Post-Blast Axial Capacity of CFRP Strengthened RC Columns

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Abstract. An experimental investigation was carried out to evaluate the post-blast capacity of CFRP protected reinforced concrete (RC) columns. A total of five half-scale RC columns were tested under simulated blast pressures using a shock tube testing apparatus. Three columns were strengthened with CFRP laminates of two different lay-ups, while the other two columns were left unprotected to serve as control columns. Results of this study proved that CFRP protected RC columns have substantially higher blast resistant and post-blast axial capacity than as-built columns. CFRP protection laminates containing ±45° woven laminas showed the best performance with the most ductile response.

1. Introduction

Over the last two decades, a large number of civilian structures have become the target of terrorist attacks using car bombs. More than 14,000 global terrorist attacks, killing more than 20,000 people, were reported in 2007 by the US Department of State (Buchan and Chen, 2010). This highlights the vulnerability of critical infrastructure to the threat of blasts.

The significant dynamic loads formed by explosions can comprehensively damage critical structural components like columns. In multi-story buildings, the failure of a single column of the lower levels can lead to an overwhelming effect on the overall structural integrity (Agnew, 2007). Columns are responsible for the overall strength and stability of the structure, and their failure can result in high risk of developing progressive collapse. Past blast events showed that preventing progressive collapse can noticeably decrease the number of casualties. Hence, it is essential to ensure that all lower columns in multi-story buildings are blast-resistant against the threat applied. In this case, the progressive collapse can be mitigated, and the associated number of casualties can be minimized since blast-resistant columns can maintain sufficient post-blast axial capacities.

Application of surface-bonded or wrapped fibre reinforced polymer (FRP) laminates on existing RC structures is one of the most efficient blast retrofit approaches has been used in recent years. The exceptional engineering properties of FRP composites make them an excellent choice of material for
retrofitting. However, available research in this area is very limited (Buchan and Chen, 2007). This is due to the lack of comprehensive studies on the FRP in relation to their optimized micro design and performance under extreme shocks, the high cost of field blast, potential hazards during testing, and lack of experience in dealing with live explosives. Consequently, these tests have been limited to military and national security research projects, and results of such tests are often classified information and are not published. Therefore, the majority of structural engineers lack knowledge on performance and design of structures subjected to blast shock waves.

In recent years, new testing techniques have become available for simulating blast effects in a lab controlled testing environment with little potential for experimental hazards. The shock tube of the structures laboratory of the University of Ottawa is an example of such a highly controlled simulated blast testing facility. It provides a safe environment with little operating cost while generating blast pressures simulating the shock wave of a blast event. Previous studies only focused on investigating the performance of FRP strengthened RC columns protected by unidirectional fibres placed either in the transverse or longitudinal direction (UD 0° or UD 90°). The post-blast axial load capacity of FRP strengthened RC columns has not been evaluated. The current study aimed at investigating the post-blast axial capacity of non-seismically detailed RC columns wrapped with two different CFRP laminates in which different fibre orientations per laminas were used. This study is part of a larger joint research project between the National Research Council Canada (NRC) and the University of Ottawa that focused on the protection of existing critical concrete infrastructures against the effects of blasts using CFRP.

2. Experimental Program

A total of five non-seismically detailed RC columns were tested using the University of Ottawa shock tube facility. Three columns were strengthened with CFRP laminates of two different lay-up, each lamina formed from either a unidirectional fibre with a specified orientation or a woven fibre, while the other two columns were left unprotected. The description of test specimens, materials characteristics, including those of the CFRP laminates; test setup; and loading protocol, are presented in this section.

2.1. Description of Test Specimens, Material Properties and the Construction Process

All the RC columns investigated in this research program had 150 mm x 150 mm x 2438 mm dimensions. Each concrete column was reinforced longitudinally with four 10M rebars (reinforcement to gross cross-sectional area ratio, $\rho = 1.78\%$) and laterally with 6.3 mm diameter closed steel ties spaced at 100 mm. Concrete cover provided was 10 mm, measured to the exterior edge of the ties. Once the concrete casting process was over, the specimens were covered with two layers of wet burlap and plastic sheet for curing for 30 days. When curing period was over, the columns were kept in the NRC structures lab until the test date. All column corners were rounded to a radius equal to 10 mm to avoid stress concentration on externally applied CFRP. At the blast test dates, columns had a concrete compressive strength equal to 33 MPa.

2.2. Description and Application of CFRP Laminate

Three of the five columns were strengthened with selected configurations of CFRP laminates. These configurations include sequences of two type laminas: i) unidirectional CFRP, and ii) woven $[\pm 45^\circ]$ CFRP. In the unidirectional CFRP laminas, the fibres were oriented in one direction, while in the woven $[\pm 45^\circ]$ CFRP laminas, the fibres were weaved in two orthogonal directions. The wet lay-up process was used to ensure the continuity of the laminas. The epoxy-hardener ratio used for the resin was 1:3. The column surface was first prepared and vacuumed prior to the application of FRP layers to ensure a proper bond with concrete. CFRP laminas were cut to the desired length and dimensions. The unidirectional fibres in the hoop direction (transverse direction) are symbolized as UD [0°]. The fibres along the longitudinal direction of the column are labelled as UD [90°]. CFRP coupon tests were performed according to ASTM D-3039 specifications to establish the mechanical properties of each
CFRP laminate. Five coupons of 25 mm x 250 mm were cut from each CFRP laminate using a water jet cutting equipment to ensure a clean-cut, and to prevent any CFRP damage that might occur along the coupon edges. The stress-strain relationships obtained were always linear for all the different types of CFRP laminates considered in this study. The mechanical properties of the CFRP material tested is given in Table 1.

2.3. Test Matrix

Three CFRP strengthened RC columns, and two unstrengthened RC columns were tested under simulated blast loads. Test specimens had a concrete compressive strength equal to 33 MPa. Strengthened elements were bonded with two different CFRP multilayer protection system. The Test Matrix of the current study is given in Table-2.

2.4. Test Setup

All columns were subjected to lateral pressure simulating a blast-induced shock wave. Column specimen was installed at the front of the shock tube. The pressure produced by the shock wave was collected by a steel load transfer assembly covering the entire end of the shock tube, referred to as the “steel curtain” and transferred to the column as uniformly distributed load. The load transfer assembly consists of eight horizontal HSS ribs (76.2 mm x 76.2 mm x 6.3 mm thick) attached to a 2080 mm x 2080 mm x 0.71 mm thick steel sheet. The steel curtain transfers the simulated blast load by accumulating the shock wave pressure generated by the shock tube. Accordingly, the curtain is accelerated, and the dynamic pressure is transferred to equally spaced point loads distributed along the entire height of the column. This is illustrated in Fig. 1.

A quasi-static axial load system was used to apply the column axial load with appropriate boundary conditions prior to the application of blast loads. The system provides simply supported boundary conditions in the lateral direction with a roller and a pin at the bottom and top ends of the column, respectively, and a pin-pin boundary in the axial direction of the column. The lateral supports were spaced at 2200 mm c/c, supported by very stiff steel beams, which were attached to the body of the shock tube at the top and at the bottom, as shown in Fig.1. Axial load was applied by placing two hydraulic jacks with a capacity of 1500 kN each, at the column base. A load cell with a capacity of 2000 kN was mounted on the 910 mm thick reinforced concrete ceiling of the blast-laboratory to monitor the axial load-time history. The shock tube was controlled by a firing system to start the test. An ultra-high-speed data acquisition system with $10^6$ capacity of data point per second per channel was employed to monitor the test. Lateral displacements at column’s mid-span were monitored by two identical laser displacement sensors (Fig. 1). Both a high-speed video camera and a high definition still picture camera were used to capture the progression of the tests.

2.5. Test Procedure and Loading Protocol

2.5.1. Blast loading protocol

Once the column specimen was firmly attached to the shock tube, strain gauges, pressure sensors, laser displacement sensors, and the high-speed video camera were connected to the HPM data acquisition system. An axial load of 400 kN was applied prior to the tightening of the lateral supports. Then the driver section of the shock tube was filled with pressurized air up to the required level of pressure. Test started when the air pressure in the spool section was drained, causing an imbalance in pressures on either side of the aluminum diaphragm, causing it to puncture, rushing the pressurized air at supersonic velocities towards the expansion shock tube nozzle.

2.5.2. Testing post-blast axial capacity

The post-blast axial capacity of selected CFRP strengthened columns (columns that experienced small lateral displacement with no visual damage) was investigated experimentally. This test started after the lateral blast loading took place. At the end of the blast the column experienced a residual mid-height displacement. Upon releasing the axial load, this residual mid-height displacement
decreased to a lower value. A new axial load was applied monotonically until the maximum capacity of the column was reached. The application of the axial load continued until the failure of the test column. The test ended by releasing the axial load.

3. Results and Discussions

Columns of the current investigation were prepared in sets, where each set had two identical columns except that one set had only a single column. Columns in a given set were subjected to different levels of blast pressure and/or axial load, although the difference in load was small, sometimes resulting from unintended experimental variations. The first test was performed using a target blast pressure that was believed to bring the column to its capacity. This target pressure was
established based on previous tests and engineering judgement. Subsequent tests on identical columns of the set were conducted under either increased or decreased blast pressures and/or axial loads to capture the column capacity, while also investigating the effects of change in load on column performance. Often, the differences in test blast pressures and/or axial loads within the same set were small.

The results of the tests conducted in this study are summarized in Table 3. The firing parameters measured include driver pressure (\(P_D\)), reflected pressure (\(P_r\)), reflected impulse over the positive phase (\(I_r\)), duration of positive phase (\(t_d\)), and pre-blast axial load applied (\(AL\)). The experimental results include maximum and residual mid-height deflections (\(d_{\text{max}}\) and \(d_{\text{residual}}\), respectively), maximum support rotations (\(\theta_{\text{max}}\)), duration needed to reach maximum mid-height deflection (\(t_{\text{max}}\)), residual axial load (\(AL_{\text{residual}}\)), axial load at maximum mid-height deflection (\(AL_{\text{axial max}}\)), and the maximum applied blast force (\(F_o\)) which is equal to \(P_r\) times the area of the steel curtain of the shock tube (4.4 m\(^2\)).

By the end of the blast test, Columns C1.1 and C1.2 experienced substantial damage, and hence both columns had zero post-blast axial capacity. Columns C1.1(as-built), C2.1 (UD[0\(^\circ\)/90\(^\circ\)/0\(^\circ\])W[±45\(^\circ\)]2, and C3 (UD[0\(^\circ\)/90\(^\circ\)/0\(^\circ\)]) were subjected to blast loads of 200 kN, 200 kN, and 185 kN, respectively. Since these columns were tested under almost the same blast load, the comparison of their mid-height displacements would indicate the effects of different laminate designs on the column blast response. Fig. 2 shows that Columns C2.1 and C3 provided the best performance and their dynamic behaviours were very close to each other although Column C2.1 was subjected to a blast pressure 7.45 % higher than that for Column C3.

The post-blast axial capacity of C2 and C3 (CFRP protected columns) were investigated in the experimental program. These columns were tested for residual axial capacity because they did not experience large residual lateral displacements, and also did not have any visible damage after the blast test.

Fig. 3 compares the post-blast axial capacities of Columns C2 and C3. It is important to mention that the residual axial loads were released prior to the application of the post-blast axial loads. These columns were previously subjected to blast effects of varying magnitudes. Hence, the maximum and residual mid-height displacements and the residual axial loads applied were not the same as those attained at the end of the blast test.

It can be seen in Fig. 3 that Column C2, which is wrapped with CFRP laminate containing [±45\(^\circ\)] woven fabrics showed more ductile behaviour than Column C3 that contained unidirectional fibres only. Column C3 failed abruptly after yielding, whereas Column C2 sustained the applied axial load for relatively high post-yield mid-height displacements.

The post-blast axial capacity of 884 kN was recorded in Column C3. The multi-layer CFRP laminate bonded to this column contained three plies of unidirectional CFRP running in the hoop direction. Therefore, this column was expected to have an axial capacity higher than C2, which was 865kN.

Although the post-blast axial capacity of Column C3 was slightly higher than the capacity of Column C2, the overall axial behaviour of Column C2 was more ductile than Column C3. Furthermore, Column C3 was exposed to a blast load that was 11 % smaller than the corresponding load applied to Column C2. It can be concluded that, as in the case of columns subjected to blast pressures, columns tested under monotonically increasing axial compression showed a ductile failure mode when the CFRP jacket included fibres oriented in ±45\(^\circ\) orientation.

Results of the current investigation showed that CFRP strengthened RC columns have significantly higher blast resistance than the corresponding as-built columns. Furthermore, the CFRP laminates provide columns with enough post-blast axial capacity that can prevent the collapse of the entire RC structures (progressive collapse) when they are exposed to severe blast loads.
4. Conclusions

The following key conclusions can be drawn from the present experimental investigations:

• Among the two CFRP laminates investigated for column jacketing in this study, the laminate that contained laminas with ±45° woven fibres, in combination with laminas with unidirectional fibres placed in the column’s longitudinal and transverse directions, showed the best blast performance with the most ductile response.

• The residual axial load capacity and ductility of columns, established under monotonically increasing static loading improve with CFRP wrapped laminates. The column tests indicated that columns strengthened with CFRP laminates, especially those with ±45° fibres, showed more favourable blast performance than those non-protected columns.
### Table-1: Mechanical properties of the CFRP laminates

| CFRP Stacking Sequence | Thickness (mm) | Tensile Strength (MPa) | Modulus of Elasticity (GPa) | Rupture Strain | Tensile Strength (MPa) | Modulus of Elasticity (GPa) | Rupture Strain |
|------------------------|---------------|------------------------|----------------------------|----------------|------------------------|----------------------------|----------------|
| UD [0/90/0] W[±45]₂   | 2.86          | 242.9                  | 20.1                       | 0.013          | 466.2                  | 32.2                       | 0.013          |
| UD [0₂/90₀] UD [0]    | 3.48          | 326.8                  | 21.4                       | 0.012          | 475.4                  | 28.5                       | 0.013          |

### Table-2: Test Matrix

| Column Name | Column Type       | Number of Columns | CFRP Retrofitting | FRP Stacking Sequence | Type of CFRP Layer | Number of Plies/Layer |
|-------------|-------------------|-------------------|-------------------|-----------------------|-------------------|------------------------|
| C1          | Non-Seismic       | ² C1.1&C1.2       | As-built          | x                     | x                 | x                      |
| C2          | Non-Seismic       | ² C2.1&C2.2       | ✓                 | UD [0/90/0] W [±45]₂    | Lamina-1: Unidirectional 0 | 1                       |
|             |                   |                   |                   |                       | Lamina-2: Unidirectional 90 | 1                       |
|             |                   |                   |                   |                       | Lamina-3: Unidirectional 0 | 1                       |
|             |                   |                   |                   |                       | Lamina-4: Woven ±45 | 2                       |
| C3          | Non-Seismic       | 1                 | ✓                 | UD [0₂/90₀] UD[0]      | Lamina-1: Unidirectional 0 | 2                       |
|             |                   |                   |                   |                       | Lamina-2: Unidirectional 90 | 2                       |
|             |                   |                   |                   |                       | Lamina-1: Unidirectional 0 | 1                       |
| Col. | AL (kN) | PD (kPa) | Pr (kPa) | Ir (kPa.ms) | Id (ms) | Fp (kN) | d_max (mm) | θ_max (degrees) | t_max (ms) | d_residual (mm) | AL_residual (kN) | AL@d_max (kN) |
|------|---------|---------|---------|-------------|--------|--------|----------|---------------|----------|----------------|-----------------|--------------|
| C1.1 | 411     | 345     | 51      | 477.4       | 21     | 200    | 125.3    | 6.5           | 50.8     | 110.2          | 61.6           | 47           |
| C1.2 | 402     | 345     | 53      | 488         | 20.6   | 208.5  | 156.9    | 8.1           | 54.8     | 127.3          | 3.6            | 16.7         |
| C2.1 | 410     | 345     | 48      | 472.9       | 20.8   | 200    | 53.5     | 2.8           | 25.6     | 20             | 294            | 294          |
| C2.2 | 440     | 345     | 54      | 503.2       | 21.24  | 208.5  | 59.3     | 3.1           | 26.4     | 18.5           | 334            | 334          |
| C3   | 422.5   | 330     | 49      | 463         | 22     | 185    | 51.3     | 2.7           | 23.9     | 20.5           | 396            | 267.7        |
References
Agnew, E., Majanishvili, S., and Gallant, S., “Concrete Detailing for Blast”, Structure Magazine, January 2007.
Buchan, P. A., and Chen, J. F., “Blast Resistance of FRP Composites and Polymer Strengthened Concrete and Masonry Structures- A state-of-the-art review”, Composites: Part B38 (2007) 509-522.
ASCE. (2010). “Minimum Design Loads for Buildings and Other Structures”, ASCE/SEI 7, Reston, VA.
Sasani, M., Kazemi, A., Sagiroglu, S., and Forest, S., “Progressive Collapse of an Actual 11-Story Structure Subjected to Severe Initial Damage”, Journal of Structural Engineering, ASCE, September 2011.
Malvar, L. J., Crawford, J. E., and Morrill, K. B., “Use of Composites to Resist Blast” Journal of Composites for construction, ASCE, November-December 2007.
ASCE. (1996). “The Oklahoma City Bombing: Improving Building Performance through Multi-Hazard Mitigation”, Federal Emergency Management Agency, FEMA 277, ASCE, Reston, VA.