Effect of FRP Retrofitting on Post-Blast Axial Capacity of Reinforced Concrete Columns

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Abstract: An experimental study was performed to examine the enhancement in axial capacity of HP-CFRP wrapped reinforced concrete columns subjected to simulated air blast. Tests were conducted in an academic testing environment using a shock tube. Four half scale reinforced concrete columns (150 mm x 150 mm x 2438 mm) were tested under single blast shot. Two columns were externally strengthened with UD [0/90] W $[\pm45]_2$ UD [0] CFRP sheets, and the other two columns were left unprotected to serve as control columns. The columns were subjected to axial compression of 50 % of the column ultimate axial capacity. In order to examine the residual axial capacity of the tested columns, they were loaded axially up to ultimate load capacity after the application of the blast load. The damage generated at the critical zone was completely prevented by the application of the CFRP jacketing. It is found that columns externally strengthened with CFRP laminate are capable to carry high axial load compared to unprotected columns after a major blast event.

1. INTRODUCTION

The safety of critical infrastructure systems such as highway bridges and important buildings should be ensured against both unintentional and intentional hazards to ensure public safety, public security, and to minimize the disruption of services provided by these infrastructure systems and the associated socio-economic impacts. There is a growing concern with the security of North American's critical infrastructure that should be effectively protected to minimize its risk of failure due to extreme shocks induced intentional hazards such as blast due to explosives. An acceptable performance against extreme shocks can be achieved by providing practical and cost-effective protective systems for the critical concrete elements of bridges and buildings that are identified as vulnerable. Reinforced concrete RC structures that constitute the key load bearing elements of critical highway bridges and buildings should be designed or retrofitted to minimize-their risk of failure against extreme shocks such as blast. These critical RC structures should have adequate post blast strength and deformation capacity to reduce the risk of structural failure or progressive collapse. Limited studies haven carried out to investigate the effects of CFRP jacketing on the blast behaviour of RC columns[1, 2]. Thus, more research are required to fully understand the behaviour of these materials under the threat of explosion.

The objective of this study is to investigate the effect of high performance carbon fiber reinforced polymer HP-CFRP protection on the residual axial capacity and lateral damage of RC columns when subjected to simulated blast load. In this study, CFRP laminate is applied on the external surface of the column after rounding the column corners. Four protected and non-protected half scale concrete columns are tested using shock tube simulating blast loads (Fig. 1).

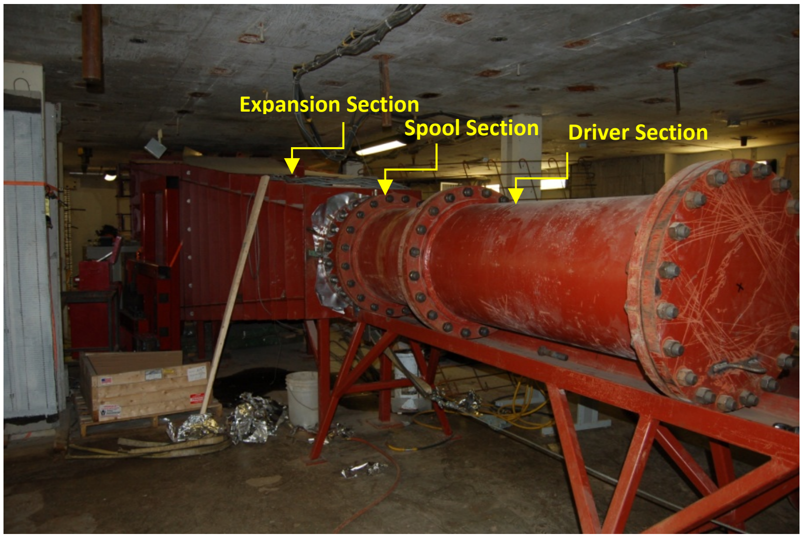


Fig. 1 Shock Tube Testing Machine – Structures Laboratory – University of Ottawa

2. EXPERIMENTAL PROGRAM

This experimental program aims at studying the effect of CFRP jacketing on the dynamic response and post-blast axial capacity of RC columns subjected to simulated blast load. Four half scale reinforced concrete columns were investigated under the effect of simulated blast pressure using the shock tube available at the structures laboratory of University of Ottawa. Two RC columns were left unprotected while the other two columns were retrofitted with CFRP laminate. The description of the specimen details, materials used, CFRP strengthening system utilized, test setup, and loading protocol are presented in this chapter.

2.1 Specimen Details

All RC specimens investigated in this research had 150 mm x 150 mm x 2438 mm dimensions. Wooden formwork was fabricated to attain the required geometry of the specimens. Each concrete column was reinforced longitudinally with 4-M10 deformed rebars, one at each corner. Columns were also reinforced laterally with 6.3 mm closed steel ties spaced at 100 mm c/c. Mechanical properties of the steel reinforcement employed in this experimental program are given in Table-1. Clear concrete cover provided was 10 mm. The columns were instrumented with 16 electric resistance strain gauges, placed on the steel reinforcement at various positions. Concrete used for casting the columns was supplied by a local ready-mix concrete company. Concrete compressive strength was 33 MPa. Once column's casting was over, all test samples were covered with two layers of wet burlap and plastic sheet and were left for curing for 30 days. Formworks were removed after 14 days. When curing period was over, RC specimens were kept in a lab environment until the test date. All columns' corners were rounded to a radius of 10 mm in order to prevent the premature CFRP wrap failure due to stress concentration at the edges of the retrofitted columns. Two columns were left unprotected to serve as control columns, while the other two columns were externally strengthened by CFRP warping. The stacking sequence adopted for the CFRP protection system applied was UD [0/90]-W $[\pm45]_2$-UD [0]. The CFRP jacket was applied to the entire height of the column, however 120 mm from each column's end was left unwrapped. A hand lay-up procedure was employed to apply the CFRP layers to the columns. Epoxy- hardener ratio used was 1:3. Tensile strength, modulus of elasticity, and strain at rupture of the CFRP laminate used is given in Table-2. Results shown in table-2 were obtained from the tensile test of five CFRP coupons.

Table-2 Steel Reinforcement Mechanical Properties

	M10 (11.3 mm longitudinal rebar)	6.3 mm closed steel tie
Yield Stress, f_y (*MPa*)	572	521
Yield Strain, ε_s (*MPa*)	0.0025	0.0045
Ultimate Stress, f_u (*MPa*)	748	578
Ultimate Strain, ε_u (*MPa*)	0.0771	0.0405

Table-2 CFRP Laminate Mechanical Properties

Stacking Sequence UD-[0/90/0] W-[±45]$_2$	Tensile Strength (MPa)	Modulus of Elasticity (GPa)	Rupture Strain
(longitudinal direction)	243	20	0.0126
(hoop direction)	466	32	0.0134

2.2 Test Setup

All samples were subjected to transverse loading simulating a blast induced shock wave. The tests were conducted using the shock tube testing machine at the structures laboratory of the University of Ottawa. The tested columns were installed at the front of the shock tube. The blast pressure produced by the shock wave was transferred to the test specimen by a “lateral load transfer element” LLTE. The LLTE is formed from a thin steel plate stiffened by eight horizontal HSS ribs (76.2 mm x 76.2 mm x 6.3 mm and 2438 mm long) mechanically attached to a 2438 mm x 2438 mm x 0.71 mm thick steel sheet. This loading approach is based on accumulating and transferring the pressure generated by the shock tube through the LLTE to equally spaced loading strips distributed along the entire height of the column (Fig. 2).

A simply supported boundary in the lateral direction is providing through a steel roller at the top and bottom of the column. These lateral supports are spaced at 2200 mm c/c, and they are attached to the body of the shock tube at the top and bottom by four 15.9 mm steel bolts at each of the column ends. This prevented the lateral movement at the ends while permitting full rotation[3]. Axial load was applied by placing two hydraulic jacks with a capacity of 1500 kN each, at the column base. The axial load is transferred to the column through a customized stiff steel element (Fig. 3). A customized spherical steel pin was placed on the column bottom to ensure a three dimensional rotation of the column when applying the axial load. A load cell with a capacity of 2000 kN was mounted on the 910 mm thick reinforced concrete ceiling of the laboratory to record the axial load (see Fig. 4). A high speed HPM data acquisition system was employed to collect the data. Lateral displacements at mid-span were accurately monitored by two laser displacement sensors (Fig. 2). Both a high-speed video camera and high definition camera were used to capture the progression of the test.

2.3 Testing Procedure and Loading Protocol

After the concrete element was firmly attached to the shock tube, the strain gauges, pressure sensors, laser displacement sensors, and the high speed video camera were connected to the data acquisition system. An axial load of about 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 section.

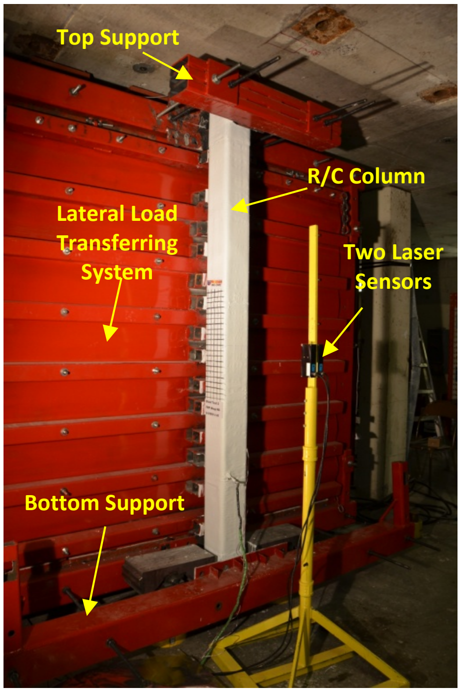


Fig. 2 Test Setup

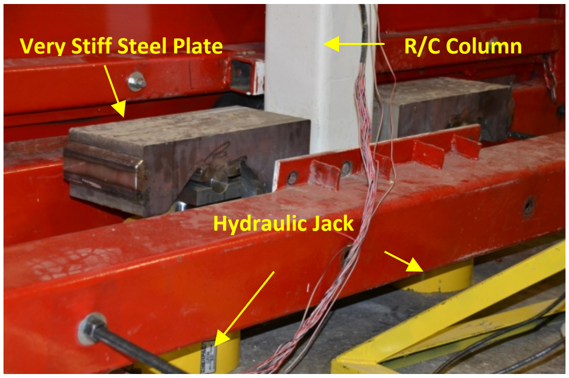


Fig. 3 Axial load system

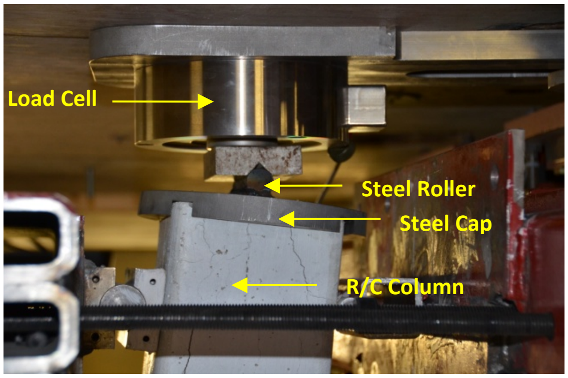


Fig. 4 Axial load monitoring

4. EXPERIMENTAL RESULTS

Test data included time history of; column's mid-height displacement, reflected pressure at the end of the expansion section, and axial load. All columns were subjected to a single shot action. Below is a description of each test.

As-built Col.1

Driver pressure selected for this test was 345 ±5 kPa. It can be seen from Fig. 5 that this driver pressure resulted in a peak reflected pressure of 51 kPa and a reflected impulse over the positive phase of 479 kPa.ms. The positive phase duration was 20.6 ms. Maximum and residual column's mid-height displacements were 125.3 mm ($\theta_{max.}$ = 6.5˚) and 110.2 mm respectively. Maximum mid-height displacement occurred at the instant 50.8 ms from the start of the test. Maximum axial load applied prior to the test was 411 kN, however the residual axial load was only 61.6 kN.

This test resulted in a complete crushing of the compression concrete and extensive tension cracks at the column's mid-height. Buckling of the longitudinal compression rebars was also observed at the critical section.

As-built Col.2

Driver pressure selected for this test was 345 ±5 kPa. It can be seen from Fig. 6 that this driver pressure resulted in a maximum reflected pressure of 53 kPa and a reflected impulse over the positive phase of 488.2 kPa.ms. The positive phase duration was 20.5 ms. Maximum and residual column's mid-height displacements were 156.9 mm ($\theta_{max.}$ = 8.1˚) and 127.3 mm respectively. Maximum mid-height displacement occurred at the instant 54.8 ms from the start of the test. Axial load applied prior to the test was 402 kN, however the residual axial load was only 3.6 kN.

This test resulted in a complete crushing of the compression concrete and extensive tension cracks at the column's mid-height. Buckling of the longitudinal compression rebars was also observed at the critical section.

CFRP Col.1

Driver pressure selected for this test was 345 ±5 kPa. It can be seen from Fig.7 that this driver pressure resulted in a maximum reflected pressure of 48 kPa and a reflected impulse over the positive phase of 472.9 kPa.ms. The positive phase duration was 20.9 ms. Maximum and residual column's mid-height displacements were 53.5 mm ($\theta_{max.}$ = 2.8˚) and 20 mm respectively. Maximum displacement occurred at the instant 25.6 ms from the start of the test. Axial load applied on the column prior to the test was 410 kN, however the residual axial load was 294 kN. At the end of the blast event, the column stayed intact and no visible damage was seen.

CFRP Col.2

Driver pressure selected for this test was 345 ±5 kPa. It can be seen from Fig. 8 that this driver pressure resulted in a maximum reflected pressure of 54 kPa and a reflected impulse over the positive phase of 502 kPa.ms. The positive phase duration of this test was 20.8 ms. Maximum and residual column's mid-height displacements were 59.3 mm ($\theta_{max.}$ = 3.1˚) and 18.5 mm respectively. Maximum displacement occurred at the instant 26.4 ms from the start of the test. Axial load applied prior to the test was 440.1 kN, however the residual axial load was only 334.1 kN. At the end of the blast event, the column stayed intact and no visible damage was seen.

5. DISCUSSION

The CFRP jacketing employed in this study significantly enhanced the dynamic behaviour of the RC columns when exposed to blast loads. Fig.9 compares the mid-height displacement time history of the as-built and CFRP modified columns investigated. It can be noticed that the maximum and residual mid-height displacements of CFRP Col.1 were 57.6 % and 82 % respectively smaller than the corresponding displacements of As-built Col.1. This is because the CFRP wrapping system applied increased both the flexural capacity and ductility of the RC member. The flexural capacity was improved by the additional tensile forces provided to the section by the longitudinal fibers, while ductility was modified by the confinement action provided by the fibers in the hoop direction. Concrete confinement enhances ductility by increasing the ultimate and maximum compressive strains of concrete and also by preventing buckling of the longitudinal compression rebars.

The significant damage observed in the as-built columns is completely prevented when the CFRP protection system was applied. This can be explained by the substantial increase in the column resistance. The CFRP wrap enhanced the concrete strength due to the confinement and works as an additional flexural reinforcement. Fig. 10 shows the post blast test damage noticed at the critical section in As-built Col.1. This damage can be categorized by the crushing of the compression concrete and the extensive tensile cracking at the plastic hinge region of the column. On the other hand, Fig. 11 shows the CFRP-Col.1 right after the application of the blast load. It can be observed that column CFRP-Col.1 stayed intact and no trace of damage was detected.

The pre-blast axial load applied on the investigated columns decreased while the columns displaced laterally during the blast test. Because the as-built columns experienced fairly large mid-height displacement when subjected to blast, the initial axial load applied dropped to almost zero at the end of the test. Conversely, the initial axial load applied on the CFRP jacketed columns dropped by only 28 % after the test. It is well known that the presence of the axial load on the section improves the flexural capacity and activate the confinement functionality of the wrapping CFRP.

The post-blast axial capacity of the CFRP protected columns was evaluated in the present study. As the control columns lost their axial capacity after the blast test due to their severe damage, hence no post-blast axial load is applied on them. On the other hand, at the end of the blast test, the residual axial load was completely released from the CFRP protected columns. While the column was still installed at the front of the shock tube, the axial load was reapplied gradually up to the column failure. The failure of axially loaded column can be identified by the point at which the column fails to carry more load. Column CFRP-Col.1 was axially loaded to 630 kN, then the loading was ended due to the crushing of the concrete at the top end of the column (Fig. 12.a). Note that the column ends were left unwrapped. The unwrapped length was 120 mm from each end. To prevent this premature failure, the top and bottom ends of column CFRP-Col.2 were wrapped by three layers of UD [0] CFRP fabric (Fig. 12.b). Post-blast axial capacity of column CFRP-Col.2 reached 860 kN. This indicated that the CFRP jacketing have improved the post-blast axial capacity of RC columns. This potent feature of the CFRP wrap is important in preventing any probable progressive collapse scenario in RC structures when subjected to blast threats.

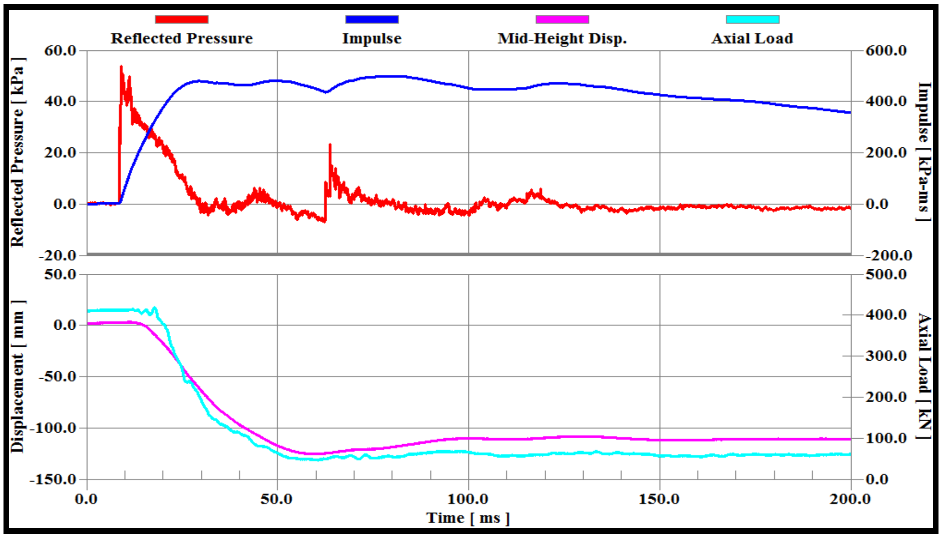


Fig. 5 Time history of; Reflected Pressure, Impulse, Mid-Height Displacement, and Axial Load for As-Built Col.1

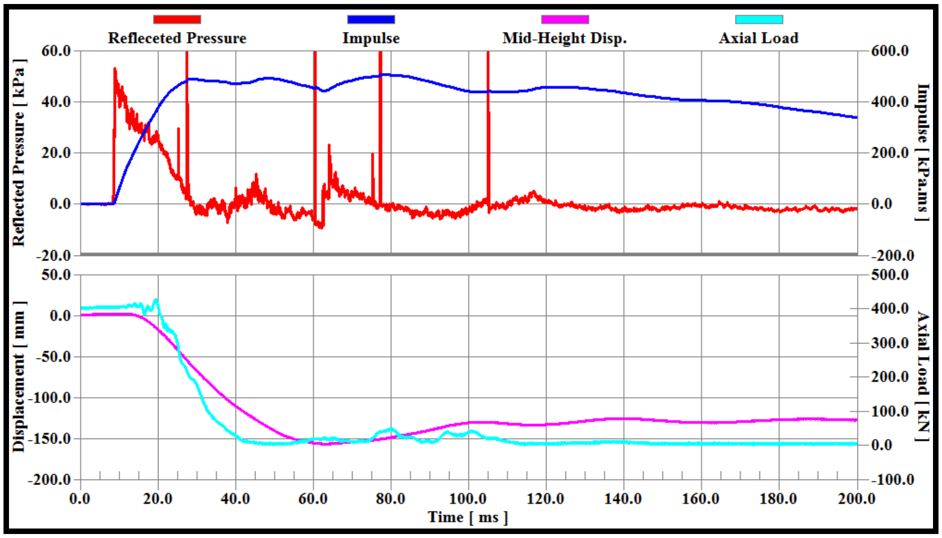


Fig. 6 Time history of; Reflected Pressure, Impulse, Mid-Height Displacement, and Axial Load for As-Built Col.2

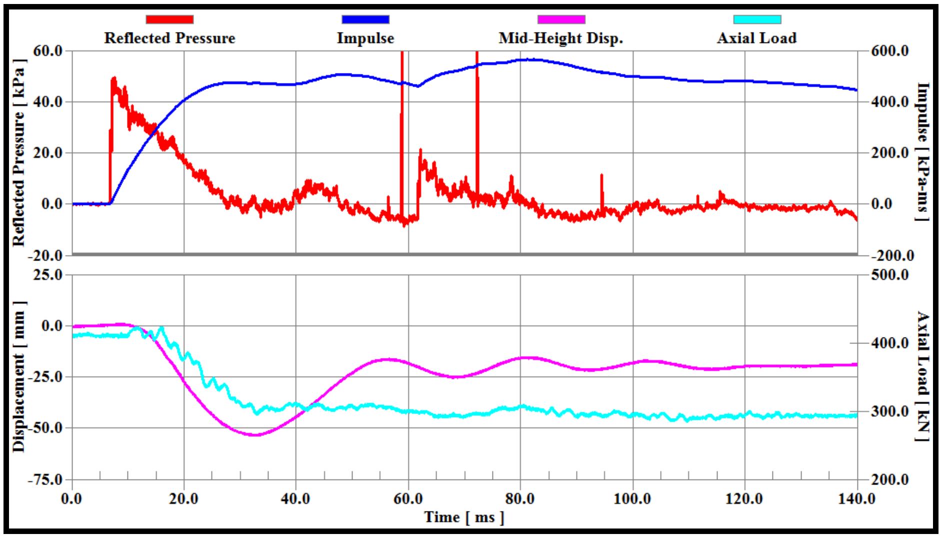


Fig. 7 Time history of; Reflected Pressure, Impulse, Mid-Height Displacement, and Axial Load for CFRP Col.1

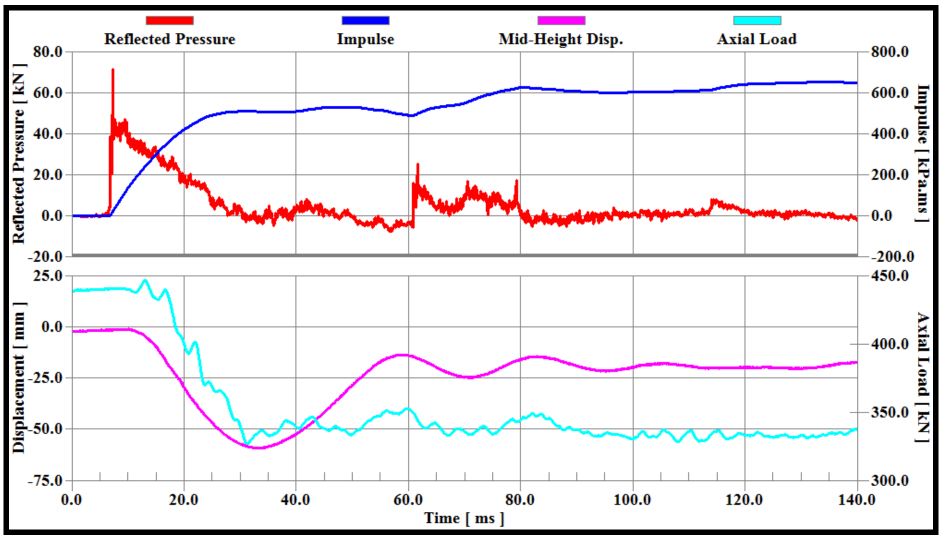


Fig. 8 Time history of; Reflected Pressure, Impulse, Mid-Height Displacement, and Axial Load for CFRP Col.2

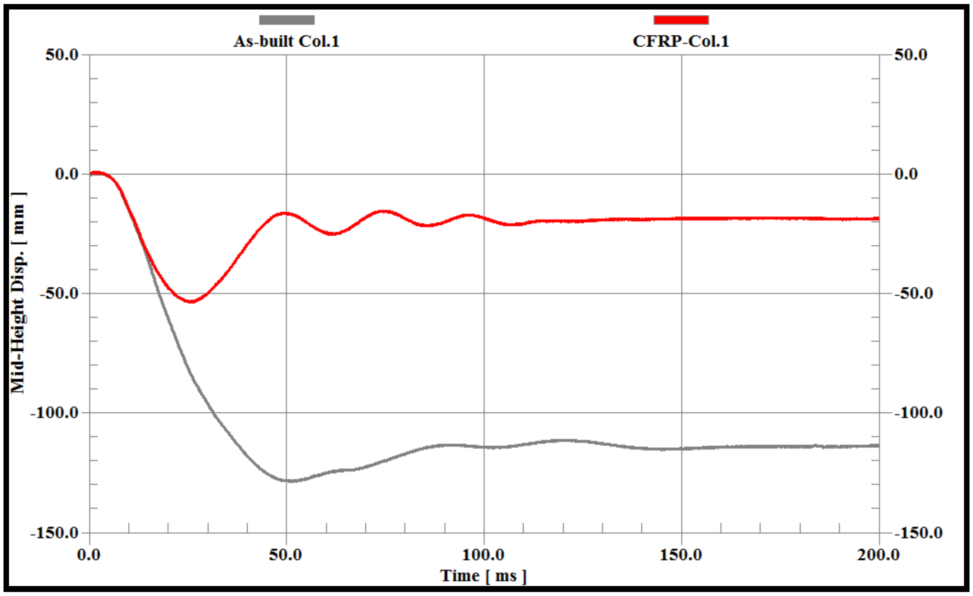
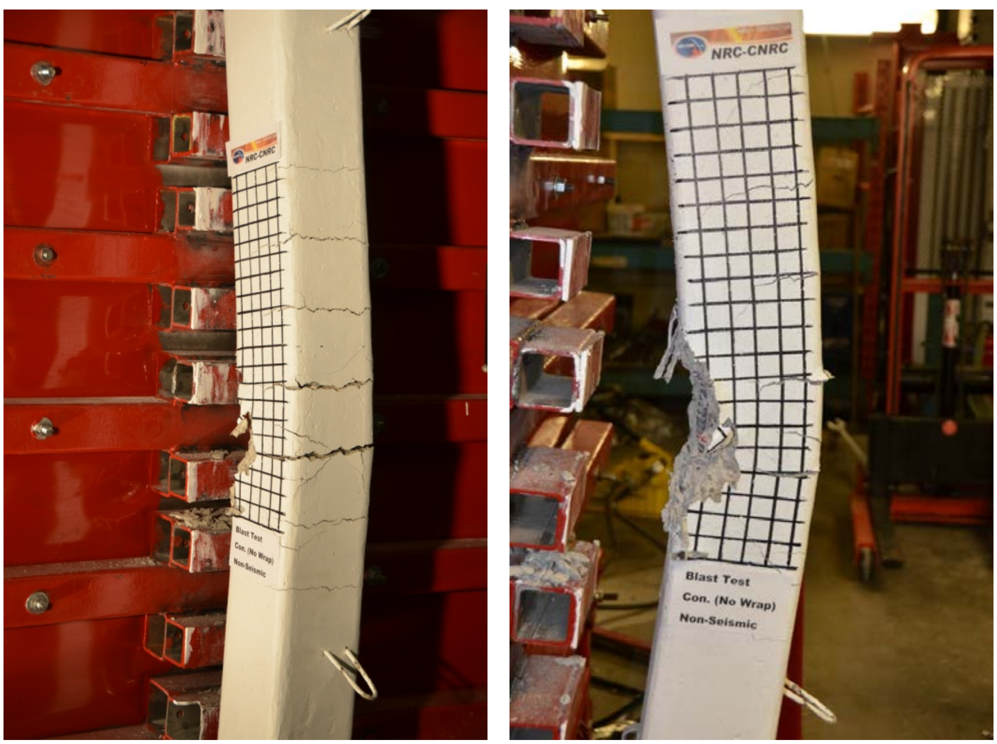


Fig. 9 Mid-height displacement time history of As-built Col.1 and CFRP-Col.1

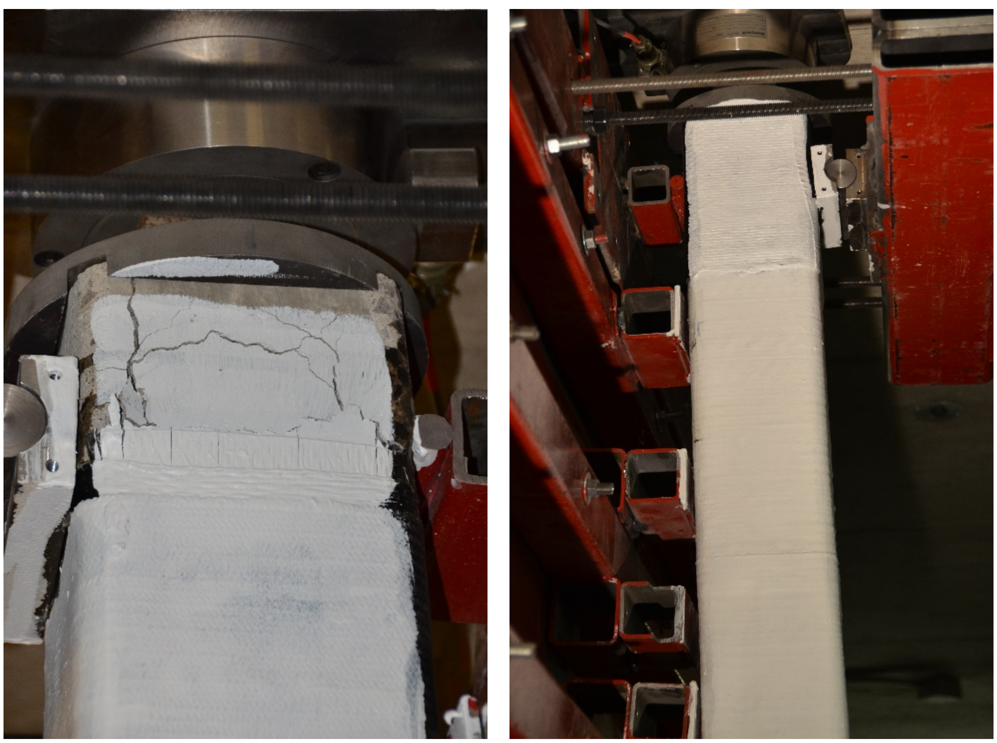


(a) (b)

Fig. 10 Level of damage of column As-built Col. front view b) side view

(a) (b)

Fig. 11Level of damage of CFRP Col. a) front view b) side view



(a) (b)

Fig. 12 Top end condition. a) CFRP-Col.1 b) CFRP-Col.2

5. SUMMARY AND CONCLUSIONS

In this investigation, four half scale reinforced concrete columns were subjected to simulated blast loads using a shock tube. Two columns were CFRP protected while the other two were left unretrofitted to serve as control columns. Maximum and residual displacement at the column's mid-height, degradation in the applied axial load, level of damage at plastic hinge region, and post-blast axial capacity of the columns were observed and discussed.

The lateral displacement due to blast load at column's mid-height was significantly reduced when the columns are protected using CFRP wrapping technique. This resulted in less degradation of the axial load during the blast test. Damage generated at the critical zone was completely prevented by the application of the CFRP jacketing. It is found that after a major blast event, RC columns externally strengthened with CFRP laminate are capable to carry high axial load compared to unprotected RC columns.

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