Blast testing of CFRP and SRP strengthened RC columns

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Abstract

Blast testing on scaled reinforced concrete columns was conducted to study the behaviour of Steel Reinforced Polymer (SRP) wrapped columns in both flexure and shear. Two vertical testing frames were constructed to support each two columns per blast in a fixed-fixed configuration while applying a static axial load of 300 kN. The specimens were exposed to blast waves at a variety of incident pressures which resulted in damage from minor to severe. A reflected impulse which resulted in moderate damage was then selected and used to study the effects of varying the density of SRP wraps. CFRP strengthening was also used in order to compare the effects of the two strengthening materials. An SRP/CFRP hybrid combination using SRP for longitudinal or flexural strengthening and CFRP sheets for transverse or shear strengthening was tested. It was observed that the SRP strengthened columns were quite similar to those strengthened with CFRP. The experimental results were compared to both analytical SDOF models as well as numerical models created using advanced explicit analysis software. SRP appeared to be a very effective external strengthening material for increasing the resistance of concrete components, providing similar performance to other FRP (CFRP) wraps at potentially lower cost. The SRP materials proved to be quite resilient even when exposed to a close-proximity explosion where spalling of the RC columns was significantly reduced.
Keywords: blast, reinforced concrete columns, SRP, CFRP, strengthening.

1 Background

During the past decade, significant research has been carried out on the strengthening of reinforced concrete (RC) slabs, beams and columns using

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externally bonded carbon fibre reinforced polymer (CFRP) sheets. CFRP sheets bonded to the surface of concrete members have been found to be an efficient and effective strengthening method that requires little heavy equipment or manpower to install but can significantly enhance their strength and serviceability. CFRP sheets have been proposed as a method of strengthening concrete and masonry components against the effects of blast. Initial tests show that they may be very appropriate for some blast strengthening situations [1]. Steel reinforced polymer (SRP) sheets have recently been proposed as an alternative to CFRP to strengthen reinforced concrete beams. Initial tests with the material applied to concrete beams indicates that SRP appears to have a much higher lateral shear strength and is much tougher than CFRP sheets [2]. Because of this property, SRP sheets may be more suitable than CFRP sheets for strengthening concrete components subject to blast. Early testing using SRP as transverse or shear strengthening for scaled columns [3] indicated both good structural performance of the wraps as well as high resilience when exposed to a near field explosion.

2 Experimental study

2.1 Concrete specimens

To determine the suitability of SRP sheets for strengthening RC members against the effects of blast loading, a series of destructive tests were conducted using explosives and scaled RC columns strengthened with various configurations of SRP and CFRP external strengthening. This program builds on the lessons learned from previous blast testing of SRP strengthened RC members (Carrière, 2004). Transverse and longitudinal cross-section profiles of these columns are shown in Figures 1 and 2, respectively. The concrete specimens were 150 mm by 150 mm in cross-section. The total length of the specimens was 2100 mm and the unsupported length during testing was 1500 mm. The section was reinforced with four 10 mm diameter reinforcing bars and 6 mm ties spaced at 100 mm. The 28-day compressive strength of the concrete was 44 MPa, the yield strength of the internal reinforcing steel was 450 MPa and the ultimate strength was 630 MPa.

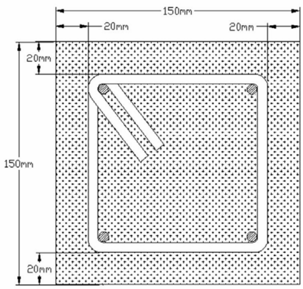

Figure 1: Transverse cross-section of RC specimen. Carrière (2004).

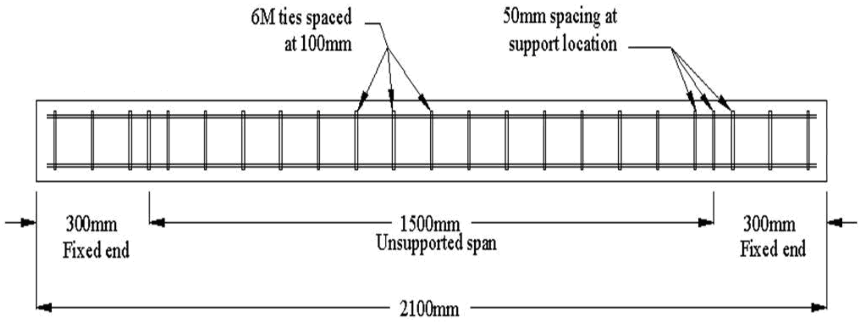

Figure 2: Longitudinal cross-section of RC specimen.

2.2 Specimen strengthening with CFRP and SRP

Specimens were strengthened with either MBrace® CF130 CFRP sheets or Hardwire® 3x2 SRP sheets in either the transverse and/or longitudinal direction. 300 mm at each end of each column specimen was strengthened using SRP sheets, where the columns were fixed into the testing frame, regardless of configuration. Specimen strengthening configurations were selected to facilitate several comparisons. These comparisons include varying the blast intensity for SRP strengthened (longitudinal and transverse) columns, varying the quantity of longitudinal SRP strengthening at a constant blast load, comparing the effect of longitudinal versus transverse strengthening, and finally comparing the effectiveness of CFRP v. SRP materials for strengthening in either the longitudinal or transverse direction. Numerous control columns were also tested. Specimen configurations are given in Table 1. Longitudinal strengthening, when applied, was only bonded to the side of the column opposite the explosive charge.

For this project, a high density 300 mm wide SRP tape was selected, with a 3x2 chord type and a protective brass coating. The epoxy used to adhere the SRP to the RC specimens was SikaDur® 330, a two-component, moisture-tolerant, high-strength, and high-modulus epoxy resin. Ancillary testing on SRP specimens (Prentice, 2006) indicated that the manufacturer's specified modulus and ultimate strength of 77.9 GPa and 1170 MPa respectively were representative of the material. These values were used for this project. CFRP strengthening materials used were MBrace® CF130 CFRP sheets. Ancillary testing on CFRP specimens carried out in prior projects indicated that the CFRP had a fibre modulus and rupture strain of 228 GPa and 1.67% respectively.

The initial step in fabricating the specimens was to prepare the concrete surfaces. Initially, the longitudinal sheet of 1500 mm was applied to the specimens. The width of the SRP sheet was 120 mm while the width of the CFRP sheet was 40.1 mm in order to achieve similar stiffness as the SRP. For the specimens wrapped with SRP, the SRP was first bent into square-shaped strips using a sheet metal bender. The length of each side of the square strip was

2 mm greater than the 150mm width of the RC members. Since the strips were cut to 700 mm lengths prior to bending, this resulted in a 92 mm overlap of the material. A 1 to 2 mm layer of epoxy was spread on the surface of the concrete member before the SRP strips were applied. Several wraps of copper wire were used to hold each SRP strip in place during curing. A final layer of epoxy was applied using the copper wire as a thickness gauge for the final layer. The RC member was clamped with strips of plywood that were wrapped in sheets of plastic and applied to all four sides. After curing for twenty four hours, the clamps and plywood were removed. All wrapped specimen dried for at least a week before being tested.

The methods used to strengthen the columns with CFRP sheets were similar to those used for SRP. For the columns with CFRP transverse reinforcement it was necessary to round the corners of the RC Columns to a radius of .02 m to avoid a premature failure of the CFRP.

Table 1: Specimen configuration and blast parameters.

	Specimen	Strengthening		Charge Weight (kg C4)	Range (m)
		Longitudinal (% SRP K)	Transverse ?		
Control	A1	nil	nil	65	4
	B1	nil	nil	65	5
	C1	nil	nil	100	4
	D1	nil	nil	100	5.25
	I1	nil	nil	49*	4
SRP	A2	SRP	SRP	65	4
	B2	SRP	SRP	65	5
	C2	SRP	SRP	100	4
	D2	SRP	SRP	100	5.25
	I2	SRP	SRP	49*	4
% SRP	F2	SRP	SRP	90	4.5
	E1	SRP (75%)	SRP	90	4.5
	E2	SRP (50%)	SRP	90	4.5
L v. T	G2	nil	SRP	100	5.25
	G1	SRP	nil	100	5.25
CFRP	F1	SRP	CFRP	90	4.5
	H1	CFRP	CFRP	100	4
	H2	CFRP (75%)	CFRP	100	4

Notes: K is equivalent stiffness of SRP application. No number implies 100%.
*Hemispherical charge.

2.3 Testing facility

Testing was conducted on a Canadian military establishment. Labour support for the testing program was provided by the Canadian Forces' 2 Combat

Engineer Regiment. To hold the RC specimens in place during the explosive testing, two steel vertical test frames were designed and constructed. Each frame was anchored and counter-balanced to resist the blast loading. The testing frame restrained a 300 mm length at each end of the specimen, resulting in a fixed-ended boundary condition.

To simulate column behaviour, it was necessary to apply an axial load to the specimens during blast loading. This was applied as a static load prior to each test. Hydraulic jacks were used to apply a 300 kN per column vertical compressive load to the extensible frame that constrained the columns. Threaded rods running through the frame were tightened into position and sustained the load at the start of the test. The jacks were removed prior to testing..

To facilitate the application of the blast loading, the explosive charge was placed on a platform at mid-column height a specified distance from the face of the column. Distances to the charge were measured to the centre of gravity of the charge. With two supporting frames, a maximum of 4 columns at 2 different distances were tested per explosive charge.

2.4 Testing program

The intent of this testing program was to examine the performance of various strengthening schemes, as noted in Table 1. Blast loads were applied that would cause moderate damage in the strengthened specimens, but were likely to heavily damage an unstrengthened column. As an ideal, it was preferred to increase both distance and charge size for equivalent blasts so as to approach planar blast waves and minimize fireball effects. Maximum charge size limitations and resource allocations also affected the blast load selections. The program planned with spherical charges but due to the softness of the ground, hemispherical charges had to be used.

2.5 Instrumentation

Instrumentation was mounted on the specimens and in the free-field in the vicinity of the explosions. Instrumentation included strain gauges, accelerometers and pressure transducers. High speed video also captured the explosion. The blast was initiated from, and all instrumentation and monitoring personnel were located in, an Armoured Data Acquisition Vehicle (ADAV), located approximately 100 m from the blast location. Four strain gauges were mounted on the reinforcement inside the concrete members to monitor any deformation inside the RC members during the residual strength testing. Two gauges were located at mid height of the column while two others were situated near the anticipated plastic hinge location at the support. Accelerometers were monitored with a WaveBook/516E™ 1 MHz Ethernet based portable high-speed waveform data acquisition system. Free field blast pressures were collected using five 34 MPa (5000 psi) PCB™ Free Field Blast Pressure Probes. These probes were used for each test and positioned at various distances and at right angles from the blast within the free field. Two probes were relocated for each test to be at the same distance from the charge as the column specimens in the two frames. The probes were positioned at a height of 1.5 m off the ground. This height was selected to avoid disturbances to the blast wave resulting from surface effects. Readings from the probes were made using an MREL® DataTrapII high speed data recorder that recorded channels at 5MHz per channel. Some columns were affixed with a Model 52 accelerometer by Measurement Specialties Inc. capable of measuring 2000g at 7 kHz. The accelerometers were affixed to the rear face at mid-height of the columns. High speed video of the explosions was recorded using an Olympus i-Speed video camera recording at 1000 frames per second (fps). All data acquisition units and the camera were initiated by trigger wired mounted around the explosive. C-4 explosive was arranged into either a square or hemispherical bundle for each test and was electronically detonated with the initiation originating at the centre of the bundle. The charge was placed on a wooden platform at the mid-height of the columns as shown in Figure 3.

Figure 3: Experimental setup in the field.

3 Experimental results

Summary results of each specimen tested are given in Table 2. Rotations are given at mid-height of the column based on the plastic deformation and mid-height displacements that were observed. Rotations are for the final static deformed shape of the column. Instrumentation difficulties with some of the accelerometers precluded reasonable calculation of the maximum dynamic deflections.

3.1 SRP and CFRP subjected to blast

For all tests the specimens were located between 4 and 5.25 m from the COG of the explosive. This caused each specimen to be exposed, in succession, to the high-pressure blast wave followed by the heat of the afterburn. Further, on inspection of the specimens, it was apparent that small debris objects acted as secondary projectiles and struck the specimens in numerous spots. Figure 4 shows some of the damage experienced by the SRP wrapped specimens. Areas where the epoxy resin has superficially delaminated are apparent as are small isolated damage areas due to the impact of debris projected during the blast. These damage areas tend to be localized and of a superficial nature.

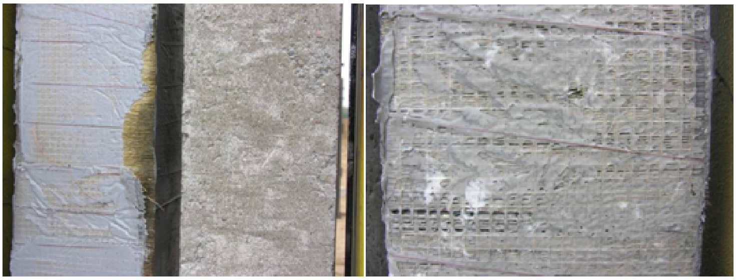

Figure 4: Blast Damage to SRP resulting from 49 kg blast. Some impact damage from debris was evident.

CFRP specimens also suffered damage to the laminate dependent on the magnitude of the blast experienced. Pieces of CFRP sheets were torn off of the columns in several places ranging from small to modest sized (150 mm). At equivalent distance and charge size, the SRP appeared to suffer less surface damage than the CFRP.

3.2 Reinforced concrete columns subjected to blast

The results of the RC columns subjected to blast are given in Table 2. Charge sizes were slowly increased during the early tests until a complete failure of the unstrengthened RC column was completely destroyed. Total destruction of the unstrengthend RC column occurred at a blast of 100 kg (C4) at a range of 4 m with significant damage and end rotation apparent in the specimen tested at 5.25 m at a charge of 100 kg. These related to peak overpressures of 1930 kPa and 1327 kPa for the partially damaged and fully damaged columns respectively. The strengthened columns were tested in this range in order to denote improvements relative to the destroyed control columns. (For all tests, the frame was not fixed to the ground so the columns were not exposed to the full effect of the pressure nor the impulse)

3.3 SRP Strengthened reinforced concrete columns subjected to blast

Columns fully strengthened with SRP in both the longitudinal and transverse directions were paired with the various control beams previously described. As would be expected, where insignificant damage to the unstrengthened columns was noted, the SRP strengthened columns were also undamaged. In the instance of the severely damaged control beam (4.6° mid-height rotation) its paired strengthened beam was only damaged slightly (1.2° mid-height rotation). In the case of the totally destroyed unstrengthened column, its matched SRP column suffered major deformations (6.3° mid-height rotation), including rupture of the SRP longitudinal strengthening but otherwise remained intact and able to carry significant residual load. Rupture of the SRP strengthening of Column C2 post residual axial testing is shown in Figure 5.

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For the series of columns with varying amount of longitudinal SRP, only slight damage was noted with little permanent deformation in the columns.

For the two columns which were strengthened with either longitudinal or transverse SRP, both exhibited minor permanent deflections (0.4 and 0.3 degrees respectively) of roughly the same magnitudes. Permanent cracks, delamination and spalling were evident in the specimen strengthened with longitudinal SRP only. The control beam tested at the same reflected impulse suffered major damage (4.6°) though it survived the blast. Notably, the column strengthened with SRP in both the longitudinal and transverse directions and loaded at the same reflected impulse had slightly higher permanent deflections (1.2°) than the columns strengthened with one or the other type of strengthening.

Table 2: Specimen results following blast.

	Specimen	Scaled distance Z	Rotation at mid height (degree)	Remarks
Control	A1	0.94	0	Intact
	B1	1.18	0	Intact
	C1	0.82	N/A	Total destruction
	D1	1.07	4.6	Cracks (up to 3mm), spalling
	I1	1.03	0	Intact
SRP	A2	0.94	0	Intact
	B2	1.18	0	Intact
	C2	0.82	6.3	Compression bulge, longitudinal SRP rupture
	D2	1.07	1.2	Cracks (up to 0.5mm)
	I2	1.03	0	Intact
% SRP	F2	0.95	0	Intact
	E1	0.95	0.9	Crack (1mm)
	E2	0.95	0	Intact
L v. T	G2	1.07	0.3	Cracks (up to 0.35mm)
	G1	1.07	0.4	Cracks, de-lamination, spalling
CFRP	F1	0.95	0	Small pieces of CFRP torn off (up to 3 cm long)
	H1	0.82	1.5	Cracks, small pieces of CFRP torn off, longitudinal CFRP rupture
	H2	0.82	1.3	Pieces of CFRP torn off (up to 15 cm long), longitudinal CFRP rupture

Applying SRP on RC columns required much less effort than the application of CFRP if the recommended surface preparation and rounding off of the corner for the CFRP application is considered.

3.4 CFRP strengthened reinforced concrete columns subjected to blast

The CFRP strengthened specimens (H1 and H2) tested at the equivalent charge/distance as an SRP strengthened column (C2) had less plastic deformation. The transverse reinforcement of the CFRP columns was 3 times the stiffness of the equivalent SRP strengthened column. This resulted from the desire not to leave gaps in the transverse strengthening. It was accepted that the transverse CFRP strengthened columns would be stiffer. The CFRP strengthened columns were bent locally at the plastic hinges but remained largely straight between the plastic hinges. Conversely, the SRP strengthened column had a distributed curvature along its full length.

Figure 5: Column C2 post blast and post residual axial testing. Some transverse strengthening removed.

4 Conclusions

The following conclusions are deduced from the experimental results:

- Significantly less damage was observed in columns strengthened with longitudinal and transverse SRP then in un-strengthened specimens
- Columns strengthened with SRP appeared to be more ductile the those reinforced with CFRP
- SRP appeared to better resist small projectile impact then CFRP

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