers (straight, corrugated, and hooked-end fibers) with different fiber contents (0, 1%, 2%, and 3%) on workability, compressive strength, and flexural behavior of UHPC. The flexural behavior included first crack strength and deflection, peak strength (ultimate flexural strength) and deflection, and toughness indexes. Based on the characteristics of load–deflection curve and established models, a flexural load–deflection model was proposed. This paper should have important significance in better understanding the reinforcing and toughening characteristics of UHPC.

2. Experimental program

2.1. Raw materials

A P.I 42.5 Portland cement complying with the Chinese Standards GB175-2007 was used [13]. Table 1 summarizes its chemical composition and density. Silica fume with average particle size of 0.1–0.2 μm and specific surface area of 18,500 m^2/kg was used. Its chemical composition is also shown in Table 1. Three steel fibers, including straight, corrugated, and hooked-end fibers with tensile strength of approximately 2800 MPa were used. They have a diameter of 0.2 mm and length of 13 mm. River sand with maximum particle size of 2.36 mm were used. A polycarboxylate-based superplasticizer (SP) from BASF with water-reducing efficiency greater than 30% was used. Its solid content is 20%.

2.2. Mixture proportions

Based on the previous study [14], mixture proportion of UHPC with a water-to-cementitious materials (W/CM) ratio of 0.18 was used, as shown in Table 2. The SP dosage was fixed at 2% by the mass of the cementitious materials. Steel fiber contents of 0, 1%, 2%, and 3% by the volume of concrete were used. UHPC mixtures with straight, corrugated, and hooked-end fibers were designated as A, B, and C, respectively, as shown in Table 2.

2.3. Mix procedure and sample preparation

For the mix procedure, dry powders, including cement, silica fume, slag, and natural quartz sand, were first mixed for 3 min at a high speed. Then water and superplasticizer were added and mixed for approximately 6 min at a low speed. Afterward, steel fibers were added through passing a sieve with size of 5 mm and mixed for another 6 min until the mixtures were uniformly distributed. When UHPC mixtures were ready, they were casted into $40 \times 40 \times 160$ mm^3 molds by two layers, and vibrated for 60 times at each layer to consolidate the mixtures. The specimens with molds were kept in a room at 20 °C for 24 h. They were covered by plastic sheets to prevent moisture losing until demolding. After that, specimens were cured in saturated lime water at 20 °C until designed age of 3, 7, 28, and 90 d.

2.4. Experimental methods

2.4.1. Flowability

The flowability of all UHPC mixtures was measured in accordance with the Chinese standards GB/T 2419-2005 [15]. The mixtures were cast into a mini cone mold placed on an automatic jolting table. The mold was lifted vertically and jolted for 25 times. Then two diameters perpendicular to each other were determined and mean value was reported.

2.4.2. Flexural behavior testing

Three-point flexural testing through displacement control was conducted to examine the effects of steel fiber content and shape on flexural behavior and toughness indexes of UHPC. The span was 100 mm. The deflection at the center of the specimens was measured using a LVDT installed at the center of the specimens. An MTS testing machine with 20,000 KN load cell was used. Its loading rate was set at 0.2 mm/min. Averages of three samples for each batch were reported as tested results.

2.4.3. Compressive strength testing

Six broken samples after flexural testing were used for determination of compressive strength. The loading rate was 2.4 KN/s. Averages of six samples for each batch were reported as tested results.

3. Results and discussion

3.1. Effects of steel fiber content and shape on flowability of UHSC

Fig. 1 shows the effects of steel fiber content and shape on flowability of fresh UHPC mixtures. The flowability of the control batch (A0) was 215 mm. With incorporation of 1%, 2%, and 3% straight steel fibers, the flowability gradually decreased by 14.9%, 25.6%, and 38.1%, respectively. This might be due to increased specific surface area associated with the increase of fiber content [16]. Moreover, the steel fibers were randomly distributed in the matrix and acted as skeleton, and eventually prevented the flow of fresh concrete [17].

The flowability was also affected by the fiber shape. The UHPC samples with hooked-end fibers had the lowest flowability compared to those with straight and corrugated fibers. The flowability of mixtures with 1%, 2%, and 3% hooked-end steel fibers were reduced by 20.9%, 35.8%, and 51.2% compared to those with the same amount of straight fibers. For the mixtures with 1%, 2%, and 3% corrugated fibers, it reduced by 17.7%, 31.2%, and 45.1%, respectively. This was mainly because deformed fibers could increase the friction between fibers and aggregates so as to increase the coher-

Table 1
Chemical composition and density of cementitious materials.

Chemical composition	CaO (%)	SiO_2 (%)	Al_2O_3 (%)	Fe_2O_3 (%)	SO_3 (%)	MgO (%)	Na_2O_{eq} (%)	K_2O (%)	C (%)	Density (g/cm^3)
Cement	62.49	21.18	4.73	3.41	2.83	2.53	0.56	/	/	3.11
Silica fume	1.85	93.9	/	0.59	/	0.27	0.17	0.86	1.06	2.15

Table 2
Mixture proportions of UHPC.

No.	Steel fiber content by volume (%)	Cement (kg/m^3)	Silica fume (kg/m^3)	Sand (kg/m^3)	Water (kg/m^3)	Super-plasticizer (kg/m^3)	Steel fiber (kg/m^3)
A0	0	809	270	1079	177	21.6	0
A1	1	800	267	1067	175	21.3	78
A2	2	792	264	1056	173	21.1	156
A3	3	784	261	1045	171	20.9	234
B1	1	800	267	1067	175	21.3	78
B2	2	792	264	1056	173	21.1	156
B3	3	784	261	1045	171	20.9	234
C1	1	800	267	1067	175	21.3	78
C2	2	792	264	1056	173	21.1	156
C3	3	784	261	1045	171	20.9	234

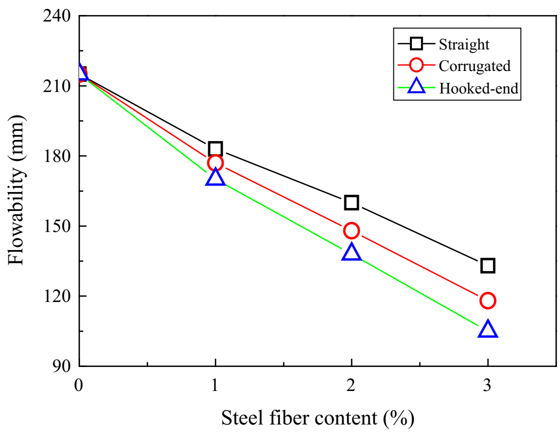


Fig. 1. Effects of steel fiber content and shape on flowability of fresh UHPC mixtures.

ence with the matrix, and thus reduced the flowability [15]. Besides, change in fiber shape leads to strengthening effect among fibers, which made fibers prone to bundle with each other [16].

3.2. Effects of steel fiber content and shape on compressive and ultimate flexural strengths of UHPC

3.2.1. Effects of steel fiber content on compressive and ultimate flexural strengths of UHPC

Fig. 2 shows the change in compressive and ultimate flexural strengths of UHPC with different straight fiber contents at 3, 7, 28, and 90 d. It can be seen that both the compressive and ultimate flexural strengths increased gradually with fiber content and age. The compressive and flexural strengths of reference UHPC sample (A0) were 70.3 and 10.5 MPa, respectively, at 3 d. They increased to 105 and 19 MPa at 90 d. However, 3% straight steel fibers significantly increased the 90 d compressive and flexural strengths over 150 and 40 MPa. As we know, increased steel fiber content could decrease average space between fibers, which made more fibers to sustain load and lead to multi-cracks. Meanwhile, the stress between fiber and matrix reduced with increase of fiber content, which delayed the formation and propagation of cracks, and thus resulted in the increase of strengths [18].

As illustrated in Fig. 2, the strength increase rate slowed down with age. Especially, the flexural strengths at 28 and 90 d were almost the same. This was mainly because of relatively dense structure of UHPC associated with very low water-to-cementitious materials ratio, which did not have enough free water for the hydration of cement at later ages [19].

3.2.2. Effects of steel fiber shape on compressive and ultimate flexural strengths of UHPC

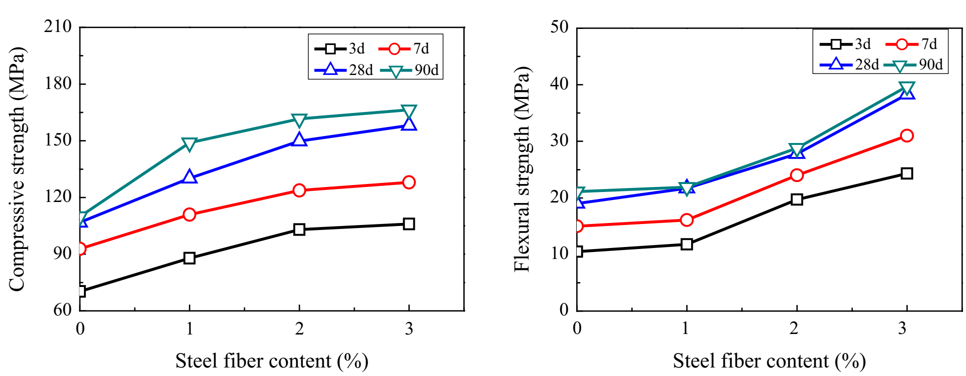
Fig. 3 illustrates the effects of fiber shape on compressive and ultimate flexural strengths of UHPC with and without steel fiber at 28 d. The UHPC with hooked-end fibers had the highest compressive and flexural strengths, while that with straight fibers showed the lowest corresponding values. The compressive strength of the reference UHPC sample was 106.8 MPa at 28 d. It increased by 21.9%, 40.3%, and 48.0% when 1%, 2%, and 3% straight steel fibers were added. With incorporation of 1%, 2%, and 3% hooked-end fibers, the compressive strengths increased by 33.7%, 48.7%, and 59.0%. Same trend could be observed for flexural strength. This may be attributed to different bonding strength associated with fiber shape. The bonding strength at fiber–matrix interface is mainly provided by chemical bond, anchorage mechanical force associated with fiber-end, and friction. It was suggested that hooked-end fibers provide better mechanical interlock compared with other shaped fibers [20,21].

3.3. Effects of steel fiber content and shape on flexural load–deflection curves of UHPC

3.3.1. Effects of steel fiber content on flexural load–deflection curves of UHPC

The effects of fiber content on flexural load–deflection curves of UHPC at 28 d is illustrated in Fig. 4. A suddenly drop after cracking was observed for the control UHPC. When fiber was incorporated, the UHPC could sustain further load even after cracking. However, steel fiber content had little effect on the load–deflection curves before pre-cracking, while had considerable effect on that at post-cracking. Moreover, with increased steel fiber content, the curves became voluminous with greater peak load. This was due to more fibers to sustain load at the cracks. At pre-cracking stage, although both fiber and UHPC matrix sustain load together, the relatively low stress resulted in similar bond stress for the UHPC with different fiber contents. After cracking, only fiber sustained load through mechanical interlock and friction at fiber–matrix interface. Besides, on the descending part of the curve, toothing shape could be observed, which indicated steel fibers were gradually pulled out from matrix. This agrees well with the findings from Yazici [22].

The effects of straight steel fiber content on first crack strength and flexural toughness of UHPC at 28 d were evaluated according to ASTM C1018 [23]. The results were summarized in Table 3. The fiber content had little effect on pre-cracking strength and



(a) Compressive strength (b) Ultimate flexural strength

Fig. 2. Effects of fiber content on compressive and flexural strengths of UHPC with straight steel fiber.

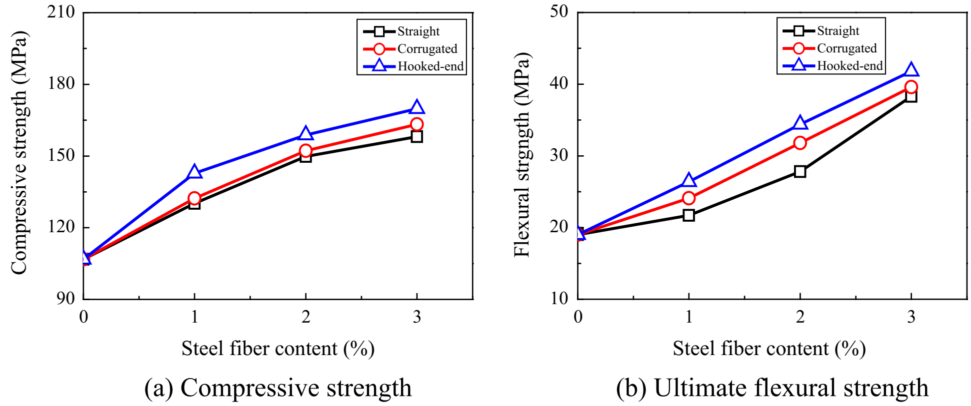


Fig. 3. Effects of steel fiber content on compressive and ultimate flexural strengths of UHPC at 28 d.

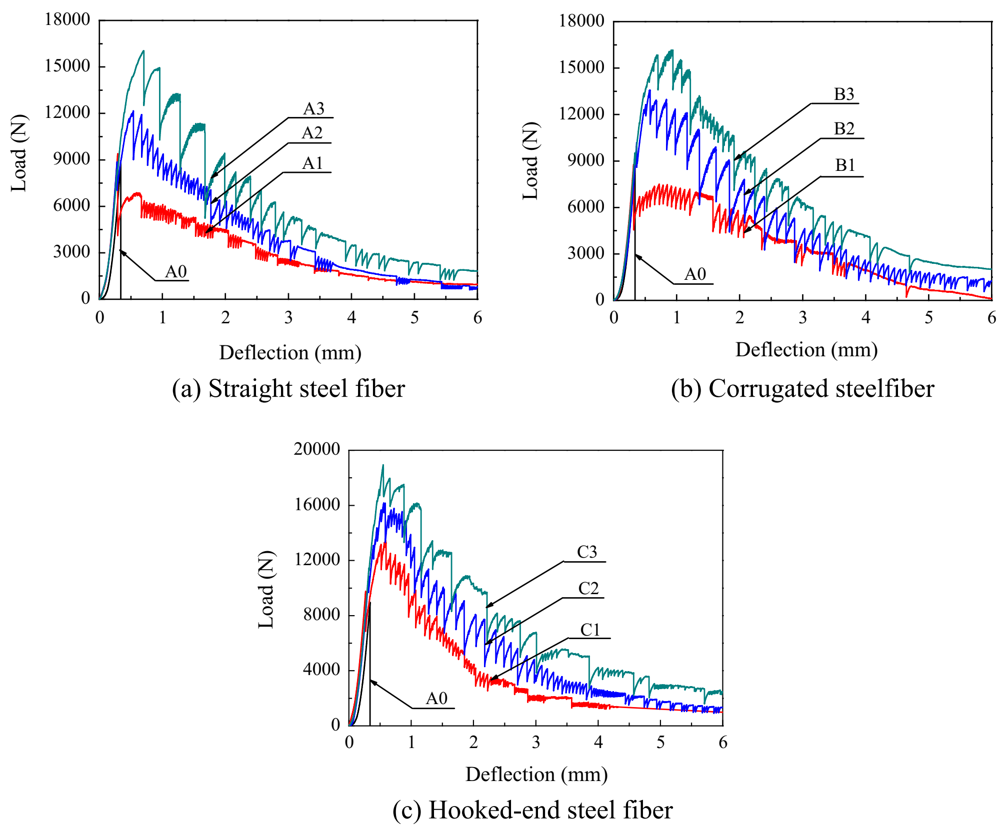


Fig. 4. Effects of steel fiber content on flexural load–deflection curves of UHPC at 28 d.

Table 3
Effects of straight steel fiber content on flexural behavior of UHPC at 28 d.

No.	First crack strength (MPa)	First crack deflection (mm)	Peak strength (MPa)	Peak deflection (mm)	Toughness indexes		
					η_5	η_{10}	η_{20}
A0	19.0	0.30	19.0	0.30	1.00	1.00	1.00
A1	19.2	0.31	21.7	0.36	4.79	9.08	14.56
A2	19.3	0.32	27.8	0.53	7.86	14.95	22.05
A3	19.9	0.33	38.3	0.80	10.17	19.78	27.10

pre-cracking deflection, but had a significant effect on peak strength and peak deflection. Without any fiber, the peak strength and peak deflection were 19.0 MPa and 0.30 mm, respectively. When 1%, 2%, and 3% straight fiber were added, the peak strength increased by 14.2%, 46.3%, and 101.6%, and the peak deflection increased by 20.0%, 76.7%, and 166.7%. These results corresponded well with those reported by Yoo et al. [24,25], who suggested that the first crack stress was mainly controlled by UHPC matrix strength rather than fiber.

The toughness indexes η_5, η_{10}, and η_{20} are the values by dividing the area up to a deflection of 3, 5.5, and 10.5 times of the first crack deflection by the area up to first crack. They reflect the ability

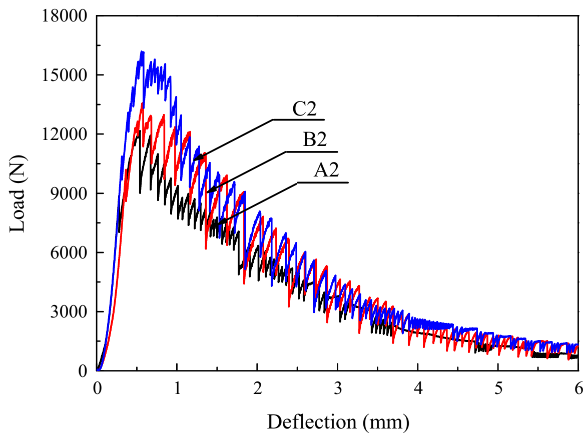


Fig. 5. Effects of steel fiber shape on load–deflection curves of UHPC at 28 d.

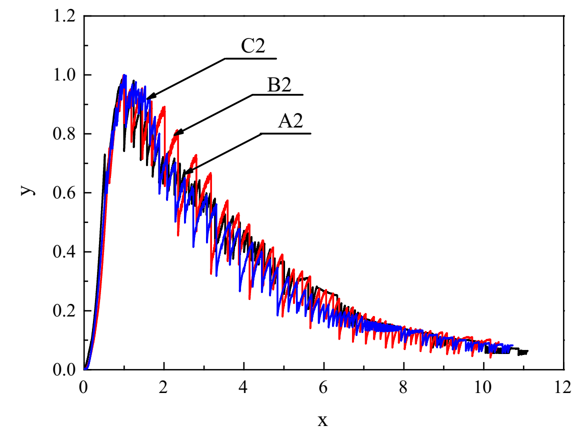


Fig. 6. Normalized flexural load–deflection curves of UHPC.

of energy consumption of UHPC after cracking. In general, the higher the toughness index is, the greater the energy consumption and the better the toughness would be. As can be seen from Table 3, the toughness indexes increased with the increase of fiber content. The toughness indexes η_5, η_{10}, and η_{20} of UHPC with 1% fibers were 4.79, 9.08, and 14.56 times higher than those at the first crack. The corresponding values of UHPC with 2% fibers increased by 7.86, 14.95, and 22.05 times, while increased by 10.17, 19.78, and 27.10 times for those with 3% fibers.

3.3.2. Effects of steel fiber shape on flexural load–deflection curves of UHPC

The effects of fiber shape on flexural load–deflection curves of UHPC with 2% fibers is shown in Fig. 5. It can be seen that UHPC with hooked-end fibers had the highest peak load, while those with straight fibers had the lowest peak load. This was attributed to different bonding properties associated with fiber geometry. Abu-Lebdeh [26] reported that concrete with hooked-end fibers showed an increase of 115% and 95% in peak load and pullout energy when compared to that with smooth straight fibers.

The toughness indexes calculated according to ASTM C1018 are summarized in Table 4. The fiber shape had little effect on first crack strength and first crack deflection but a considerable effect on peak load and peak deflection. When 2% straight fibers was incorporated, the peak load and peak deflection were 27.8 MPa and 0.53 mm, respectively. The peak loads were enhanced by 14.4% and 23.7% with incorporation of 2% corrugated and hooked fibers. The peak deflection increased by 26.4% and 43.4%, respectively. It can be also seen from Table 4 that the toughness indexes increased in the order of straight, corrugated, and hooked-end fiber. The η_5, η_{10}, and η_{20} of UHPC with 2% straight fibers were 7.86, 14.95, and 22.05 times greater than those at first crack. It increased to 8.99, 15.94, and 23.27 times when 2% corrugated fibers were incorporated, and further increased to 9.62, 17.62, and 24.82 times with 2% hooked-end fibers.

3.4. Fitting of load–deflection curves

The typical flexural load–deflection curve can be generally divided into ascending and descending parts, as shown in Fig. 6. At the ascending part, the load increased almost linearly with deflection, and then peak load was obtained. Afterward, the load gradually decreased to almost zero.

According to literature [27,28], the normalized flexural load–deflection curve can be expressed as follows:

(1) when $x = 0$, $y = 0$;
(2) when $0 \leqslant x < 1$, $\frac{d^2y}{dx^2} < 0$, slop decreased at ascending part;
(3) when $x = 1$, $y = 1$, $\frac{dy}{dx} = 0$, at peak load point;
(4) when $x > 1$, $\frac{d^2y}{dx^2} = 0$, inflection point at descending part;
(5) when $x > 1$, $\frac{d^3y}{dx^3} = 0$, the maximum curvature point at descending part;
(6) when $x \to \infty$, $y \to 0$, $\frac{dy}{dx} \to 0$;
(7) when $x \geqslant 0$, $0 \leqslant y \leqslant 1$.

Wee et al. [29] evaluated the constitutive relationship and found that the model proposed by Wang et al. [30] fitted well with the experimental results:

$$y = \frac{A_1x + B_1x^2}{1 + A_2x + B_2x^2} \tag{1}$$

where A_1, B_1, A_2, and B_2 are four unknown parameters.

However, in research conducted by Wang et al. [30], parameters were determined through direct fitting of the experimental results, which made it complicated and physical meaning uncertain. By combining the characteristic of the curve and the uniaxial compressive model proposed by Wang et al. [31], a model of flexural load–deflection of UHPC was proposed as follows:

In the ascending part:

$$Y = \frac{Ax - x^2}{1 + (A - 2)x}, \quad 0 \leqslant x \leqslant 1 \tag{2}$$

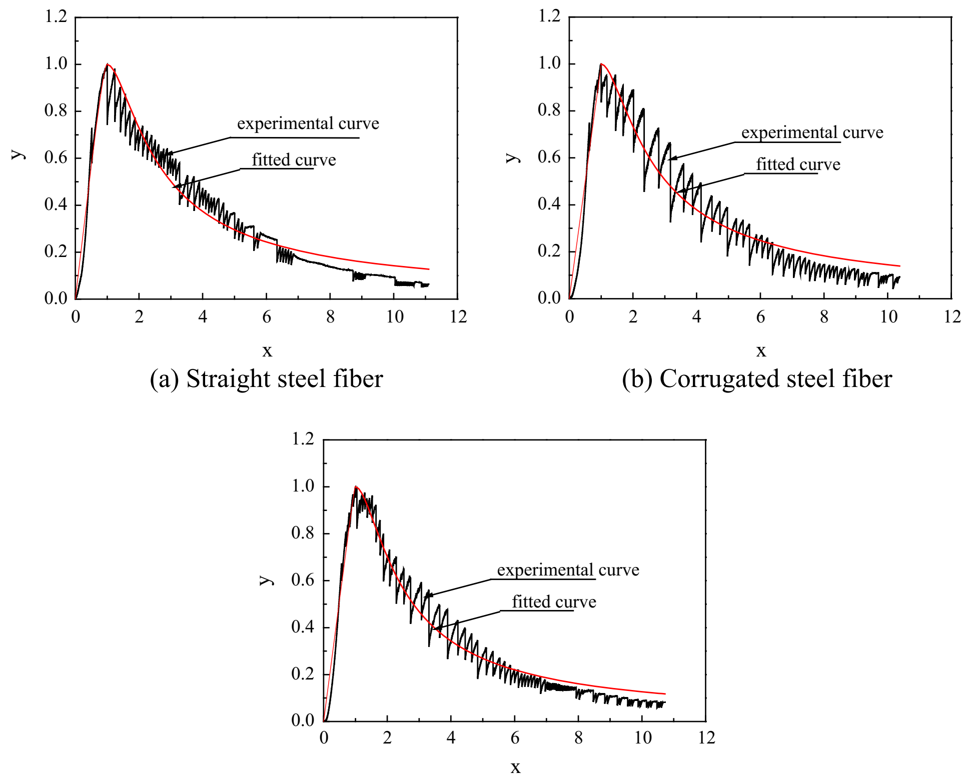
In the descending part:

$$Y = \frac{x}{B(x - 1)^2 + x}, \quad x > 1 \tag{3}$$

where y is the ratio of given load to the peak load $y = F/F_{\text{peak}}$; x is the ratio of given deflection to the deflection corresponding to the

Table 4
Effects of steel fiber shape on flexural behavior of UHPC at 28 d.

No.	First crack strength (MPa)	First crack deflection (mm)	Peak strength (MPa)	Peak deflection (mm)	Toughness index		
					η_5	η_{10}	η_{20}
A2	19.3	0.32	27.8	0.53	7.86	14.95	22.05
B2	20.5	0.35	31.8	0.67	8.99	15.94	23.27
C2	20.6	0.36	34.4	0.76	9.62	17.62	24.82



(a) Straight steel fiber

(b) Corrugated steel fiber

(c) Hooked-end steel fiber

Fig. 7. Typical flexural load–deflection curve of UHPC from experimental and fitting results.

Table 5
Fitting parameters of A, B, and correlation coefficient.

No.	A	Correlation coefficient	B	Correlation coefficient
A2	1.149	0.967	0.745	0.940
B2	1.000	0.938	0.729	0.924
C2	1.036	0.959	0.850	0.963

peak load $x = \delta/\delta_{peak}$; A and B are the two parameters obtained by least squares fitting, $A \geqslant 1$, $B \geqslant 0$.

According to proposed load–deflection model and least square fitting, the fitting results are shown in Fig. 7. The corresponding parameters are summarized in Table 5.

It can be seen from Fig. 7, the fitting results in the ascending part fitted well with experimental results. Although in the descending part, the fitting results were not as good as in the ascending part because affected by complicated factors, such as experimental methods and equipment, fiber content and shape, cracking developing path, and characteristic of interfacial of transition zone. However, high correlation coefficients greater than 0.90, as listed in Table 5, indicated good fitting.

4. Conclusions

Based on the results from this study, the following conclusions can be drawn:

(1) The incorporation of steel fiber significantly reduced the flowability of UHPC. With the increase of fiber content, the flowability gradually decreased. The flowability of UHPC without fiber was 215 mm. With 1%, 2%, and 3% straight fibers, the flowability decreased by 14.9%, 25.6%, and 38.1%. Incorporation of deformed fibers could also decrease flowability. Compared with UHPC samples with 3% straight fibers, the flowability of samples with 3% corrugated and hooked-end fibers decreased by 45.1% and 51.2%.

(2) The compressive and ultimate flexural strengths increased both with the increase of fiber content and age. The compressive and ultimate flexural strengths of UHPC samples without any fiber were 105 and 19 MPa at 90 d, respectively. With incorporation of 3% straight steel fibers, the corresponding values reached over 150 and 35 MPa. UHPC samples with 3% hooked-end and corrugated fibers could increase the compressive strengths by 48% and 59% at 28 d compared to those with the same amount of straight fiber.

(3) Steel fiber content had little effect on the first crack strength and first crack deflection of flexural load–deflection curve of UHPC, but considerable effect on the peak load. When 2% straight, hooked-end, and corrugated fibers were added, the peak load increased by 46.3%, 81.1%, and 61.4%, and the peak deflection increased by 76.7%, 153.3%, and 123.3%.

(4) Based on characteristics of flexural load–deflection curves and typical uniaxial compressive constitutive model, a new constitutive model for flexural load–deflection curve was proposed. It fitted well with the experimental results with correlation coefficient over 0.9.

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