EFFECT OF ULTRA-HIGH PERFORMANCE FIBRE-REINFORCED CONCRETE ON THE BLAST PERFORMANCE OF REINFORCED CONCRETE BEAMS

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Abstract

This paper presents the results from an experimental program which examines the behaviour of UHPFRC beams under simulated blast loads. As part of the study a series of three large-scale reinforced concrete beams are tested under blast loads using the Shock-tube at the University of Ottawa. The specimens include one beam built with conventional high-strength concrete (HSC) and two beams built with Compact Reinforced Composite, a proprietary UHPFRC. The effect of UHPFRC on blast behaviour is examined by comparing the mid-span displacements, blast resistance and failure mode of the beams. Overall the results confirm the superior blast resistance of UHPFRC when compared to conventional high-strength concrete. In addition to reducing displacements at equivalent blast loads, the use of UHPFRC in beams leads to an ability to resist greater blast loads. The addition of high-strength reinforcement in the UHPFRC beams further improves blast resistance.

Résumé

Cet article présente les résultats d'un programme expérimental qui examine le comportement de poutres en BFUP sous l'effet de charges explosives simulées. Dans cette étude trois poutres de grande taille sont testées au souffle en utilisant le tube à choc de l'Université d'Ottawa. Les corps d'épreuve comprennent une poutre en béton à hautes performances (BHP) conventionnel et deux poutres en CRC®, un BFUP breveté. L'effet du BFUP sur la réponse au souffle est étudié en comparant le comportement des poutres en termes de déformations à mi-portée, de capacité ultime et de mode de rupture. Les résultats confirment la résistance supérieure des BFUP aux effets de souffle par rapport au BHP. En plus de réduire les déformations sous l'effet de charges semblables, l'utilisation du BFUP augmente la capacité des poutres à résister aux charges de souffle. L'utilisation d'armatures à haute résistance dans les poutres en BFUP améliore encore la résistance au choc et au souffle.

1. INTRODUCTION

Recent developments in materials science have led to the emergence of a new generation of high-performance concretes with impressive properties. Ultra-high performance fibre reinforced concrete (UHPFRC) is a promising material in this category which has the potential of revolutionizing the construction industry. This advanced material shows increased compressive strength, high tensile resistance and superior toughness when compared to conventional concrete, properties make this material very well suited for heavily-loaded structural applications. The high toughness and fragmentation resistance of UHPFRC also make it an attractive material for use in the blast-resistant design of structures.

This paper presents the results from an ongoing experimental program which is examining the behaviour of UHPFRC beams under simulated blast loads. As part of the study a series of three large-scale reinforced concrete beams are tested under gradually increasing blast pressures using a high-capacity shock-tube at the University of Ottawa. The specimens include one beam built with conventional high-strength concrete (HSC) and two beams built with Compact Reinforced Composite (CRC), a proprietary UHPFRC [1]. The effect of UHPFRC on blast behaviour is examined by comparing the mid-span displacements, blast resistance, damage tolerance and failure mode of the beams.

2. BACKGROUND

2.1 Previous research on the dynamic behaviour of UHPFRC

Recently, several studies have been conducted to examine the response of UHPFRC materials and structures under extreme dynamic loading (see Table 1). Several researchers have examined the impact response of UHPFRC at the material and structural levels, mostly on slabs and beams tested using drop-weight impact machines [2-5]. A relatively fewer number of studies have focussed on blast behaviour, with most existing research conducted on one-way panels tested under close-in explosions [6-12].

The impact performance of CRC (the UHPFRC used in this research) under high stress-rates has been studied by Bindiganavile et al. [5]. In this study, CRC flexural beams having dimensions of 100 mm x 100 mm x 350 mm were tested under quasi-static and impact loads using an instrumented impact machine (with drop-heights of 250, 500, 750 and 1000 mm). Companion specimens built with steel fibre reinforced concrete (SFRC) and polymeric fibre reinforced concrete (PFRC) were also tested. The performance of the beams was compared in terms of peak load and toughness (area under the load-deflection curve). The study found the peak load and toughness of CRC increased with increasing stress-rate. The authors noted that while SFRC and PFRC shows brittle response with increase in drop-height, CRC showed improved performance. Moreover, the authors noted that brittle behaviour, a characteristic of high stress-rate response, manifests itself only at very large stress rates for CRC.

The performance of CRC under blast loading has been studied by Aoude et al. [12]. In this study, reinforced concrete columns built with CRC and conventional concrete were tested under shock-tube induced blast loading. The results demonstrated the superior blast performance of the CRC columns, with increased blast resistance, better control of displacements, and increased damage tolerance when compared to conventional RC columns. The performance of the CRC columns was found to be positively affected by an increase in fibre content, use of fibres with enhanced properties, use of seismic detailing and increase in longitudinal steel reinforcement ratio.

Table 1: Previous studies on the impact and blast behaviour of UHPFRC

Author	Testing method	Type of Specimen
Habel & Gavreau [2]	Impact (Drop-weight)	One-way panels
Fujikake [3]	Impact (Drop-weight)	Beams
Yoo et al. [4]	Impact (Drop-weight)	Beams
Bindiganavile et al. [5]	Impact (Drop-weight)	Beams (unreinforced)
Cavill et al. [6]	Blast (Live explosive)	One-way panels
Ngo et al. [7]	Blast (Live explosive)	Prestressed Panels
Wu et al. [8]	Blast (Live explosive)	One-way panel
Barnett et al. [9]	Blast (Live explosive)	One-way panels
Ellis et al. [10]	Blast (Shock-tube)	One-way panels (unreinforced)
Yi et al. [11]	Blast (Live explosive)	Two-way panels
Aoude et al. [12]	Blast (Shock-tube)	Columns

3. EXPERIMENTAL PROGRAM

3.1 Specimen designs

Three reinforced concrete beams were built and tested in this research program. The beams were tested under gradually increasing blast pressures using the University of Ottawa Shock-tube. Table 2 summarizes the design details of the specimens.

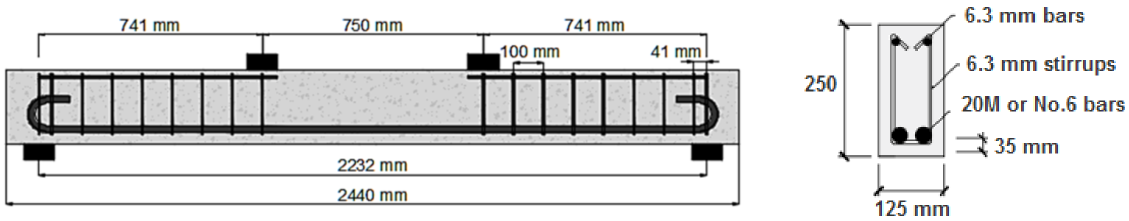


Figure 1: Beam dimensions and reinforcing details

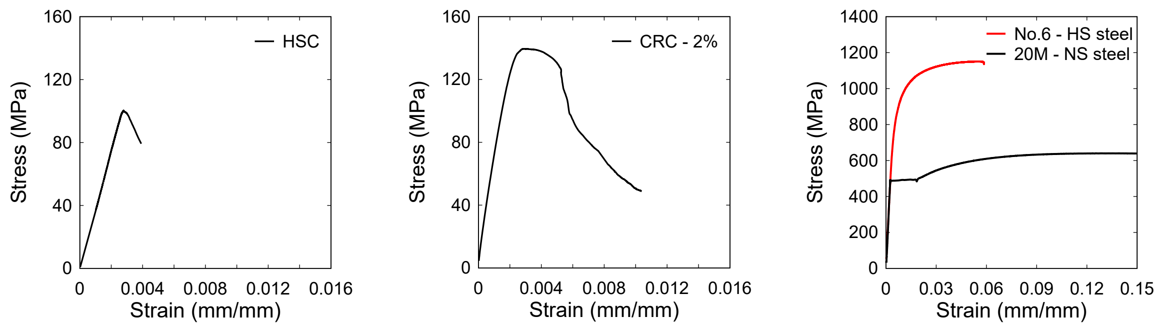
As shown Figure 1, the beams had dimensions of 125 mm x 250 x 2440 mm and were simply supported over a span of 2232 mm, with a constant moment region of 750 mm and two equal shear spans of 741 mm. One beam was cast with plain high-strength concrete (HSC) with the two UHPFRC beams cast with CRC. Longitudinal reinforcement in the HSC beam and one of the UHPFRC beams consisted of 2-20M Grade 400 MPa Canadian size bars (d_b = 19.5 mm, A_s = 300 mm^2), resulting in a reinforcement ratio of ρ = 2.4%. The remaining UHPFRC beam was built with 2-No.6 American Size (d_b = 19 mm, A_s = 284 mm^2), ASTM A1035 high-strength (MMFX) reinforcing bars. The beams were reinforced with U-shaped stirrups, made from 6.3 mm diameter smooth steel wire, spaced at 100 mm in the shear spans. To facilitate constriction 2 – 6.3 mm bars were also provided at the top of the beams in the shear spans. Specimen nomenclature reflects the design details of the beams, and includes information on: concrete type (HSC vs. CRC), longitudinal reinforcement size (20M or No.6 bars) and steel type (normal-strength or high-strength; where "HS" indicates the use of high-strength bars).

Table 2: Beam test matrix

Beam I.D.	Concrete Mix	Concrete Strength f'c (MPa)	Steel fibre properties		Steel reinf. properties	
			Length/dia. (mm/mm)	V_f (%)	Type	Flexural Steel
HSC-0-20M	HSC	104	-	-	Normal	2 - 20M
CRC-2%-20M	CRC	154	13 /0.20	2.0	Normal	2 - 20M
CRC-2%-No.6(HS)		153		2.0	HS	2 - No.6

3.2 Materials

The high-strength concrete in this study had a target strength of 100 MPa. The mix contained cement, slag, silica fume, coarse aggregate (½" and ¾"), sand and liquid admixtures (super-plasticizer and set retarder). The UHPFRC specimens were constructed with CRC having a volumetric fibre content of 2%. The mix contains Portland cement, microsilica, quartz sand and admixtures which are incorporated into the mixture in the form of dry powder [1]. The fibres used in this study had a length of 13 mm, a diameter of 0.2 mm and a tensile strength of 2750 MPa. The properties of the concrete in terms of compressive strength, obtained by testing 100 mm x 200 mm cylinders, are summarized in Table 2. The normal-strength 20M longitudinal steel reinforcement had an average yield strength of 462 MPa, while the 6.3 mm steel wire used for the transverse reinforcement had an average yield strength of 645 MPa. The high-strength No.6 reinforcing steel had an average yield strength of 855 MPa (obtained using the 0.2% offset method) and an ultimate strength of 1153 MPa. Sample stress-strain curves for HSC, CRC and steel reinforcement are shown in Figure 2.



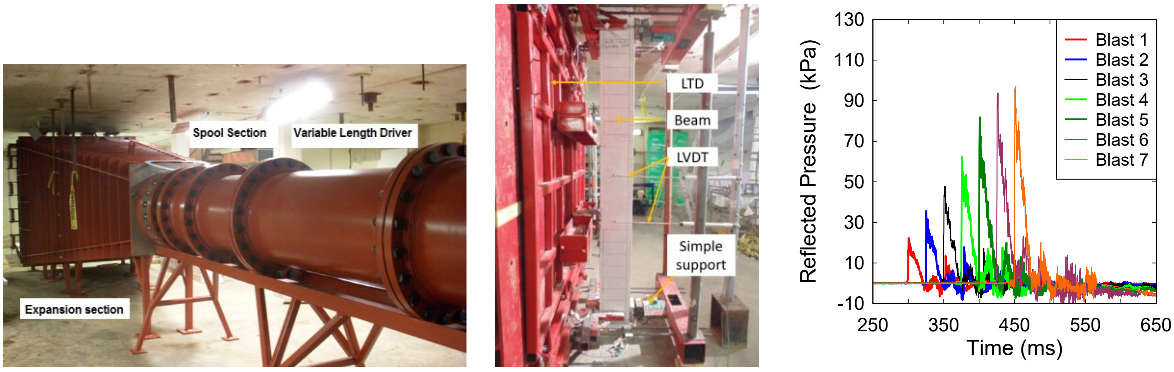
a) HSC (compression) b) CRC (compression) c) Long. steel (tension)

Figure 2: Material stress-strain relationships

3.2 Test setup

The University of Ottawa Blast Research Laboratory is equipped with a high-capacity shock-tube that can simulate the shockwaves generated by the hemispherical free air surface bursts of explosives. As shown in Figure 3a, the shock-tube consists of four main components: (1) a variable length driver section (which generates the shockwave energy), (2) a spool section (which controls the firing of the shockwave), (3) an expansion section and (4) a rigid end test frame (where specimens are attached). The square testing frame has a 2 m x 2 m opening. For beams and other non-planar elements, a load transfer device (LTD) is used to collect the shockwave pressure at the shock-tube opening and impart loading onto the structural member. In the current study, the LTD resulted in the application of blasts under four-point bending. Figure 3b shows a typical beam prior to testing. The beams were secured to the shock-tube using simple (pin) supports.

The shockwave parameters (reflected pressure, positive phase duration and reflected impulse) are controlled by adjusting the driver length and driver pressure. In the current study, the beams were tested under gradually increasing blast pressures until failure, with the driver length kept constant at 2743 mm and driver pressures increased in 70-140 kPa increments. Pressure measurements near the load transfer device were used to record complete reflected pressure-time histories for each test. Examples of the shockwaves for Blasts 1 (Impulse, Ir ≈ 240 kPa-ms) to Blast 7 (Ir ≈ 1080 kPa-ms) are included in Figure 3c. Shockwave properties are also summarized in Table 3. Complete displacement-time histories were recorded using two linear variable differential transducers (LVDT) placed at 1/2 (mid-height) and 1/3rd span of the beam (see Figure 3b). A high-speed camera was placed at the side of the beams during testing, and recorded response at a frame rate of 500 frames per second.



(a) Shock-tube components (b) Beam setup (c) Sample shockwaves

Figure 3: Beam setup for dynamic test

4. RESULTS

Table 3 summarizes the experimental results for the three beam specimens, including the shockwaves properties for each test (reflected pressure P_r, reflected impulse I_r, positive phase duration t_p) as well as beam response in terms of maximum (δ_{max}) and residual (δ_{res}) mid-span displacements and corresponding maximum support rotation (θ_{max}). Figure 4 shows the progression of damage and failure in the beams, while Figure 5 compares the displacement response of the beams at selected blasts.

Table 3: Blast test results

Beams	Blast #	Shockwave Properties			Displacement		Support Rotation
		P_r (kPa)	I_r (kPa*ms)	t_p (ms)	Max. (mm)	Residual (mm)	θ_{max}
HSC-0-20M	1	23.6	244.3	20.7	10.4	2.0	0.5
	2	39.2	360.0	18.4	15.1	0.2	0.8
	3	57.4	538.2	18.8	32.9	12.4	1.7
	4	68.8	702.6	20.4	118.1	71.7	6.1
CRC-2%-20M	1	23.6	234.3	23.9	4.6	1.3	0.2
	2	36.6	367.7	20.8	10.8	1.4	0.6
	3	55.0	549.8	21.6	16.8	2.4	0.9
	4	65.6	708.1	22.5	25.9	7.8	1.3
	5	77.2	831.8	23.4	48.5	25.3	2.5
CRC-2%-No.6(HS)	1	22.3	246.3	23.9	6.0	1.2	0.3
	2	35.7	361.5	20.3	11.0	0.4	0.6
	3*	*Data not captured					
	4	62.2	720.5	22.1	25.0	1.3	1.3
	5	81.9	906.0	22.5	33.8	1.3	1.7
	6	94.2	1085.2	23.4	49.8	16.6	2.6
	7	97.7	1078.4	23.4	98.4	67.3	5.0

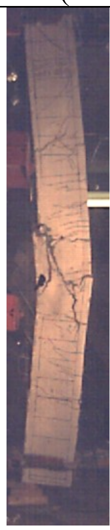
Blast 4			Blast 5		Blast 7
HSC-0-20M	CRC-2%-20M	CRC-2%-No.6(HS)	CRC-2%-20M	CRC-2%-No.6(HS)	CRC-2%-No.6(HS)
					

Figure 4: Beam damage progression after blast testing

4.1 Beam HSC-0-20M

Beam HSC-0-20M was constructed with high-strength concrete and 20M normal-strength steel. Blast 1 and Blast 2 were meant to test the beam within the elastic range, and resulted in cracking of concrete and small residual displacements. The reinforcement in the beam yielded after blast 3, resulting in larger residual displacements, and an increase in crack widths. Blast 4 was the last shot for this specimen and resulted in maximum and residual displacements of 118 mm and 72 mm. As shown in Figure 4, failure occurred in the compression zone due to severe concrete crushing at mid-span. High-speed video shows the generation of significant secondary fragments at failure.

4.2 Beam CRC-2%-20M

Beam CRC-2%-20M had identical properties to HSC-0-20M but was constructed with UHPFRC (CRC having 2% fibres). Blast 1 and Blast 2 kept the longitudinal tension reinforcement within the elastic range and resulted in hairline cracks in the constant moment region. Blast 3 pushed the tension steel into the inelastic range but caused no major increase in damage. The beam survived Blast 4, showing the benefit of the use of UHPFRC with maximum and residual displacements of 25.9 mm and 7.8 mm. As shown in Figure 4, two major cracks formed at the point load locations, but were bridged by the fibres. Application of Blast 5 loads resulted in significant widening of the critical cracks with fibre pullout (width of ~ 10 mm), and therefore the specimen was deemed to have failed. The maximum and residual displacements for the last shot were 48.5 mm and 25.3 mm.

4.3 Beam CRC-2%-No.6 (HS)

The final specimen of the experimental program was constructed using UHPFRC and No.6 high-strength reinforcing bars. Blast 1 and Blast 2 resulted in limited strains in the high-strength tension steel bars; as a result the beam showed limited deformations. No data was captured for Blast 3, however, damage in the beam was negligible after this shot. Blast 4 resulted in mid-span displacement of 25 mm, with reduced residual displacement when compared to the previous specimen (1.3 mm vs. 7.8 mm). The beam survived Blast 5, showing the benefits of combining UHPFRC and MMFX high-strength steel. Further flexural cracks developed after this blast with the formation of inclined shear cracks in the shear spans. The beam was tested under two additional blasts, with failure ultimately occurring after Blast 7 due to damage in the midspan compression zone. High-speed video shows the beam generated very little secondary blast fragments at failure (see Figure 4).

5 DISCUSSION OF RESULTS

The effects of UHPFRC and high-strength steel were investigated in this research. The performance criteria used to asses the effect of the test variables includes: the magnitude of blast failure load, maximum and residual displacements and failure mode. The magnitude of blast failure load can be found in Table 3, and Figure 5 compares the displacements at selected blasts (complete displacement data can be found in Table 3).

5.1 Effects of UHPFRC on beam performance

Comparison between the behaviour of beams HSC-0-20M and CRC-2%-20M reveals the significant improvements in blast performance for the beam built with UHPFRC. The

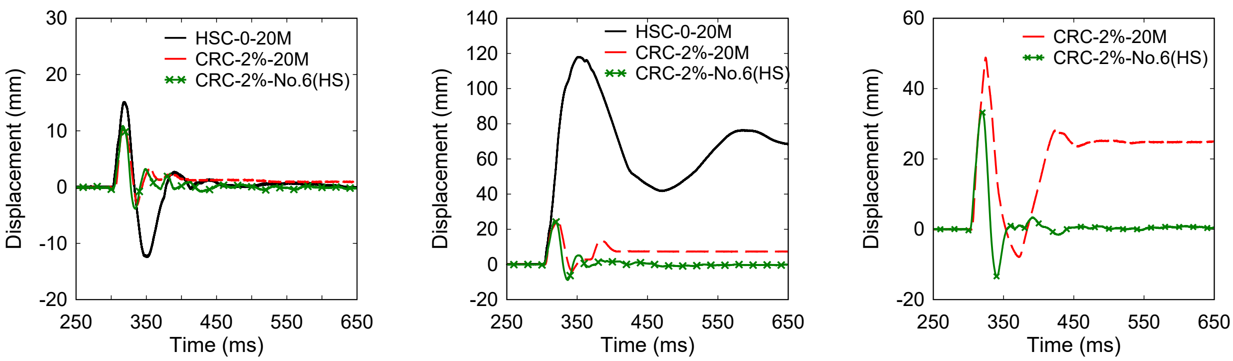
UHPFRC beam failed at Blast 5 due to fibre pullout, while the companion HSC beam, failed at Blast 4 owing to severe concrete crushing in the compression zone. The UHPFRC beam also showed improved behaviour in terms of reducing maximum and residual displacements. As shown in Table 3 and Figure 5, beam CRC-2%-20M reduced maximum displacements by 29%, 49% and 78% after Blast 2, Blast 3 and Blast 4, respectively when compared to the HSC beam. Residual displacements for the two beams were similar at Blast 2 since the steel was still within the elastic range. However, at Blast 3 and 4, beam CRC-2%-20M significantly reduced residual deformations by 81% and 89% when compared to the HSC beam. From high-speed video, failure of the HSC beam resulted in significant blast fragments, while the UHPFRC beam showed very little debris at failure.

5.2 Effects of combining UHPFRC and high-strength steel on beam performance

Comparison of the performance of beams CRC-2%-20M and CRC-2%-No. 6(HS) allows for a study of the effects of combining UHPFRC and high-strength steel. The use of high-strength steel in CRC-2%-No. 6(HS) allowed the beam to resist higher blast loads, with failure occurring at Blast 7, when compared to the companion UHPFRC beam with normal-strength steel which failed at Blast 5. It is noted that beam CRC-2%-No. 6(HS) also shows a 50% increase in failure impulse when compared to beam HSC-0-20M which was built with conventional materials (1078 vs. 702 kPa-ms).

Displacements are similar for the two UHPFRC beams at Blasts 1 and 2 since the steel reinforcement was still within the elastic range. No data was recorded at Blast 3 for CRC-2%-No. 6(HS). The beams experienced similar maximum displacements at Blast 4, however the use of high-strength steel in CRC-2%-No. 6(HS) significantly reduced residual displacement by 84% when compared to CRC-2%-20M. At Blast 5, maximum and residual displacements were reduced by 30% and 95% for the UHPFRC beam with high-strength bars when compared to the companion with normal-strength bars which suffered failure at this shot.

Failure of specimen CRC-2%-No. 6(HS) would occur at Blast 7. Despite the intense blast and damage, high-speed video shows no obvious secondary fragmentation at failure (see Figure 4) which contrasts the failure of beam HSC-0-20M which was built with conventional materials. In summary, the results show important benefits in the combined use of UHPFRC and high strength reinforcement in beams tested under blast loading.



(a) Blast 2 (b) Blast 4 (c) Blast 5

Figure 5: Mid-span displacement time-histories after Blast 2, 4 and 5

6 CONCLUSIONS

The following conclusions can be drawn from this study:

- The results demonstrate that using UHPFRC in beams improves blast performance by reducing maximum and residual displacements under equivalent blast loads and increasing overall blast resistance;
- The combined use of UHPFRC and high-strength steel reinforcement leads to further enhancements in the blast performance of beams and results in reduced displacements at equivalent blasts and increased blast capacity;
- The use of UHPFRC had an important effect of reducing damage and secondary blast fragments in beams subjected to extreme blast loading.

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