Experimental investigation into the shear resistance of a reinforced UHPFRC web element

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Abstract
Ultra-high performance fiber reinforced concrete (UHPFRC) can be implemented in combination with steel reinforcing bars to enhance the performance of UHPFRC elements subject to shear stresses. This paper presents an experimental investigation into the behavior of a UHPFRC web element in shear. Two I-shaped beams are constructed out of UHPFRC, with longitudinal reinforcing bars in the tension flange. One of the beams includes transverse bars in the web; the other contains no transverse bars. When loaded to failure in a three-point bending test, the specimen with transverse bars exhibits greater shear strength than the specimen without transverse bars. The observed strengths of both specimens show good agreement with a proposed expression for estimating the shear strength of UHPFRC elements. The proposed expression is based on a truss model for shear resistance, and it treats UHPFRC fibers as reinforcement with a variable angle of inclination, bridging shear cracks at an angle perpendicular to the length of the crack.

1. Introduction

Ultra-high performance fiber reinforced concrete (UHPFRC) is a class of cement composite materials characterized by high compressive strength (greater than 150 MPa or 22,000 psi), tensile strain hardening behavior, low permeability, and self-compacting performance during pouring. These properties are achieved through mix designs that include a high volume percentage of fine discontinuous fibers (2% to 10%, typically steel), no course aggregate, a large amount of cementitious paste relative to the volume of fine aggregate, and high-range water reducing admixtures (superplasticizers).

UHPFRC is distinct from high performance concretes – which tend to exhibit high compressive strength, low permeability, and workability, but only modest tensile strength and no tensile strain hardening, and from other fiber reinforced concretes – which may exhibit reduced crack widths at certain stress levels, but not necessarily any of the property requirements listed above.

Compared to normal concrete, the properties of UHPFRC permit the use of smaller cross-sectional dimensions, reduced concrete cover, and often a reduction in transverse reinforcement required for confinement. UHPFRC may also enable the use of new forms and longer service life for structures, unattainable in concrete or steel, as a result of its combined strength, formability, and durability.

To date, UHPFRC has been successfully applied in several civil engineering projects, but the material appears to have potential for further exploitation of its properties. New structures in UHPFRC include pedestrian bridges in Canada, Korea, and Japan; roof structures in France and the Netherlands; and a roadway bridge in the United States [5, 7]. UHPFRC has also been used to strengthen existing structures and provide improved resistance to environmental exposure for bridges in Switzerland and Slovenia [2, 3, 10].

While civil engineering applications to date have typically used UHPFRC in forms similar to prestressed concrete girders or protective overlays, studies indicate that the use of mild steel reinforcing bars in UHPFRC sections can exploit the properties of UHPFRC while taking advantage of additional strength and ductility afforded by bar reinforcement [8].

Shear behavior of UHPFRC elements is an important topic of research, aimed at ensuring the safety of UHPFRC structures while permitting full exploitation of UHPFRC's properties. Existing guidelines and standards characterize UHPFRC shear strength using formulas similar to those used for reinforced concrete. The Swiss code [11] includes special provisions for design of fiber reinforced concrete members, but calculations for shear strength reference the provisions for normal concrete members unless greater values for ultimate resistance are verified by testing. French provisions [1] for design of UHPFRC members propose an expression for shear strength V_u that superimposes the strength contributions of concrete V_{Rb}, transverse reinforcing bars V_a, and fibers V_f:

$$V_u = V_{Rb} + V_a + V_f \tag{1}$$

In this equation, the concrete contribution is a modified version of that used for normal reinforced concrete, the contribution of reinforcing bars is the same as in normal reinforced concrete, and the contribution of fibers is added. Experimental tests of I-shaped UHPFRC beams with no transverse reinforcing bars indicate that the French provisions are effective for estimating shear strength of web-like rectangular sections, but they tend to underestimate the shear strength of flanged sections [6].

The purpose of this study is to characterize the shear behavior of an I-beam made out of UHPFRC and to evaluate the effects of using transverse reinforcing bars with UHPFRC. By comparing specimens with and without transverse reinforcing bars, we aim to estimate the relative contributions of UHPFRC and transverse reinforcing bars to a member's shear strength and ductility.

2. Experimental program

Two I-shaped beams are constructed out of UHPFRC, with longitudinal reinforcing bars in the tension flange. One of the beams includes transverse (vertical) bars in the web; the other contains no transverse bars. The area of longitudinal bars is chosen such that both specimens are expected to reach their shear strength before reaching their flexural strength. The specimens are loaded to failure in a three-point bending test.

Figure 1 shows the dimensions and reinforcement layout for each specimen. The two specimens are identical, except for the presence or absence of transverse bars. Both specimens are constructed by pouring UHPFRC into wooden I-shaped forms, oriented such that the flanges are vertical and the web is horizontal during casting. The UHPFRC mix generally flows to fill the form, but to minimize voids, trowels are used to guide UHPFRC into the beam flanges and web, and the specimens are lightly vibrated by tapping with a hammer on the exterior of the forms. In such thin elements, fibers tend to orient themselves parallel to the plane of the flange or web, rather than perpendicular to it.

Table 1 lists the materials used in both specimens. Tensile strength of the UHPFRC is governed by pullout of fibers.

Figure 2 shows the test setup used for both specimens. A hydraulic jack applies monotonically increasing deflection to the midspan, at a rate of 0.5mm/min.

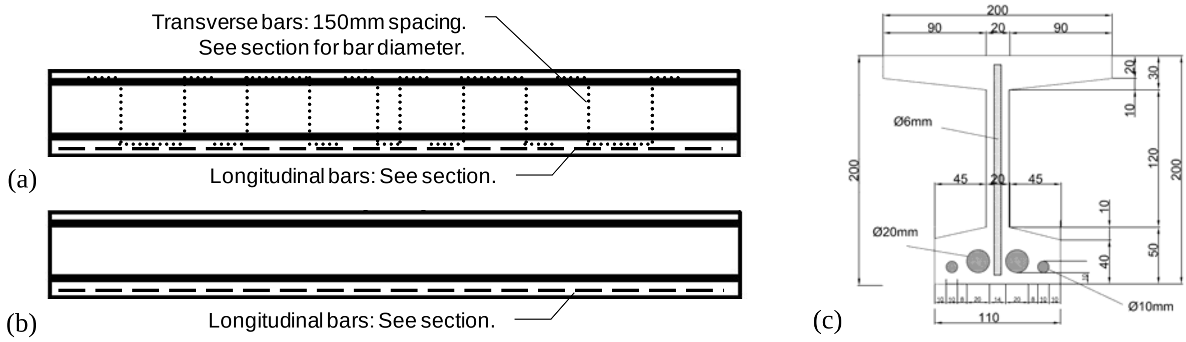


Figure 1: Specimen dimensions and reinforcement. (a) Elevation with vertical bars. (b) Elevation without vertical bars. (c) Section.

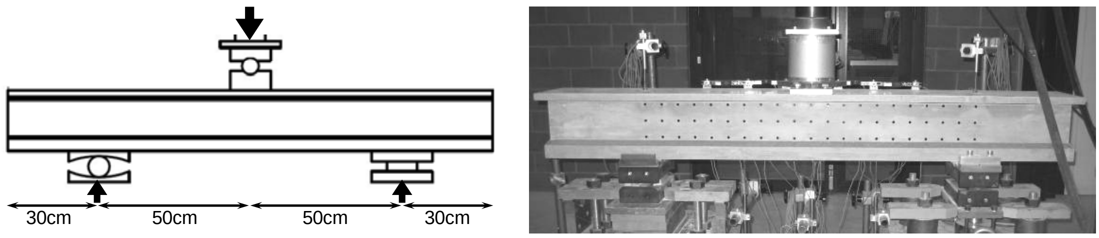


Figure 2: Test setup

Table 1: Materials

Material	Properties	Notes
UHPFRC : HIFCOM mix design [12]	f_c = 150 MPa (22 ksi) f_t = 10~16 MPa (1.5~2.3 ksi) E = 47 GPa (6800 ksi) Straight steel fibers: 13mm x 0.16mm Ø, 3% vol.	Average of 2 cylinder compression tests: 147, 152 MPa Tensile tests by Oesterlee [9] Average of 2 cylinder compression tests: 46, 48 GPa
Reinforcing bars: Grade B500B	f_y = 500 MPa (73 ksi) f_{ye} = 625 MPa (91 ksi)	Nominal yield Expected yield, average of tensile tests

3. Results

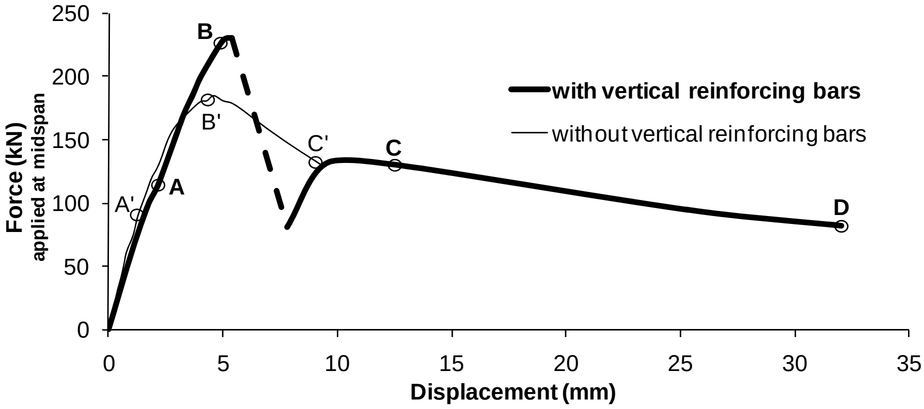
Figure 3 plots the force-displacement response and cracking pattern for each specimen, and Table 2 compares the specimen strengths. The specimen with transverse reinforcing bars shows greater shear strength than the specimen without transverse bars.

Both specimens exhibit primarily diagonal cracking, indicating shear failure in the web. At a force level of approximately 50% of peak force, microcracks proliferate at 45°. Between 50% and 100% of peak force, macrocracks become visible and open as force increases. The specimen with transverse reinforcing bars exhibits two primary macrocracks, whereas the specimen without transverse bars exhibits only one. The pair of cracks in the reinforced web occurs at approximately 45°, apparently constrained between two vertical bars prior to failure; the crack in the unreinforced web occurs at a flatter angle, approximately 35°. At peak force, fibers pull out of the primary crack(s), and a transverse bar fails in the specimen with bars, resulting in a sudden decrease in strength. This drop in resistance is indicated by a dashed line between two recorded data points in the force-displacement plot of Figure 3.

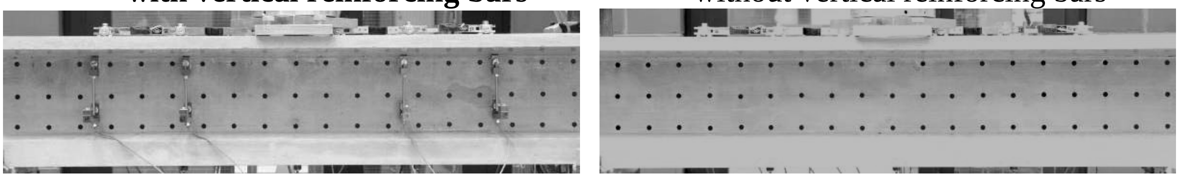
In both specimens, post-peak residual strength comes from the flanges acting independently in double curvature to span over the failed portion of the web. In the specimen without transverse bars, the test was stopped after all fibers had pulled out of the primary shear crack. After this point, the flanges work independently in the same manner as in the specimen with transverse bars.

Table 2: Shear strength

	UHPFRC with transverse bar reinforcement	**UHPFRC without transverse bar reinforcement**
failure mechanism	Diagonal crack through web	Diagonal crack through web
peak shear force = 0.5 x force applied at midspan	115 kN (26 kips)	92 kN (21 kips)
sectional shear strength = shear force / (depth x web thickness)	29 MPa = 2.4 $\sqrt{f_c'}$ (4200 psi = 28 $\sqrt{f_c'}$)	23 MPa = 1.9 $\sqrt{f_c'}$ (3300 psi = 22 $\sqrt{f_c'}$)



with vertical reinforcing bars without vertical reinforcing bars



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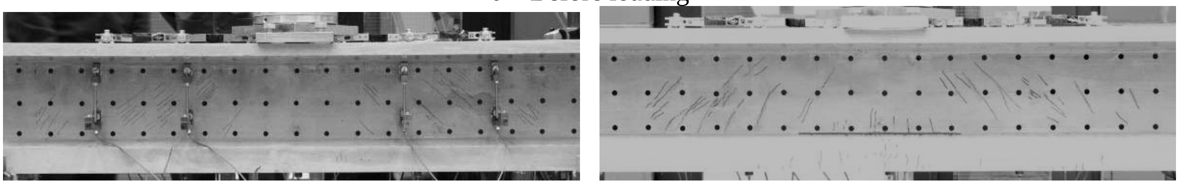
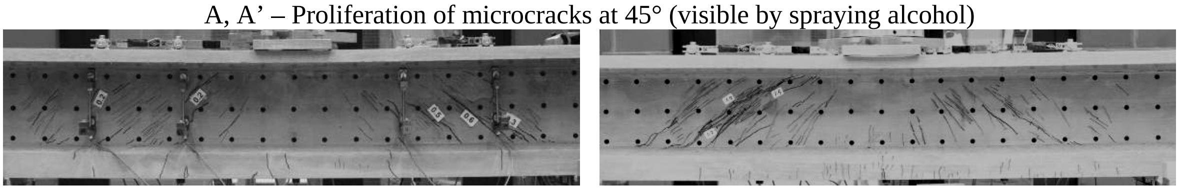
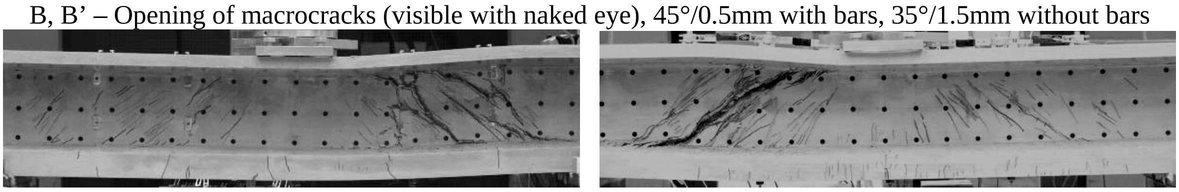


A, A' – Proliferation of microcracks at 45° (visible by spraying alcohol)



B, B' – Opening of macrocracks (visible with naked eye), 45°/0.5mm with bars, 35°/1.5mm without bars



C, C' – Transverse bar failure, fiber pullout of primary crack(s)

D – Flanges acting independently over the failed portion of the web

Figure 3: Force-displacement response and cracking pattern

4. Model to estimate shear strength

Results presented above indicate that transverse reinforcing bars and UHPFRC contribute to the shear strength of the beam, so a useful analytical model might express the shear strength as a sum of contributions[1] from transverse bars V_s and from UHPFRC V_{UHPFRC} :

$$V = V_s + V_{UHPFRC} \tag{2}$$

Unlike some models for shear strength of reinforced concrete members, this formulation does not include a term for the contribution of "concrete" because UHPFRC contains only fine aggregate, so compression strength and aggregate interlock are unlikely to play a significant role in beam shear strength of UHPFRC elements.

The difference in strength between the two specimens shows good agreement with a truss model for shear strength provided by transverse reinforcing bars:

$$V_{se} = \frac{A_s}{s} z f_{ye} \left(\cot\alpha + \cot\beta\right)\sin\beta \tag{3}$$

		value used in calculation
V_{se}	expected contribution of transverse reinforcing bars	**20.6kN**
A_s	cross-sectional area of one reinforcing bar	28.3mm^2
s	spacing of reinforcing bars	150mm
z	effective shear depth of the section	175mm
f_{ye}	expected yield stress of reinforcing bars	625MPa
α	angle of inclination of shear crack or compression strut	45°
β	angle of inclination of reinforcing bars	90°

The difference in shear strength between the two specimens is 115 – 92 = 23 kN, which is approximately equal to the contribution of reinforcing bars calculated using Equation 3 above.

The strength of the specimen with no transverse reinforcing bars shows good agreement with a model that treats UHPFRC fibers as reinforcement with a variable angle of inclination, bridging shear cracks at an angle perpendicular to the length of the crack:

$$V_{UHPFRCe} = \frac{tdf_{te}}{\sin\alpha} \tag{4}$$

		value used in calculation
$V_{UHPFRCe}$	expected contribution of UHPFRC	**90.5kN**
t	thickness of the beam web	20mm
d	depth of the section	200mm
f_{te}	expected tensile strength of UHPFRC	16MPa
α	angle of inclination of the shear crack or compression strut	45°

This proposed model is an adaptation of Equation 3, in which the area and yield stress of reinforcing bars are replaced with those of the UHPFRC web, and fibers act in the direction perpendicular to cracks ($\beta = 90 - \alpha$).

The calculated contribution of UHPFRC by Equation 4 above is approximately equal to the shear strength observed in testing for the specimen with no transverse reinforcing bars.[2]

For simplicity of the calculations presented above, the crack angle is assumed to be 45° for both specimens, and the tensile strength of UHPFRC 16 MPa. In reality, the crack angle is

[1] In members subjected to axial force, axial compression may provide an additional contribution V_p to the shear strength of the member, but this term is omitted in the analysis presented here, where the axial force is zero.

[2] Galrito [4] compares several different analytical models to estimate the shear strength of the specimens tested in this experiment. Of the models examined, one similar to that proposed here shows the best agreement with test results from this experiment.

somewhat different for each specimen, and the tensile strength of UHPFRC may vary as well based on the orientation of fibers. For example, applying the proposed model with refined assumptions for the specimen without transverse bars (crack angle 35°, UHPFRC tensile strength 13MPa) exhibits good agreement with the observed shear strength of that specimen. Also, the thick flanges on the specimens tested here may contribute to the specimen shear strength more than assumed in the calculations, which use an effective shear area only as wide as the web. This underestimate in the calculated shear area may offset the potential overestimate of UHPFRC tensile strength, which was assumed to be at the high end of the range of values observed in previous tests of this material.

5. Conclusions

Results of this investigation indicate the following:

- An expression analogous to the truss model for shear resistance provides an effective means for estimating the shear strength of UHPFRC elements. This analogy treats UHPFRC fibers as reinforcement with a variable angle of inclination, bridging shear cracks at an angle perpendicular to the length of the crack.
- Shear failure of a UHPFRC I-beam exhibits limited ductility, which could lead to sudden failure at the ultimate limit state.
- Providing transverse (vertical) reinforcing bars in the web of a UHPFRC I-beam is a viable approach for providing sufficient shear strength, in order to ensure ductile flexure-governed behavior in situations where ductility is required.

Further testing is recommended to refine the proposed expression for UHPFRC shear strength and the assumptions used for key variables:

- To reduce the uncertainty related to the influence of thick flanges used in this test, perform similar tests of I-shaped UHPFRC sections with thinner flanges (though still proportioned to fail in shear).
- Perform similar tests with larger specimens to evaluate the scale effects related to fiber length, crack width, and shear behavior.

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