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RESIDUAL CAPACITY OF BLAST-DAMAGED REINFORCED CONCRETE COLUMNS

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Abstract: The aftermath of the Oklahoma City Bombing in the United States led to intense research in the progressive collapse potential of buildings subjected to blast loading. The research works did not, however, address situations where columns in buildings do not fail but suffer some amount of damage under the effect of blast loading. The challenge faced by blast hazard engineers is assessment and determination of residual capacity of blast-damaged columns. This paper presents the results of a residual capacity test program of blast-damaged full-scale reinforced concrete columns. Eight of the columns, previously tested under live explosion loading in the near-field ($z< 1.0$ m/kg$^{1/3}$) range were tested under static condition to determine their residual capacity. Four undamaged companion columns were also tested and their response compared with that of the blast-damaged columns. In general, two columns with different transverse reinforcement spacing were tested: conventional and seismic columns. The columns were subjected to axial compression loading up to the service load level of 1000 kN and then loaded in third-point lateral loading until failure. All the previously blast-damaged columns were capable of resisting the service load. Thus, they possessed enough post-damage strength to remain in service. The reduced transverse reinforcement spacing in the seismic columns resulted in a higher residual capacity compared to the conventional columns which had larger transverse reinforcement spacing. Also, the results show that the lower level of damage sustained by columns tested at larger scaled distance resulted in higher residual capacity.

Keywords: Residual capacity; Blast-damaged; Scaled distance; Near-field; Transverse reinforcement.

1. INTRODUCTION

The aftermath of the Oklahoma City Bombing and many other more around the world led to intense research into the progressive analysis of structures subjected to blast loading (Mlakar et al (1998)). Many researchers investigated the collapse mechanisms of columns under far-field blast loading while other investigated retrofit options for hardening structures against progressive collapse. The challenges faced by structural engineers, currently, is assessment and determination of residual capacity of blast-damaged structural elements. This will enable the assessment and identification of buildings that are unsafe for continual habitation or too expensive to repair. Whereas the damage suffered by columns to far-field blast can be global such as large permanent deflections, extensive flexural and shear cracking, damage suffered in the near-field is localised. Moreover, live explosion test results of full scale columns are lacking. Thus there is a need to investigate the response of reinforced concrete columns to near-field live explosion testing and the residual capacity assessment of such columns.

Many jurisdictions, including Canada are now developing standard for the design of buildings subjected to blast loading. Most buildings considered likely targets for terrorists' action however, are existing and predates these standards for blast-resistant design. Existing buildings are likely designed in accordance with seismic design guidelines and have been shown to have inherent resistance against blast loading (Kyei and Braimah (2017)). This paper reports on follow-on testing of reinforced concrete columns previously tested under near-field blast loading. The reinforced concrete columns were not specifically designed for blast load resistance but they were detailed in accordance with the Canadian standard for reinforced concrete structures (CSA (2004)) as columns for predominantly gravity load resistance or columns for gravity load resistance but also expected to have enough ductility to undergo the lateral deformations of the seismic force resisting system (SFRS).

2. BACKGROUND

Whereas much has been reported on the response of reinforced concrete columns to far-field blast loading, scant information exist on the response of these columns to near-field blast loading. Moreover, there is a dearth of knowledge on the residual capacity of blast-damaged reinforced concrete elements. Evidence of recent blast events in major cities around the world shows that explosions at standoff distances of more than 20 m to buildings generally cause damages to their façades with minimal impact on their structural integrity (Jayasooriya et al. (2011)). Bao and Li (2010) carried out a numerical study to investigate the dynamic response and residual axial capacity of twelve (12) reinforced concrete columns subjected to close-in blast loading. The effects of axial loads, transverse reinforcement spacing and longitudinal reinforcement ratio were investigated. The gravity axial loads were applied prior to blast loading and sustained during and after the blast loading. Bao and Li (2010) limited their research to close-in explosions and used a standoff distance of 5 m for their simulations. According to Bao and Li (2010), recent terrorist attacks on public structures involved explosions at a short standoff distance (less than 10 m). Thus the choice of 5 m for use in their research. The authors observed that increased transverse reinforcement ratio in columns resulted in commensurately higher loads to fail them. Higher longitudinal reinforcement ratios also increased the moment and axial load capacity of the columns. Based on their numerical study, Bao and Li (2010) concluded that seismic detailing significantly reduced the degree of blast induced damage and subsequent collapse potential of reinforced concrete columns. Other researchers (Wu et al. (2011), Fujikake and Aemlaor (2011)) conducted research on near-field explosion effects on reinforced concrete columns and reported that the transverse reinforcement ratio increased the residual capacity of reinforced concrete columns.

In summary, research on residual capacity of reinforced concrete columns have been carried out using numerical modelling with high fidelity physics based computer codes and scaled reinforced concrete columns. There is a lack of information on the behaviour of large (full) scale reinforced concrete columns under live explosion testing and even lesser information on the residual capacity of blast-damaged columns. It is essential that the residual capacity of columns be related to the blast damage they suffer under blast loading from a given charge mass and standoff distance (scaled distance).

3. EXPERIMENTAL PROGRAM

3.1 Description of Columns

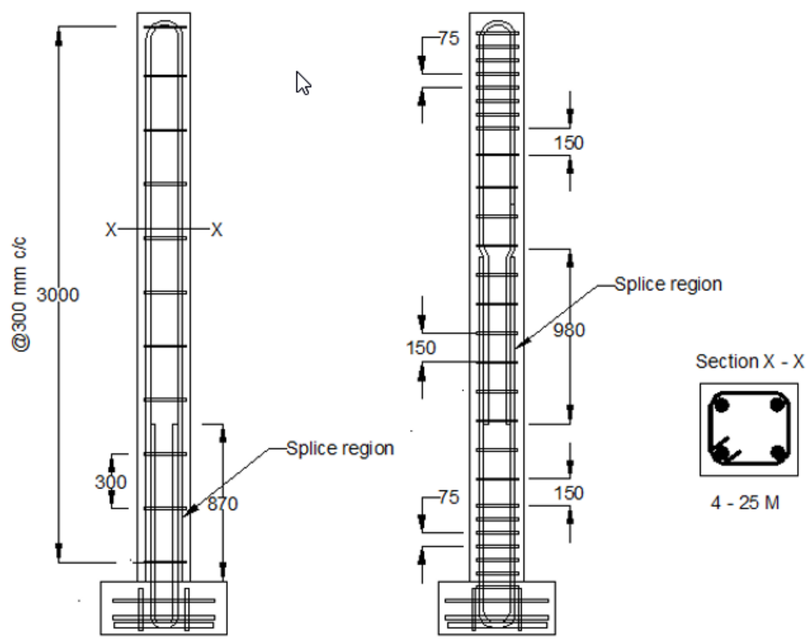
Twelve reinforced concrete columns were tested in this study. The columns had a 300×300-mm square cross section and an overall height of 3.2 m. The 28-day compressive strength of the concrete used was 41.3 MPa. The yield strength of the 25M longitudinal steel reinforcement was 474 MPa and for the 10M transverse steel reinforcement, 462 MPa. The reinforced concrete columns were cast integrally with 700×700 mm and 300 mm deep reinforced concrete footings.

Two types of columns were tested: Conventional and Seismic columns. The first type of columns was detailed with 10M transverse reinforcement spaced at 300 mm (Figure 1(a)) and termed conventional columns (CONV-#). These columns predominantly resist gravity loading. The second type of columns was detailed with 10M transverse reinforcement spaced at 75 mm within the plastic hinge zones at the top and bottom of the columns and at 150 mm between (Figure 1 (b)) and termed seismic columns (SEIS-#). The seismic columns were detailed to resist gravity loads while undergoing the lateral drifts of the

SFRS of the building but do not form part of the SFRS. Eight (8) of the columns were previously tested under live explosion testing at various scaled distances. The live explosion test results are reported elsewhere (Siba (2014), Braimah et al. (2015)). The columns suffered various levels of blast damage prior to residual capacity testing. The blast damage was caused by 150 kg of ammonium nitrate fuel oil (ANFO) at scaled distances to result in scaled distances less than 1.0 m/kg$^{1/3}$. The experimental design scaled distances were 0.25, 0.5 and 1.0 m/kg$^{1/3}$. However, the scaled distances achieved on site were slightly lower (Table 1). The four (4) columns not tested under live explosion testing are used as control specimen in the residual capacity testing.

Table 1: Summary of column details

Column designation	Tie spacing (mm)	Lap Splice (mm)	Scaled distance z (m/kg$^{1/3}$)	Permanent maximum displacement (mm)
CONV-06	300	870	0.53	33
CONV-07	300	870	0.58	64
SEIS-08	75	980	0.58	5
SEIS-09	75	980	0.52	25
CONV-11	300	870	0.88	30
CONV-12	300	870	0.82	29
SEIS-13	75	980	0.82	7
SEIS-14	75	980	0.86	16
CONV-16	300	870	Not tested	0
CONV-17	300	870	Not tested	0
SEIS-18	75	980	Not tested	0
SEIS-19	75	980	Not tested	0



(a) (b) (c)

Figure 1: Column details showing transverse detailing: (a) conventional columns (b) seismic columns (Siba (2014)).

Prior to the residual capacity testing the permanent deformation of the columns after the live explosion testing was measured and presented in Table 1. In general, the permanent deformations were lower for columns tested at a larger scaled distances in comparison with those tested at lower scaled distances. The permanent deformations were also lower for column with seismic detailing (closely spaced transverse reinforcement) in comparison with column with conventional detailing.

3.2 Test setup and procedure

The columns were loaded axially using a 1045-kN (220-kip) MTS 243.60T actuator. Figure 2 shows the experimental test setup. The lateral load was applied at third points using a 667-kN (150-kip) MTS 244.150 actuator. A hollow structural section, HSS 305×203×13 was used as a spreader beam to apply the lateral load at third-points (1 m and 2 m above the top of the footing) of the columns. The axial load was gradually applied in 50 kN increments in load-control mode up to the service load level of 1000 kN and then maintained throughout the lateral load testing. The axial service load induced an axial load ratio (ALR) of 0.32 in the columns. ALR is the ratio of the applied axial load to the axial load capacity of the column. The lateral load on the other hand was applied in displacement-control mode at a rate of 1.5 mm/minute.

Three string potentiometer were attached to the columns at third-points and at mid-height and used to measure lateral displacements along the column height. The top restraint of the column was built as a pin while the base was fixed against displacement and rotation by using two W-sections and high strength threaded rods anchored to the strong floor of the structures laboratory. The reinforced concrete columns were loaded against a reaction frame constructed from structural steel members and anchored to the strong floor of the structures laboratory.

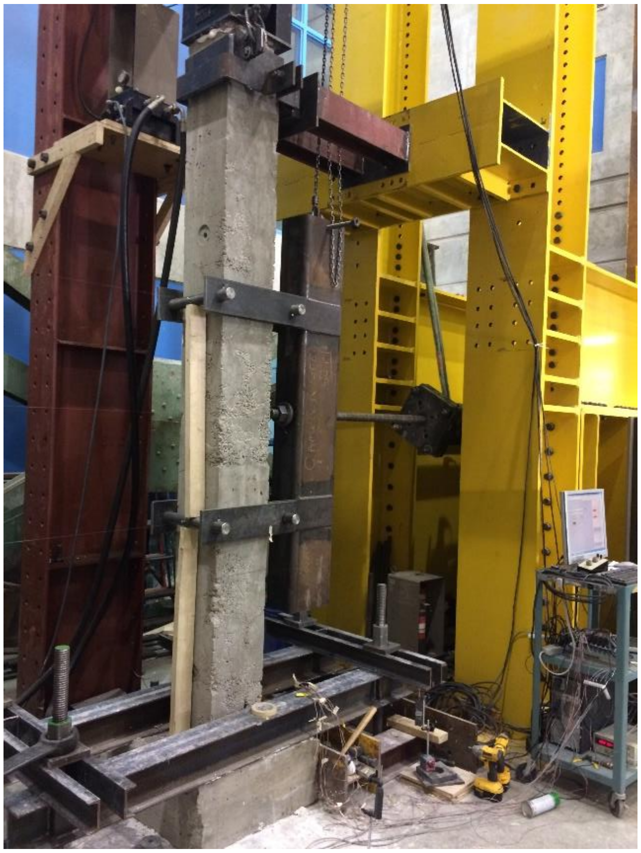


Figure 2: Photograph of experimental setup for residual capacity.

During construction of the reinforced concrete columns, 350-ohm resistance strain gauges were attached to the longitudinal reinforcements at predetermined locations. Details of the strain gauges and the location of their attachment is presented elsewhere (Siba (2014)). The data from the MTS actuators (load and stroke), column deflections from the string potentiometers and strain gauges were recorded on a computer-based data acquisition system.

4. PRESENTATION AND DISCUSSION OF RESULTS

Overall, all the columns tested in the residual capacity test program resisted the service load of 1000 kN without failure. Thus, even though damaged in the live explosion tests, the columns were able to resist their design level load without distress or failure. Hence the columns were loaded laterally to failure to assess their residual lateral load capacity. Once the columns attained their lateral load capacity, the axial load was gradually taken off to unload the column. Both the behaviour of the columns under axial loading and lateral loading were recorded and are discussed in this section.

4.1 Conventional columns

Figure 3 presents the lateral load-displacement response of the conventional columns. In general, columns exposed to ANFO explosion at a smaller scaled distance sustained lower lateral loads, i.e. possessed lower residual lateral load capacity under the service level ALR. Conventional column CONV-07 which was tested in the field at a scaled distance of 0.58 m/kg$^{1/3}$ exhibited a very high lateral load capacity. In fact the residual capacity of this column was higher than for the control columns tested under static conditions only. CONV-07 had the highest permanent deflection in a direction opposite the direction of lateral load application. This permanent deflection was increased under axial loading. Thus, under lateral loading, the axial compressive strain aided in the lateral load resistance resulting in very lateral load capacity. The control columns, CONV-16 and CONV-17, had lateral load capacities of 404.6 kN and 420.5 kN respectively. The capacities differed by less than 4%, hence the lateral load capacity of the conventional columns under ALR of 0.32 was assumed 412.5 kN (the average failure load of the control columns).

The conventional column tested in the field at a scaled distance of 0.53 m/kg$^{1/3}$ (CONV-06) exhibited a residual capacity of 37.4% of the control columns. Moreover, the columns that were tested in the field at a scaled distance of 0.88 m/kg$^{1/3}$ (CONV-11) and 0.82 m/kg$^{1/3}$ (CONV-12) exhibited residual capacities of 88.6% and 72.5% of the control columns, respectively (Table 2).

From Figure 3, it is clear that during application of the axial load to the service ALR of 0.32, some of the columns with pronounced permanent deflections experienced deflection growth due to P-δ effect. For columns CONV-06 and CONV-07, the deflection growth was restrained by the lateral actuator and shows increase in the lateral load.

Table 2: Summary of test results for CONV- # columns.

Column	Scaled distance, z (m/kg$^{1/3}$)	Axial load (kN)	Lateral load (kN)	Residual capacity (%)	Mid-height displacement (mm)
CONV-06	0.53	1000	154.2	37.4	9.4
CONV-07	0.58	1000	445.5	108*	29.78
CONV-11	0.88	1000	365.6	88.6	16.9
CONV-12	0.82	1000	298.9	72.5	17.4
CONV-16	0	1000	404.6	N/A	20.33
CONV-17	0	1000	420.5	N/A	25.0

**Permanent column displacement against lateral load application.*

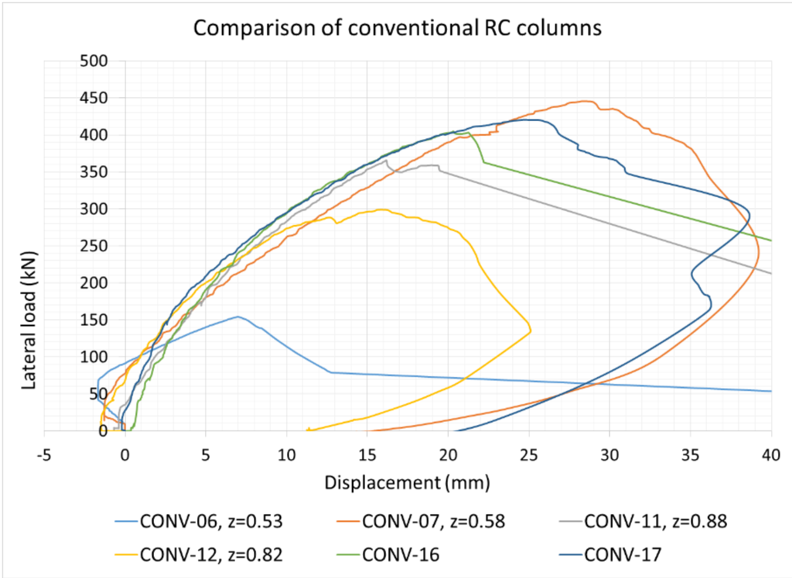


Figure 3: Lateral load versus mid-displacement for conventional columns

4.2 Seismic columns

Figure 4 presents the lateral load-displacement response of the seismic columns. SEIS-18 and SEIS-19, which were the control columns, had lateral loads capacities of 483.9 kN and 462.3 kN respectively. The average of the two (473.1 kN), is assumed as the lateral capacity of seismic columns under service level ALR. SEIS-08 and SEIS-09 tested in the field at scaled distances of 0.52 m/kg$^{1/3}$ and 0.58 m/kg$^{1/3}$ respectively exhibited lateral capacities of 67.3% and 61.9% of the control column capacity respectively. At the larger scaled distance, SEIS-13 and SEIS-14 tested in the field at scaled distances of 0.82 m/kg$^{1/3}$ and 0.86 m/kg$^{1/3}$ exhibited lateral capacities 97.5% and 88.0% of the control column capacity respectively.

As with the conventional columns, the deformation growth of SEIS-09 under the axial load regime was restrained. Thus Figure 4 shows increase in lateral load up to the lateral deflection level of about -1.6 mm. In general the initial stiffness (slope) of the seismically detailed columns appear to be similar.

Table 3: Summary of test results for SEIS- # columns.

Column	Scaled distance, z (m/kg$^{1/3}$)	Axial load (kN)	Lateral load (kN)	Residual capacity (%)	Mid-height displacement (mm)
SEIS-8	0.58	1000	318.5	67.3	16.03
SEIS-9	0.52	1000	292.9	61.9	15.6
SEIS-13	0.82	1000	461.2	97.5	22.82
SEIS-14	0.86	1000	416.4	88.0	23.2
SEIS-18	0	1000	483.9	N/A	23.6
SEIS-19	0	1000	462.3	N/A	24.2

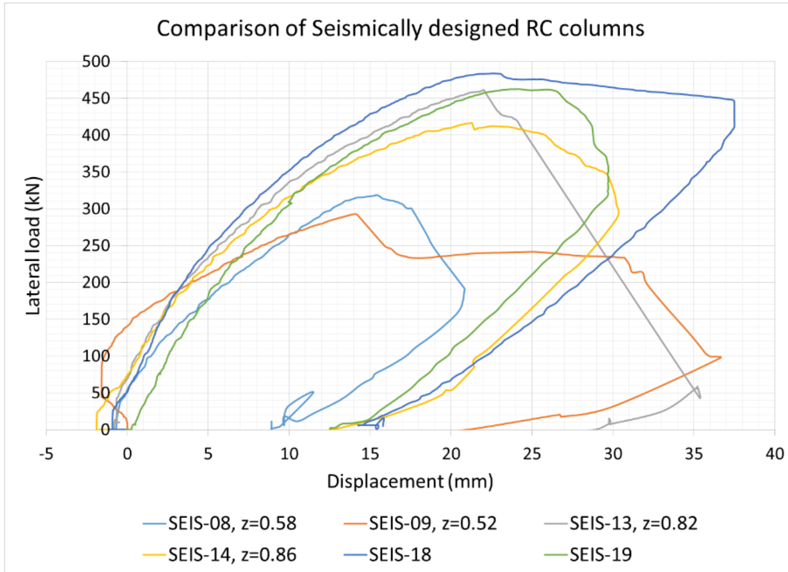


Figure 4: Load displacement curve for seismic columns

4.3 Constant scaled distance

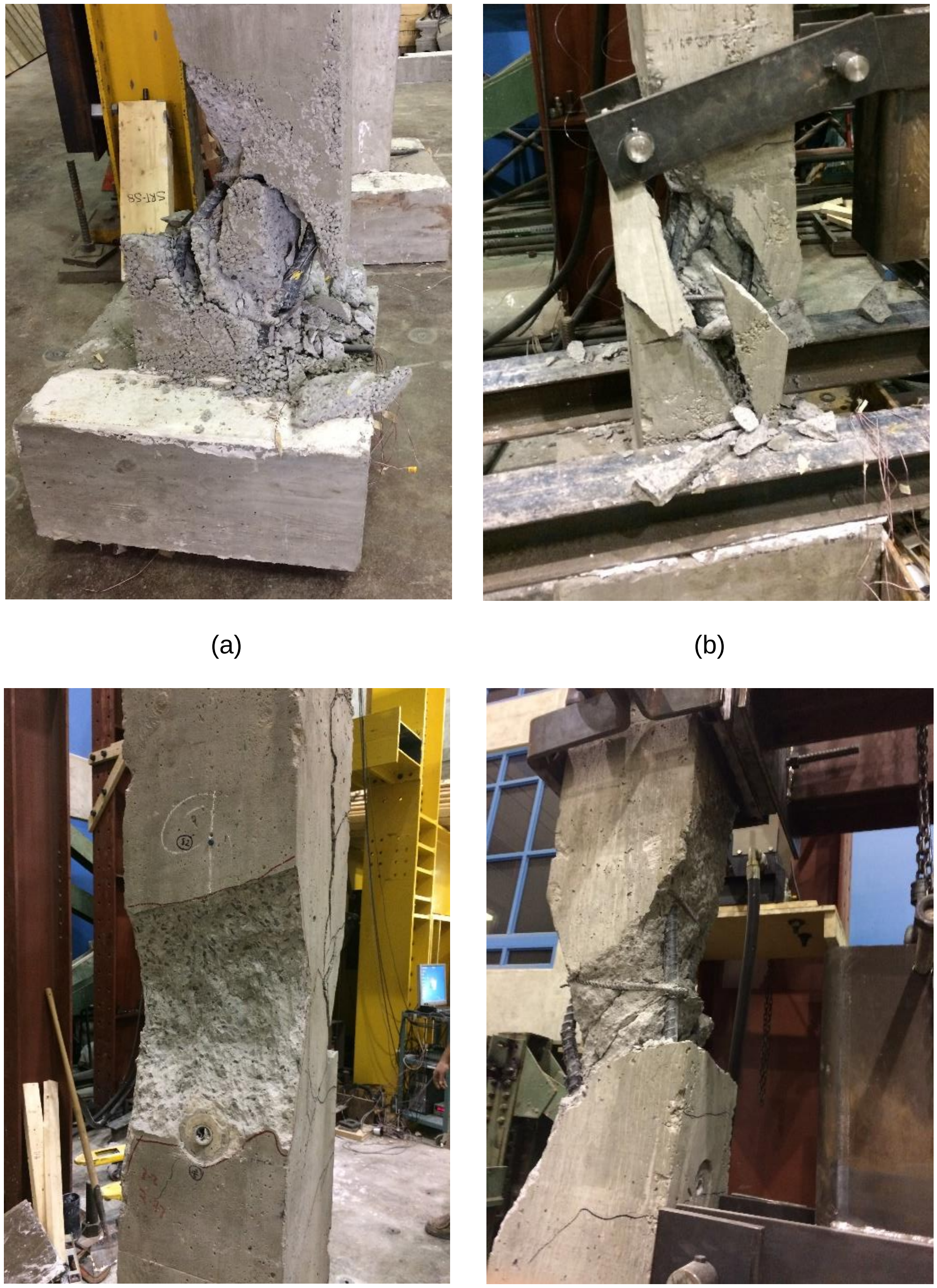
Four columns each were tested in the field under live explosion loading at a scaled distance of about 0.55 m/kg$^{1/3}$ and about 0.85 m/kg$^{1/3}$. Except for CONV-07 which exhibited a higher lateral capacity under the service level axial stress than expected, in general columns tested at a larger scaled distance had higher residual capacities. This is not unexpected as the larger the scaled distance the lower the blast damage suffered by the columns.

At comparable scaled distances, the seismically detailed columns exhibited higher residual capacities compared to the conventional. For example, at a scaled distance of 0.53 m/kg$^{1/3}$, CONV-06 had a residual capacity of 37.4% (154.2 kN) of the control while SEIS-09 tested at a scaled distance of 0.52 m/kg$^{1/3}$ had a residual capacity of 61.9% (292.9 kN) of the control. Similarly, CONV-12 and SEIS-13 both tested at a scaled distance of 0.82 m/kg$^{1/3}$ had residual capacities of 72.5% (298.9 kN) and 97.5% (461.2 kN) of the control columns respectively.

4.4 Failure modes

The dominant failure modes of the reinforced concrete columns tested in this residual capacity test program was shear failure at the bottom support and flexural failure between the two load points. In general, the conventional columns failed, predominantly, in shear close to the bottom support (Figure 5(a) and Figure 5(b)), while the seismic columns failed in flexure (Figure 5(c) and Figure 5(d)).

The lateral reinforcement was spaced at 75 mm in the seismic columns which resulted in a shear resistance of about 464.8 kN; this is 2.5 times the shear resistance of the conventional columns which had a lateral reinforcement spacing of 300 mm. Thus, the seismic columns appeared to have had enough resistance to preclude shear failure.



(a) (b)

(c) (d)

Figure 5: Post-test photograph showing (a) Shear failure in CONV-16 (b) Shear failure in CONV-11 (c) Flexural failure in SEIS-09 (d) Flexure failure in SEIS-13.

5. SUMMARY AND CONCLUSIONS

In the above study, twelve (12) reinforced concrete columns were tested in a residual capacity program. The columns were detailed with different transverse reinforcement spacing and denoted as conventional and seismic columns. The test procedure involved loading the columns to their design axial service load level and then applying lateral loading until failure. The following conclusions can be drawn from this study:

- All reinforced concrete columns, irrespective of lateral reinforcement spacing and blast damage level resisted the service load level stress without distress or failure.
- Closer transverse reinforcement spacing provides an inherently higher resistance to blast. It reduces the displacements and hence lower blast-damage. Subsequently the seismic columns had greater residual capacity in comparison with the conventional columns.
- The residual capacity of columns strongly depended on the scaled distance of the blast loading; the larger the scaled distance the higher the residual capacity.
- In general the failure mode of conventional columns was shear failure at the bottom support while seismic column failed predominantly in flexure.

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