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INVESTIGATION OF SHEAR STRENGTH OF ULTRA-HIGH PERFORMANCE CONCRETE BEAMS WITHOUT STIRRUP

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Abstract

Ultra-high performance concrete (UHPC) has a superior compressive strength and tensile strain-hardening behavior. It has been widely demonstrated in past studies that UHPC structural members have a very high shear strength, which can allow a great reduction in the use of shear reinforcement. However, these is a lack of systematic and quantitative studies on the shear strength of UHPC structural members. This study aims to fill in this gap of knowledge by investigating the shear resistance of eighteen UHPC beams without stirrups. The experimental variables of the beams include the fiber volume ratio (0%, 0.75%, and 1.5%), shear span-to-depth ratio (1.5, 2.4, and 3.3) and coarse aggregate (presence and absence). The shear strengths of the beams are obtained by using a simple four-point loading test setup with a dense array of measurement devices to monitor the detailed response of the UHPC beams. The test results show that the addition of steel fibers leads to a significant contribution to the shear strength of the beams, which can enhance the shear strength of the beams by more than four times. The results also indicate that the ultimate shear strength of the UHPC beams is closely related to the fiber content, coarse aggregate, and shear span-to-depth ratio. In particular, the influences of the fiber content and coarse aggregate on the shear strength of the beams are dependent on the shear span-to-depth ratio of the beam. Furthermore, it is found that the presence of coarse aggregate in the UHPC beams improves the fiber distribution of UHPC in the material scale and significantly increases the shear strength of short UHPC beams by more than two times in the structural scale. Multiple performance measures, including the damage pattern, shear deformation, and stiffness, are employed to assess the shear behavior of the UHPC beams without stirrups. Based on the test results, the design strength of UHPC beams without stirrup is suggested in the study.

Keywords: ultra-high performance concrete; shear strength; beams; coarse aggregate; shear span-to-depth ratio.

1. Introduction

Ultra-high performance fiber reinforced concrete(UHPFRC) is an innovative construction material for civil infrastructures [1-2]. It has superior mechanical and durability properties due to its highly packing density [3-4]. When it is reinforced with discontinuous steel fibers (typically with a volume fraction of 0.75%-2.5%), the composite can show tensile strain-hardening behavior with multiple hairline cracks prior to crack localization, and therefore it can be categorized as a type of high performance fiber reinforced cement composites [5-17]. It has been shown that fiber-reinforced UHPC has superior ductility and can absorb a large amount of deformation energy before the main crack is generated. The addition of steel fibers in UHPC also significantly enhances the shear strength and confinement of the UHPC [18-22]. The amount of confinement steel and shear reinforcement in conventional RC structural members can thus be potentially reduced by replacing the concrete material with fiber-reinforced UHPC. In addition to its advantageous mechanical properties, fiber-reinforced UHPC has significantly higher durability compared to that of conventional concrete materials due to its crack-width control and extremely low porosity.

The application of UHPC in civil infrastructure and earthquake-resistant structures has rapidly increased in recent years [23-26]. However, studies are required to understand the shear property of UHPC structural members. The objective of this study is to investigate the influence of different critical variables on the shear behavior of UHPFRC beams. The experimental variables included the shear span-depth ratio(a/d) = 1.5, 2.4 and 3.3, volume fraction of steel fiber = 0%, 0.75%, and 1.5%, and the presence or absence of coarse aggregate. Eighteen UHPFRC beams were fabricated and tested with a four-point loading setup.

2. Materials

Two different UHPC materials, termed UHPC-1 and UHPC-2, were used in the study. They had the same amount of cementitious materials, aggregate, and water-to-binder(w/b) ratio. They differed in that while coarse aggregate was used in UHPC-1, it was absent in UHPC-2. The ingredients included Type I ordinary Portland cement, silica fume, silica sand (with particle sizes ranging between 0.1 mm and 0.3 mm), quartz powder, ground granulated blast-furnace slag (GGBS), coarse aggregate (with a maximum particle size of 10 mm), polycarboxylate-based superplasticizer, water, and high-strength hooked steel fibers. The steel hooked fibers had a length of 30 mm and a diameter of 0.38 mm. The elastic modulus and nominal yield strength of the steel fibers are 201 GPa and 3070 MPa, respectively. Different volume fractions (V_f) of steel fibers, i.e., 0%, 0.75%, and 1.5%, were added in the UHPC materials.

3. Experimental program

The experimental variables of the eighteen UHPC beams included the fiber content (V_f = 0%, 0.75%, and 1.5%), coarse aggregate (presence and absence), and the shear span-to-depth ratio(a/d) of the beam (1.5, 2.4 and 3.3). All beam specimens had identical cross-sections of 150 mm by 350 mm. The longitudinal reinforcement consisted of 4-D32 and 2-D22 for the flexural tension and compression, respectively. While transverse reinforcement was absent in the test regions of all beams, it was installed on both sides of the beam beyond the supporters to enhance the anchorage strength of the longitudinal reinforcing bars. All reinforcing bars had an nominal yield strength of 420 MPa.

The design details for the eighteen UHPC beams are summarized in Table 1. The denotation of each beam consists of three parts, namely, the shear span-to-depth ratio (1.5, 2.4, or 3.3), volume fraction of steel fibers (0%, 0.75%, or 1.5%), and coarse aggregate (presence (Y) or absence (N)). For example, B3.3-F075-Y refers to the UHPC beam with an a/d ratio of 3.3, a V_f =0.75%, and coarse aggregate.

Table 1-Designs of UHPC beams

Beam types	V_f (%)	Coarse aggregate	a (mm)	d (mm)	*a/d*
B3.3-F0-Y	0				
B3.3-F075-Y	0.75	With			
B3.3-F150-Y	1.5		860		3.3
B3.3-F0-N	0				
B3.3-F075-N	0.75	Without			
B3.3-F150-N	1.5				
B2.4-F0-Y	0				
B2.4-F075-Y	0.75	With			
B2.4-F150-Y	1.5		625	260	2.4
B2.4-F0-N	0				
B2.4-F075-N	0.75	Without			
B2.4-F150-N	1.5				
B1.5-F0-Y	0				
B1.5-F075-Y	0.75	With			
B1.5-F150-Y	1.5		390		1.5
B1.5-F0-N	0				
B1.5-F075-N	0.75	Without			
B1.5-F150-N	1.5				

4. Test results

Fig. 1 shows the shear strengths of the UHPC beams normalized by $\sqrt{f_c'}$. It can be seen that the shear strength increased significantly with a lower a/d value, due to the increasing arch action for shear resistance.

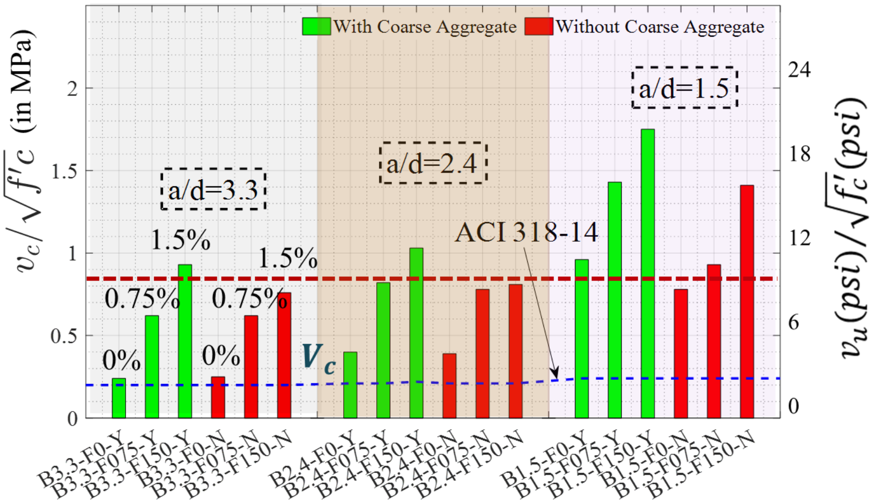

Figure 1. Shear strengths of UHPC beams

It can be observed in Fig. 1 that the influence of coarse aggregate in the shear strength of the intermediate long and long beams (i.e., a/d=2.4 and 3.3) was not visible when the fiber content was low (i.e., V_f = 0% and 0.75%). Nevertheless, when the fiber content was increased to 1.5%, the inclusion of coarse aggregate considerably improved the shear strength by about 20%. This result suggests that for the UHPC beams with a shear transfer mechanism dominant by beam action, the aggregate interlock was not effectively enhanced by the crack-width control ability due to the addition of a 0.75% volume fraction of steel fibers in UHPC. Only when the fiber content was increased to 1.5%, the associated crack-width control ability can effectively enhance the aggregate interlock in the intermediate long and long beams, thus improving the shear strength of the intermediate long and long UHPC beams. Compared to the UHPC beams with a/d=2.4 and 3.3, the enhancement of the shear strength due to the addition of coarse aggregate was substantial (more than 20%) for the short beams (i.e., a/d = 1.5) regardless of the fiber content. This is because the aggregate interlock mechanism for resisting shear was enhanced due to the increased normal compression on the diagonal crack plane as the result of the predominant arch action in short beams. In particular, the results suggest that the aggregate interlock in short UHPC beams was further enhanced by the addition of fibers, which helped restrain the diagonal cracks from opening.

Fig. 1 also shows the comparison of the shear strengths of the UHPC beams obtained by the tests and the concrete shear strength stipulated by ACI 318 [27]:

$$V_c = \left(0.16\sqrt{f_c'} + 17\rho_w \frac{V_u d}{M_u}\right) b_w \tag{1}$$

It can be seen in Fig. 1 that for the long beams without fibers (i.e., B3.3-F0-Y and B3.3-F0-N), the shear strengths of the UHPC beams obtained by the tests were very close to the code design value regardless of the addition of coarse aggregate; the shear equation in ACI 318 underestimated by less than 15%, which is considered reasonable given the conservative nature of the design equations. It is worth mentioning that the shear strength equation in ACI 318 was established based on empirical expressions originally derived for beams with a shear failure mode governed by diagonal tension (i.e., beam action). As a result, the convervativeness of the design shear strength stipulated by the code equation becomes more significant for the beams with a smaller shear span-to-depth ratio, in which the predominant shear transfer mechanism is graduatlly transformed frm the beam acton to the arch action.

Compared to the UHPC beams without fibers, it can be observed in Fig. 1 that increasing the fiber content from 0% to 1.5% consistently enhanced the shear strength of UHPC beams regardless of the a/d ratios. For intermediate long and long beams, the improvement in the shear strength was signifianct (more than 90%) after the addition of only a small 0.75% volume fraction of fibers. This can be attributed to the enhanced tensile strength in the direction orthogonal to the diagonal shear cracks in the beam after the inclusion of fibers. Furthermore, it is interesting to note that the increase in the shear strength of the UHPC beams due to a higher fiber content was more consistent when the UHPC contained coarse aggregate. This is likely because the presence of coarse aggregate in the UHPC enhanced the uniform distribution of steel fibers during the mixing procedure and thus reducing the variability in the obtained shear strength of the beams.

Notably, despite the absence of transverse reinforcement, the shear strength for the long UHPC beam with simultaneous addition of coarse aggregate and a 1.5% volume fraction of fibers was as high as $0.93\sqrt{f_c'}$. This extermely high shear strength of the UHPC material is about 10% higher than the maximum allowable design shear $0.85\sqrt{f_c'}$ for RC members stipulated by ACI 318 [27] that accounts for the contributions of shear reissitances provided by both concrete and steel specified. For the UHPC material that had no coarse aggregate (which is often used in practice and past research studies), its shear strengths in the long beams were $0.61\sqrt{f_c'}$ and $0.76\sqrt{f_c'}$ after the inclusion of 0.75% and 1.5% volume fractions of fibers, repsetively. These results were three times higher than the design concrete strength according to ACI 318. Moreover, in the cases of short UHPC beams that had predominant arch action for resisting shear, the shear strength of the UHPC beams could reach as high as $1.75\sqrt{f_c'}$. Overall, the test results demonstrated the great potential of eliminating or significantly reducing the shear reinforcement in RC members required by the design code by substituting the conventional concrete materials with UHPC.

In ACI 318, the shear stregnth of RC structural elements consists of two components that are provided by the shear reinforcement and concrete, respetively. In order to allow the design and evaluation of the shear strength for steel-reinforced UHPC beams, $V_{R/UHPC}$, a simplied shear strength model is suggested in this study. In the proposed model, it is assumed that $V_{R/UHPC}$ can be expressed as

$$V_{R/UHPC} = V_S + V_{UHPC\_0} + V_F \quad (2)$$

In this equation, V_S is the shear strength provided by the shear reinforcement. V_{UHPC_0} is the shear resistance provided by the non-fiber UHPC that does not contain coarse aggregate and it can be conservatively estimated by adopting the concrete design shear strength stipulated in ACI 318, which is justified by the test results in this study. V_F is the the additional shear resistance of the UHPC beams due to the inclusion of fibers and it can be estimated using the proposed formula

$$V_F = v_f A_c \quad (3)$$

$$v_f = k_w k_s \alpha \sqrt[3]{f_t} \quad (4)$$

In the equation, $A_c = bd$ is the effective cross-sectional area of the UHPC beam, and f_t is the unaixal tensile strength of UHPC. k_w and k_s, which are the parameters proposed for accounting for the enhanced aggregate interlock due to the addition of fibers in UHPC, are associated with the uniaxial tensile strength of UHPC and the shear span-to-depth ratio of the beam, respectively. They are expressed as

$$k_w = 0.006{f_t}^2 + 1 \quad (5)$$

$$k_s = 0.12 \ln\left(\frac{d}{a}\right) + 1.14 \quad (6)$$

When the UHPC material does not contain coarse aggregate or a lower limit of shear strength is desired, the multiplication of $k_w k_s$ is equal to 1. In Eq.(4), the parameter α is proposed to account for the influence of the shear span-to-depth ratio in the shear resistance provided by the steel fibers and it is expressed as

$$\alpha = \begin{cases} 0.56\frac{a}{d} + 1.26 \text{ for } 2.3 < \alpha \leq 3.3 \\ -1.8\frac{a}{d} + 6.7 \text{ for } 1.5 < \alpha \leq 2.3 \end{cases} \quad (7)$$

The premises of Eq. (2) are that (1) the enhanced shear resistance due to the inclusion of steel fibers can be separated from the total shear strength $V_{R/UHPC}$ and (2) the aggregate interlock mechanism can be enhanced by the addition of steel fibers and a lower shear span-to-depth ratio of the beam.

Table 2 shows the predicted V_F values for the fiber-reinforced UHPC beams using Eq. (3). The actual V_F value was the difference between the shear strengths of the target and control UHPC beams, where the control UHPC beam was the specimen that had the same a/d value as the target specimen but without fibers and coarse aggregate. It can be seen in Table 2 that the proposed strength model reasonably predicted the additional shear resistance due to the inclusion of fibers for all UHPC beams regardless of the presence of coarse aggregate and the amount of steel fibers, except for B2.4-F075-N.

Table 2. Proposed formula of steel fiber contribution

BEAM TYPES	f_t	α	k_w	k_s	v_{fa_pred}	v_{fa_exp}	$\frac{v_{fa\_pred}}{v_{fa\_exp}}$
B3.3-F0.75-N	2.45	3.11	1.00	1.00	4.19	4.27	0.98
B3.3-F150-N	5.15	3.11	1.00	1.00	5.37	5.46	0.98
B2.4-F0.75-N	4.00	2.60	1.00	1.00	4.13	4.15	1.00
B2.4-F150-N	5.93	2.60	1.00	1.00	4.71	4.76	0.99
B1.5-F0.75-N	2.56	4.00	1.00	1.00	6.31	1.55	4.07
B1.5-F150-N	5.91	4.00	1.00	1.00	7.23	7.30	0.99
B3.3-F0.75-Y	2.63	3.11	1.03	1.00	4.42	4.03	1.10
B3.3-F150-Y	5.2	3.11	1.14	1.00	6.09	6.76	0.90
B2.4-F0.75-Y	3.85	2.60	1.07	1.03	4.54	4.43	1.02
B2.4-F150-Y	6.24	2.60	1.19	1.03	5.93	5.84	1.01
B1.5-F0.75-Y	3.93	4.00	1.07	1.09	7.16	7.19	1.00
B1.5-F150-Y	5.82	4.00	1.17	1.09	9.18	9.30	0.99
Mean	-	-	-	-	-	-	0.99
SD	-	-	-	-	-	-	0.04

5. Conclusions

The shear strength of UHPFRC beams was investigated in this study. The results indicated that the use of steel fibers significantly improved the shear strength of the UHPFRC beams and reduced the concrete spalling and crushing. Moreover, inclusion of coarse aggregate in UHPFRC increased the shear strength of the UHPFRC beams. Other main conclusions are summarized as follows:

(1) For a/d of 3.3, the shear strength of UHPC beams with 0.75% and 1.5% steel fibers was increased by 150% and 280%, respectively. For a/d of 2.4, the shear strength of UHPC beams with 0.75% and 1.5% steel fibers was increased by 100% and 150%, respectively. For a/d of 1.5, the shear strength of UHPC beams with 0.75% and 1.5% steel fibers was increased by 50% and 80%, respectively.

(2) For a/d of 3.3, the contribution of coarse aggregate was not significant except for the beam with 1.5% steel fibers. The presence of steel fibers promoted the interlocking effect of coarse aggregate. For a/d of 2.4 and 1.5, the contribution of coarse aggregate was significant. A low shear span-depth ratio also increased the interlocking effect of coarse aggregate.

(3) The UHPFRC with coarse aggregate not only enhanced the shear strength but also improved the steel fiber distribution during the mixing procedure and reduced the variability of shear strength.

(4) The inclusion of steel fibers and coarse aggregate in UHPFRC beams significantly increased the shear strength, but only slightly enhanced the stiffness. It is suitable to adopt superposition to evaluate the contribution of steel fibers to shear strength.

(5) The presence of steel fibers enhanced the arch effect on shear resistance for beams with a low shear span-depth ratio. If the UHPFRC contained coarse aggregate, the arch effect was further enhanced.

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