EFFECT OF ULTRA-HIGH PERFORMANCE FIBRE REINFORCED CONCRETE AND HIGH-STRENGTH STEEL ON THE FLEXURAL BEHAVIOUR OF REINFORCED CONCRETE BEAMS

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Abstract

This paper presents the results of a study examining the effect of UHPFRC and high-strength reinforcement on the flexural behaviour of reinforced concrete beams. As part of the study, two UHPFRC and two high-strength concrete (HSC) beams are tested under four-point flexural loading. In addition to the effect of concrete type (UHPFRC vs. HSC), the study examines the effect of reinforcement grade (normal vs. high-strength bars) on the flexural behaviour of the HSC and UHPFRC beams. The results show that the use of UHPFRC in beams results in increased load-resistance, stiffness, and overall performance when compared to conventional high-strength concrete. The behaviour of the beams is also shown to be affected by reinforcement type, with the combined use of UHPFRC and high-strength steel leading to improvements in beam performance.

Résumé

Cet article présente les résultats d’une étude examinant l’effet du BFUP et d’armatures à haute résistance sur le comportement de poutres en béton armé en flexion. En particulier, deux poutres en BFUP et deux poutres en béton à haute résistance (BHR) sont testées en flexion quatre points. En plus de l’effet du type de béton (BFUP ou BHR), on examine l’effet du type d’acier (acier normal ou à haute résistance) sur le comportement des poutres en flexion. Les résultats montrent que l’emploi du BFUP dans les poutres augmente la capacité portante, la rigidité et la performance globale par rapport au béton conventionnel à haute résistance. Le comportement des poutres apparaît également sensible au type d’acier, la combinaison du BFUP et d’acier à haute résistance induisant une amélioration de la performance des poutres.

1. INTRODUCTION

Ultra-high performance fibre-reinforced concrete (UHPFRC) is an innovative material which shows superior properties when compared to conventional concrete. In addition to very high compressive strength, the material shows high tensile capacity and superior flexural toughness due to the addition of steel fibres. These properties make UHPFRC well-suited for use in heavily-loaded structural applications. In beams, the use of UHPFRC can lead to high load-carrying capacity and more efficient designs [1-3]. However, the high compressive strength and toughness of UHPFRC in flexural members can also lead to rupture of tension steel reinforcement [4]. The combined use of UHPFRC and high-strength reinforcement is a potential solution, which can allow for further improvement in structural performance.

This paper presents the results of a study examining the effect of combining UHPFRC and high-strength reinforcement on the flexural behaviour of reinforced concrete beams. As part of the study, two UHPFRC and two high-strength concrete (HSC) beams are tested under four-point flexural loading. In addition to the effect of concrete type (UHPFRC vs. HSC), the study examines the effect of reinforcement grade (normal vs. high-strength bars) on the flexural behaviour of the HSC and UHPFRC beams.

2. EXPERIMENTAL PROGRAM

2.1 Specimen designs

A total of four beams were tested in this research study (Table 1). Two beams were constructed with high-strength concrete (HSC), with two additional beams constructed with Compact-Reinforced Composite (CRC), a proprietary ultra-high performance fibre reinforced concrete (UHPFRC) [5]. As shown in Figure 1, the beams had dimensions of 125 mm x 250 mm x 2440 mm, and were tested over a simply-supported span of 2232 mm. The longitudinal reinforcement consisted of either 2 - 20M Canadian size (A_b = 300 mm^2) Grade 400 MPa normal-strength (NS) bars or 2 - No.6 American size (A_b = 284 mm^2) ASTM A1035 high-strength (HS) bars, resulting in reinforcement ratios of ρ = 2.4% and 2.2%. The beams contained transverse reinforcement, which consisted of U-shaped stirrups made from 6.3 mm smooth steel wire, spaced at 100 mm in the shear spans (see Figure 1). To facilitate construction, 2 - 6.3 mm bars were also provided at the top of the beam sections (in the shear spans only). The UHPFRC specimens were constructed with CRC having a volumetric ratio of 2% (160 kg/m^3) of steel micro-fibres.

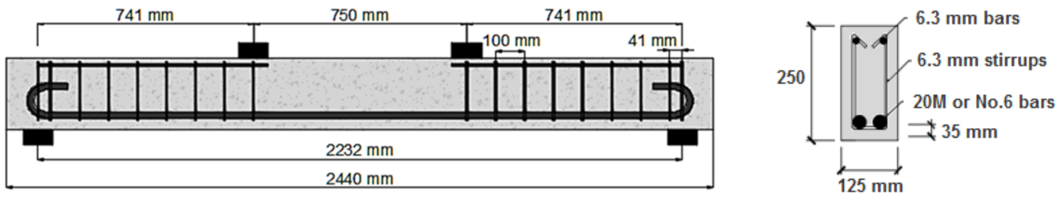


Figure 1: Beam dimensions and reinforcing details

Table 1: Beam test matrix

Beam I.D.	Concrete Mix	Concrete Strength f'_c (MPa)	Avg, Elastic Modulus (GPa)	Steel fiber properties: Length/dia. (mm/mm)	Steel fiber properties: V_f (%)	Steel reinf. properties: Type	Steel reinf. properties: Flexural Steel
HSC-0%-20M	HSC	104	36	-	-	NS	2- 20M
HSC-0%-No.6(HS)		95		-	-	HS	2-No. 6
CRC-2%-20M	CRC	154	46	13/0.2	2.0	NS	2- 20M
CRC-2%-No.6(HS)		153		13/0.2	2.0	HS	2-No. 6

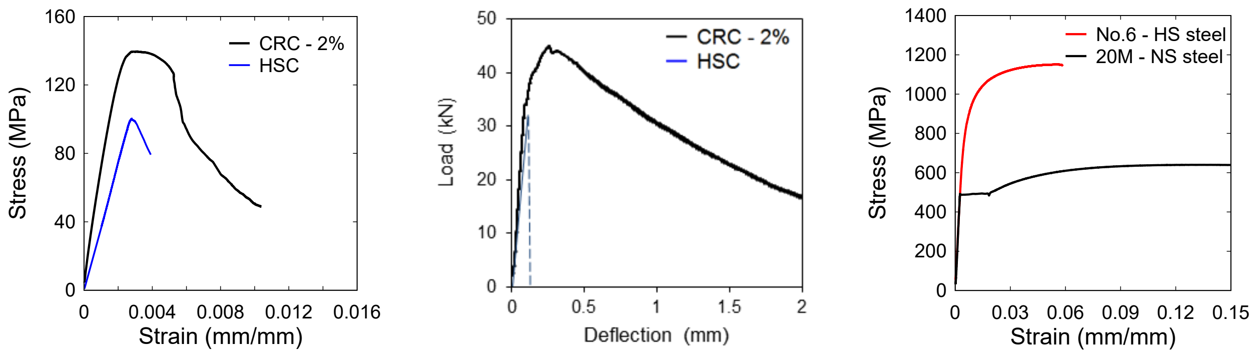
Table 1 provides information on concrete type (HSC vs. CRC), fibre content (0% vs. 2%) and longitudinal steel (20M vs. No.6; where "HS" refers to the use of high-strength bars).

2.2 Material parameters

Two types of concrete mixtures were used in this study. The HSC mix had a target strength of 100 MPa and contained cement, silica fume, slag, two sizes of coarse aggregate (19 mm and 10 mm), sand, water and admixtures which included a set-retarder and super-plasticizer (see Table 2). The UHPFRC specimens were constructed with CRC. The mix contains cement, microsilica, quartz sand and admixtures which are incorporated into the mixture in the form of a dry powder [5] (details of the manufacturer's mix are proprietary). The steel fibres had a length of 13 mm, a diameter of 0.2 mm and a tensile strength of 2750 MPa, and were incorporated in the CRC mix at a volumetric ratio of 2% (156 kg/m^3). The strength properties of the HSC and CRC, obtained by testing 100 mm x 200 mm cylinders in compression, are summarized in Table 1 and sample stress-strain curves are shown in Fig. 2. Flexural strength and toughness were assessed by testing 100 x 100 x 400 mm prisms in accordance with the ASTM C1609 standard (sample load-deflection curves are shown in Figure 2). The yield strengths for the normal-strength 20M reinforcement and 6.3 mm steel wire were 462 MPa and 577 MPa, respectively. The high-strength No.6 reinforcement had a yield strength of 855 MPa (obtained using the 0.2% offset method), with an ultimate strength of 1153 MPa. Sample stress-strain curves for the steel reinforcement are shown in Figure 2.

Table 2: HSC mix design

Component	Content
Portland Cement (GU)	440.3 kg/m^3
Slag	193.6 kg/m^3
Coarse Aggregate 1 (19 mm)	661 kg/m^3
Coarse Aggregate 2 (9.5 mm)	661 kg/m^3
Silica Fume	57 kg/m^3
Sand	872 kg/m^3
Water	186 kg/m^3
Retarder	3.3 L/m^3
Super Plasticizer	13.1 L/m^3



a) HSC & CRC (compression) c) HSC & CRC (flexure) d) Long. steel (tension)

Figure 2: Sample material properties

2.3 Test setup

All beams were tested under quasi-static four-point bending using the setup shown in Figure 3. The beams were simply supported over a span of 2232 mmm, with a constant moment region of 750 mm and two equal shear-spans of 741 mm (see Figure 1). Loading was applied using a manually operated hydraulic jack with the load transferred to the specimens as two point loads using a steel spreader beam. The load was recorded using two load-cells at the supports, with displacement at midspan captured using a cable displacement transducer. Strains in the reinforcing bars were monitored using strain-gages which were applied on the tension steel at midspan. Loading of the beams began under load-control until signs of yielding were detected. Upon yielding, loading continued under displacement-control until failure of the specimens (concrete crushing, rupture of tension steel or shear collapse).

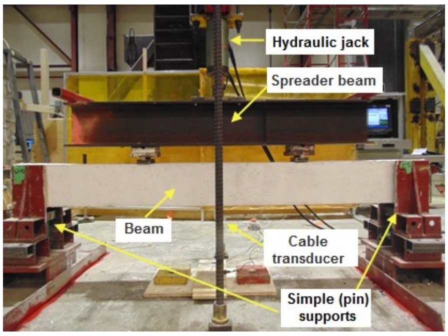
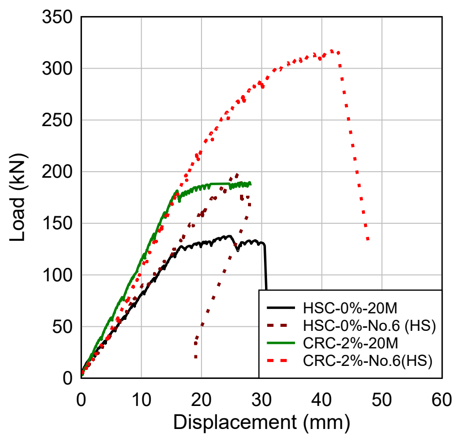
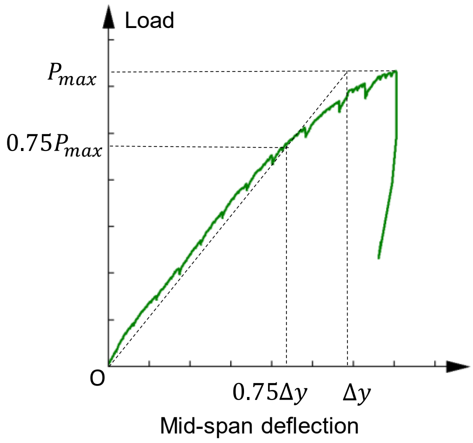


Figure 3: Beam test setup

3. EXPERIMENTAL RESULTS



(a)



(b)

Figure 4: (a) Load-deflection curves and (b) method for determining Δ_y in HS specimens

The load-deflection responses of the specimens are plotted in Figure 4a. Photographs of the beams at the end of testing, illustrating failure mode are shown in Figure 5. Table 3 summarizes key data extracted from the load-deflection curves, including yield load (P_y) and maximum load (P_{max}), yield displacement (Δ_y) and maximum (failure) displacement (Δ_{max}), beam stiffness after cracking (K), ductility (Δ_{max}/Δ_y) and toughness, taken as the area under the load-deflection curve until Δ_{max}, where failure corresponded to the sudden loss in load-carrying capacity due concrete crushing, tension steel rupture or shear failure. The beams with high-strength reinforcement do not show well-defined yield points due to the nature of the steel stress-strain relationship, and therefore yielding in these specimens was estimated using the method shown in Figure 4b [6]. Displacement at failure Δ_{max}, corresponded to the displacement at 15% reduction in peak capacity.

Table 3: Experimental results extracted from load-deflection curves

Beam I.D.	Load		Displacement		Stiffness (N/mm)	Ductility Δ_{max}/Δ_y	Toughness kN·mm
	Yield P_y (kN)	Max. P_{max} (kN)	Yield Δ_y (mm)	Failure Δ_{max} (mm)			
HSC-0%-20M	118.2	137.5	15.0	31.0	7911	2.07	2998
HSC-0%-No.6(HS)	191.8	199.0	24.7	27.2	8152	1.10	3096
CRC-2%-20M	182.3	190.0	16.0	28.0	11,023	1.75	3710
CRC-2%-No.6(HS)	281.5	318.0	26.9	45.6	11,646	1.70	9275

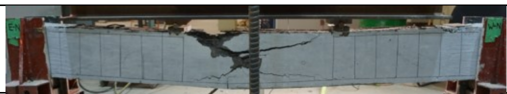
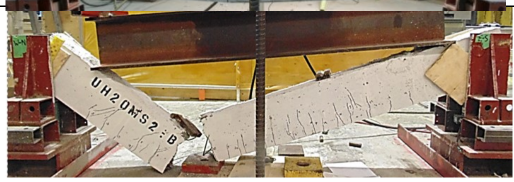
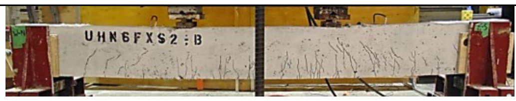
Beam I.D.	Displ. stage	Photo
HSC-0%-20M	End of test (Δ = 31 mm)	
HSC-0%-No.6(HS)	End of test (Δ = 27 mm)	
CRC-2%-20M	End of test (Δ = 28 mm)	
CRC-2%-No.6(HS)	(Δ = 35 mm)	
	End of test (Δ = 46 mm)	

Figure 5: Failure modes of all the beams

3.1 Response of Beam HSC-0%-20M

Beam HSC-0%-20M was the first beam tested in the study and was constructed with plain high-strength concrete and 20M normal-strength bars. The beam shows a response with a well-defined yield point, followed by a deflection plateau until failure occurs due to crushing of the concrete in the compression zone. Yielding in the beam occurred at 15 mm, with a maximum deflection of 31 mm, resulting in a ductility ratio (Δ_{max}/Δ_y) of 2.07. The maximum load sustained by the beam was 137.5 kN.

3.2 Response of Beam HSC-0%-No.6(HS)

The second HSC beam in the research program had similar properties to the previous beam but was built with No.6 high-strength ASTM A1035 steel. Failure in this beam occurred suddenly due to crushing of compression concrete, before the development of large beam deflections. In contrast to the previous specimen, the use of high-strength longitudinal reinforcement does not show a deflection plateau or clear yield point, although the load-deflection curve shows slight rounding in response prior to failure. Maximum mid-span deflection of 27.2 mm was recorded prior to the sudden compression failure.

3.3 Response of Beam CRC-2%-20M

The first UHPFRC beam was built with CRC and 20M normal strength longitudinal reinforcement. The beam shows a well-defined yield point (Δ_y = 16 mm) and increased load-resistance (P_{max} = 190 kN) when compared to the companion high-strength concrete beams. Failure of this specimen occurred in flexure due to rupture of the normal-strength longitudinal reinforcement at a displacement Δ_{max} = 28 mm. The beam showed limited damage in the compression zone, and relatively large deflections, prior to the abrupt rebar failure. The ductility for this beam was calculated as 1.75.

3.4 Response of Beam CRC-2%-No.6(HS)

The last beam tested in the research program was designed with CRC concrete and high-strength ASTM A1035 longitudinal rebar. Unlike the CRC beam with normal-strength steel, this specimen shows a rounded load-deflection response without a clearly defined yield point. However, the beam does sustain large deflections prior to failure. Yielding was approximated to have occurred at a displacement of 27 mm using the method defined in Figure 4b. The maximum load resisted by the specimen was 318 KN at a corresponding displacement of 45.6 mm. While the use of high-strength steel prevented rebar rupture, the specimen experienced a shear failure in the post-yielding region, with an estimated ductility ratio of 1.70.

4. DISCUSSION OF RESULTS

4.1 Effect of UHPFRC in beams with normal-strength reinforcement

The effect of concrete type can be investigated by comparing the response of companion beams HSC-0%-20M vs. CRC-2%-20M which had 20M normal-strength bars but was built with plain HSC and UHPFRC (CRC with 2% fibres), respectively. Comparison of the response of the specimens is shown in Figure 4a. Both beams show initial ascending branches with well-defined deflection plateaus, however the peak load resisted by CRC-2%-20M is 38% greater than that of HSC-0%-20M. The UHPFRC beam also shows a 39% increase in post-cracking stiffness. Comparing the displacements, beam HSC-0%-20M sustained a deflection which was 11% higher when compared to beam CRC-2%-20M. As a result, beam ductility is decreased when using UHPFRC, with Δ_{max}/Δ_y = 2.07 vs. 1.75 for beams HSC-0%-20M vs. CRC-2%-20M, respectively. However, when toughness is examined, the UHPFRC specimen presents a 24% improvement in energy-absorption capacity. Concrete type also had an effect on failure mode. Failure of the HSC specimen occurs in the post-yield region due to crushing of concrete. In contrast compression concrete in the UHPFRC specimen shows limited damage, even at large displacements. The high compressive strength and toughness of UHPFRC lead to the development of very high strains in the tension steel, eventually leading to rupture of the 20M normal-strength bars and beam collapse (Figure 5).

4.2 Effect of UHPFRC in beams with high-strength reinforcement

This comparison examines the effect of concrete type in beams designed with high-strength reinforcement. Included in this set are beams CRC-2%-No.6(HS) and HSC-0%-No.6(HS), which were built with UHPFRC and plain HSC, respectively. Comparing the response of the beams in Figure 4a, it can be seen that the use of UHPFRC leads to an increase of 60% in peak load-carrying capacity when compared to the beam built with plain HSC. Results also show that the use UHPFRC in place of HSC increases stiffness by 43%. The use of UHPFRC also extended the maximum displacement by a factor of 68% when compared to the companion HSC beam. Due to the nature of the high-strength steel, the load-displacement curves of both beams do not show well-defined yield points, however it is clear that the use of UHPFRC was better able to utilize the capacity of the high-strength bars. Failure of the HSC specimen occurs abruptly with a brittle compression failure prior to the development of large strains in the tension steel (over-reinforced behaviour). In contrast, yield strains are developed in the high-strength bars when using UHPFRC. As a result, the UHPFRC beam shows increased ductility. The use of UHPFRC also had a positive impact on energy absorption capacity, with specimen CRC-2%-No.6(HS) recording a two-fold increase in toughness when compared to HSC-0%-No.6(HS). Despite the enhancements in performance, failure in the CRC beam occurs in shear, although the beam shows a significantly large displacement of 46 mm.

4.3 Effect of steel reinforcement type in HSC beams

Comparison of the performance of beams HSC-0%-20M and HSC-0%-No.6(HS) allows for an examination of the effect of high-strength reinforcement in the plain high-strength concrete beams. Maximum load data shows that the beam reinforced with No.6 high-strength bars has a 45% increase load-carrying capacity when compared to the companion with 20M normal-strength bars. The stiffness of both beams is found to be similar. The beams also show similar energy absorption capacity, with a 3% increase in toughness for the specimen with high-strength bars. However, beam HSC-0%-No.6(HS) shows more brittle behaviour, with a lower failure displacement and a significant reduction in ductility when compared to beam HSC-0%-20M as shown in Figure 4a. While beam HSC-0%-20M shows a significant deflection plateau due to yielding of the normal-strength bars, the use of high-strength bars led to an abrupt compression ("concrete-controlled") failure in beam HSC-0%-No.6(HS).

4.4 Effect of steel reinforcement type in UHPFRC beams

The final comparison examines the effect of using high-strength reinforcement in UHPFRC beams. Included in the comparison set are beams CRC-2%-20M and CRC-2%-No.6(HS) which were built with CRC and 20M/No.6 normal-strength/high-strength bars, respectively. Comparison of the beam responses shows that the use of high-strength reinforcement in beam CRC-2%-No.6(HS) led to a significant 67% increase in maximum load-carrying capacity when compared to the companion CRC beam with normal-strength bars. As with the previous set, steel type does not have a noticeable effect on beam stiffness. Examination of the displacements show that the beam with high-strength bars sustained a 63% increase in maximum displacement. While both beams show similar ductility (Δ_{max}/Δ_y =

1.70 vs. 1.75), the CRC beam with high-strength bars shows a 150% improvement in energy-absorption capacity (toughness). The use of high-strength steel in beam CRC-2%-No.6(HS) also had an important effect on failure mode, preventing rupture of the tension steel reinforcement. Despite this, failure of beam CRC-2%-No.6(HS) eventually occurred in shear at a relatively large deflection of 46 mm. The result indicates the importance of ensuring UHPFRC beams with high-strength reinforcement are designed with sufficient shear capacity to counter increased shear demands.

5. CONCLUSIONS

This paper presented the results of a study examining the effect of UHPFRC and high-strength reinforcement on the flexural behaviour of reinforced concrete beams. The following conclusions can be drawn from this study:

– The results show that the use of UHPFRC in reinforced concrete beams with normal-strength reinforcement leads to important enhancements in ultimate load resistance, stiffness and energy absorption capacity (toughness). However, the increased compressive strength and toughness of UHPFRC leads to the development of high strains in the tension steel, which can lead to rupture of tensile reinforcement;

– The combined use of UHPFRC and high-strength reinforcement leads to further improvements in beam performance, with increases in load-carrying capacity and toughness. The use of high-strength steel was also effective in preventing rebar rupture, although the increased shear demands led to eventual shear failure;

– The results indicate the importance of carefully considering the reinforcement ratio in beams reinforced with high-strength bars. In the HSC series, the use of high-strength led to a brittle compression failure. The use of UHPFRC, with its increased compressive strength and strain-capacity, was better suited to utilize the capacity of the high-strength reinforcing bars.

ACKNOWLEDGEMENTS

The authors would like to thank CRC Technology (Hi-Con A/S) and MMFX Technologies Corporation for providing the materials used in this study.

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