RAPID SEISMIC REPAIR OF SHEAR DAMAGED CONCRETE BRIDGE COLUMNS BY TRANSVERSE PRESTRESSING

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ABSTRACT :

Reinforced concrete bridge columns subjected to strong earthquakes indicate that they may suffer from various types and levels of damage. One of the most common causes of seismic damage in shear-dominant columns is diagonal tension cracking, which may or may not result in irreparable damage. A rapid seismic repair technique was developed through experimental research, involving external post-tensioning damaged columns in the transverse direction. The technique was developed as an extension of a similar technique that had been developed for column retrofitting, known as the "RetroBelt" technology.

The repair method involves the placement of seven-wire strands around circular, square or rectangular columns and applying prestressing by means of a hand held hydraulic jack and specially developed anchors. The prestressing tends to close shear-induced diagonal cracks, improving aggregate interlock mechanism, while also providing additional shear reinforcement. The technique was verified by testing large-scale columns under simulated seismic loading. The specimens were designed to reflect seismically deficient columns with widely spaced ties. They were subjected to constant axial compression and incrementally increasing lateral deformation reversals. The columns were initially damaged by lateral deformation cycles reaching up to approximately 1% lateral drift. Relatively wide diagonal cracks were observed, signifying the yielding of tie steel. The loading was then stopped and the columns were repaired by transverse prestressing. The repaired columns were then subjected to similar loading, with increasing levels of deformation. The results indicated that the shear failure was suppressed and the mode of behaviour was changed from shear to flexure. External prestressing also improved concrete confinement and resulted in 4% and higher lateral drift capacities. The paper presents the results of the experimental investigation and the repair design methodology developed.

KEYWORDS: concrete columns; confinement; diagonal shear; post-tensioning; prestressing; reinforced concrete; seismic repair; strands; transverse reinforcement.

1. INTRODUCTION

In the aftermath of a strong earthquake the operation of lifeline structures becomes vitally important in maintaining services to the disaster area when they are most needed. Bridge infrastructure forms an integral component of transportation networks for relief, response and reconstruction efforts. Therefore, they need to be repaired in a timely manner. Conventional repair techniques usually require months and sometimes years to bring bridges up to acceptable service conditions, during which vital operations and services suffer tremendously with serious impacts on life safety and economy.

The majority of seismic damage in bridges occurs in their vertical load carrying elements, causing sufficient degradation in strength to decommission the bridge until it is repaired. One of the most common forms of seismic damage is caused by shear force reversals applied on bridge columns. Bridge columns with insufficient transverse reinforcement develop diagonal tension cracks under shear force reversals. This results in the yielding of column ties and the opening of inclined cracks wide enough to undermine column shear resistance.

A quick repair technique was developed through experimental research as an extension of previously developed seismic retrofit methodology, known as the RetroBelt System of Retrofit. The RetroBelt quick repair technique involves transverse post-tensioning shear damaged reinforced concrete columns by means of hand-held hydraulic jacks and specially developed anchors to induce lateral pressures on cracked concrete. The procedure takes a few hours to effectively restore column capacity by closing cracks as much as possible. This recovers the mechanism of aggregate interlock to a large extent, thereby increasing concrete shear resistance, while also providing additional shear reinforcement. This paper provides a summary of the experimental research conducted at the University of Ottawa in Canada and presents some of the test results.

2. EXPERIMENTAL RESEARCH

Large-scale bridge columns with square and rectangular cross-sections were designed, built and tested under simulated seismic loading. The columns were designed to reflect pre-seismic design practices for reinforced concrete columns with widely spaced ties. They were built to represent the bottom portion of a bridge column between the footing and the point of inflection. The specimens were subjected to axial compression accompanied by incrementally increasing lateral deformation reversals. They were first damaged through shear force reversals up to approximately 1% lateral drift, at which level shear deficient columns often suffer significant diagonal cracking, leading to a diagonal tension failure. The application of load is then stopped and the column is repaired by external transverse prestressing through the application of RetroBelt repair technique. Once the repair work is completed, the column is subjected to further shear force reversals under constant axial load to investigate the effectiveness of the repair technique. Figure 1 illustrates the test setup used during the experimental investigation.

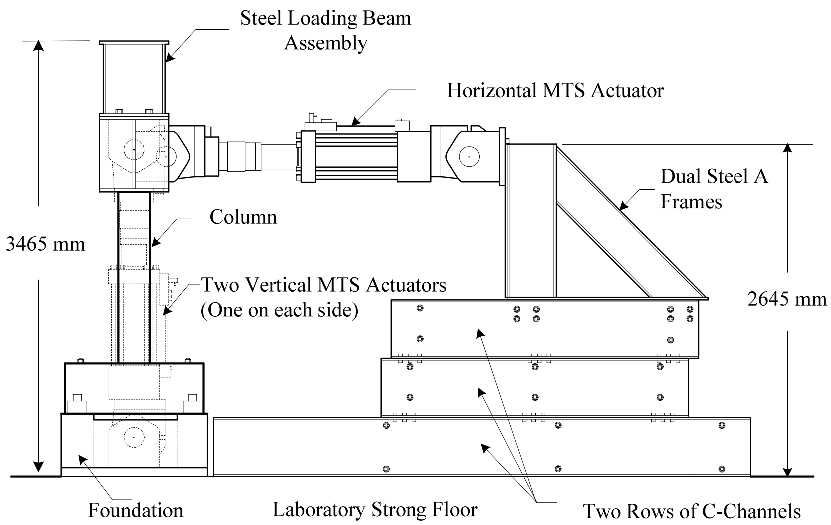
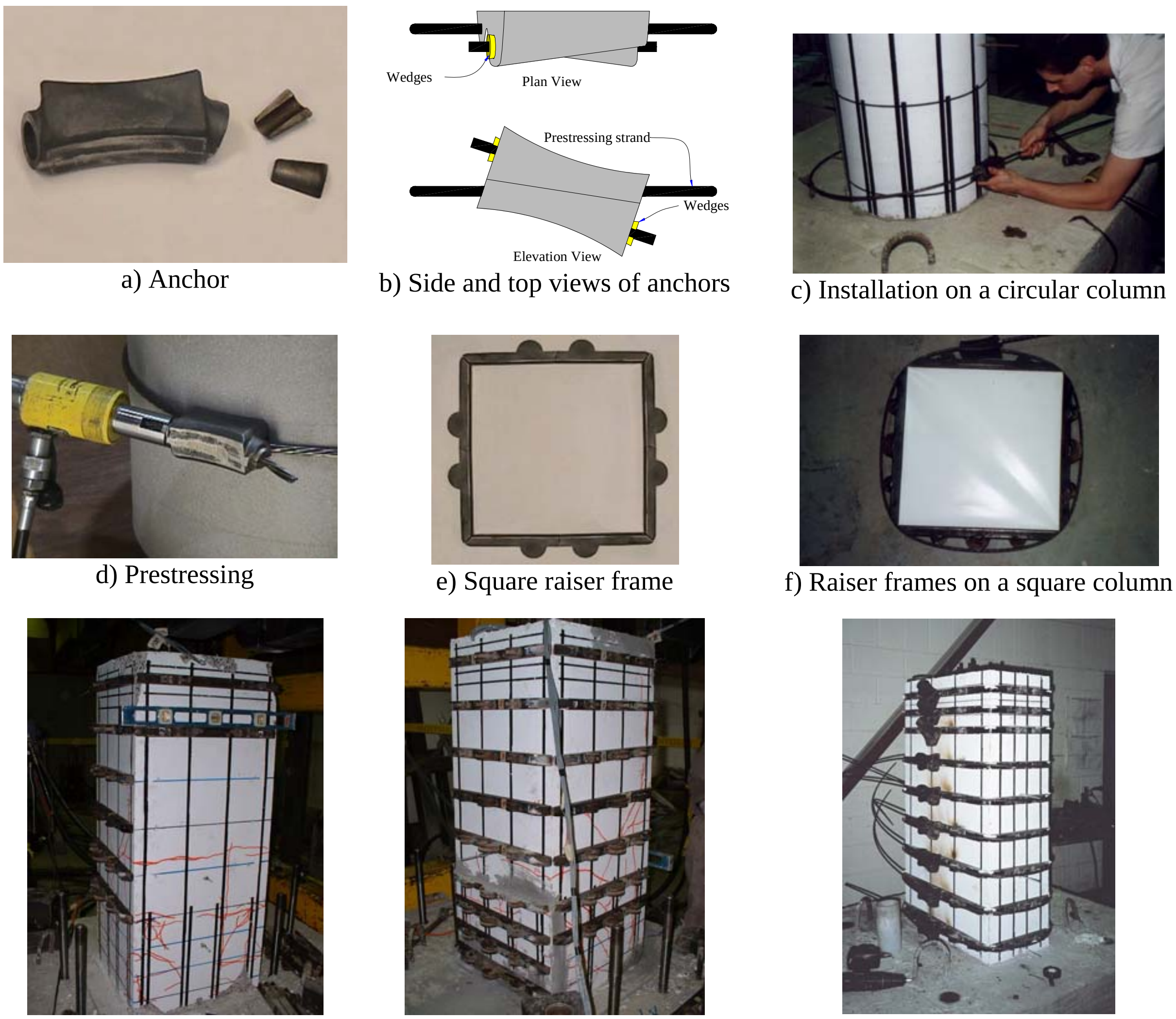


Figure 1 Test setup

2.1. Repair Technique

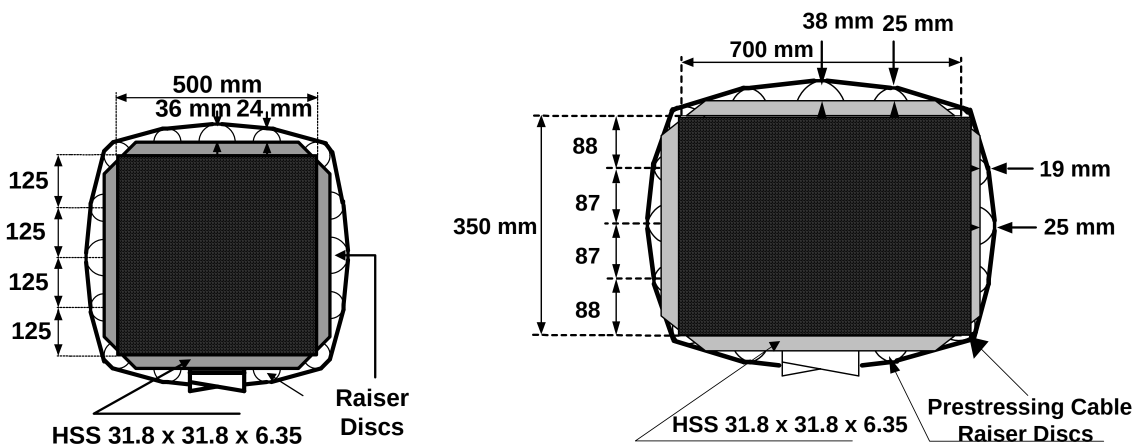
The RetroBelt repair technique consists of external transverse prestressing, applied by means of strands that are connected through special anchors. Figure 2 illustrates the hardware necessary to employ the repair technique. The transverse prestressing is done by means of standard 7-wire strands. In the experimental program reported in this paper, each strand had a 9.53 mm nominal diameter and 55 mm^2 steel area. While the strands are directly applied on circular columns, taking advantage of uniform hoop tension that develops in a circular geometry, they require raiser frames on rectangular and square columns to produce a parabolic tendon profile and activate hoop tension. The raiser frames are manufactured from hollow steel sections or cast iron pieces with semi-circular disks of different diameters welded on each side to raise the level of strands. This ensures reasonably uniform application of confinement forces on each face of column. In the experimental program, the raiser frames were manufactured from hollow steel sections (HSS 31.8x31.8x6.35mm). A specially manufactured anchor is used to perform the prestressing operation. This anchor is placed directly on the concrete surface for circular columns and on one of the raiser frames for square and rectangular columns. Round steel pieces are placed around square and rectangular column corners or small piece of greased steel strips are placed around each corner to reduce stress concentration and prevent damage to corners, while allowing the strands to slide freely during prestressing. The locations of RetroBelt hoops are first marked on the column. The hoops are hand held by one person while the other person performs the prestressing operation. For application to square and rectangular columns the raiser frames are first nailed to column concrete to ensure proper positioning during prestressing. The strands are wrapped around the raiser frames or directly on columns (for circular columns), and are locked in the anchors by means of two pairs of wedges. The use of two jacks simultaneously may be more effective. The first jack applies the prestressing force. Upon reaching the desired level of prestressing, the second jack can be used to push and lock the wedges into the anchor to eliminate anchorage losses. The level of prestressing is monitored through a pressure gauge.



a) Anchor
b) Side and top views of anchors
c) Installation on a circular column
d) Prestressing
e) Square raiser frame
f) Raiser frames on a square column
g) Placement of raiser frames
h) Repairing a square column
i) Repairing a rectangular column

Figure 2 Hardware needed for RetroBelt technology and repairing columns in the laboratory

The details of the RetroBelt repair technique applied to two test columns reported in this paper are illustrated in Figure 3.



a) Square column (SSR-R) repair details   b) Rectangular columns (RR-R) repair details

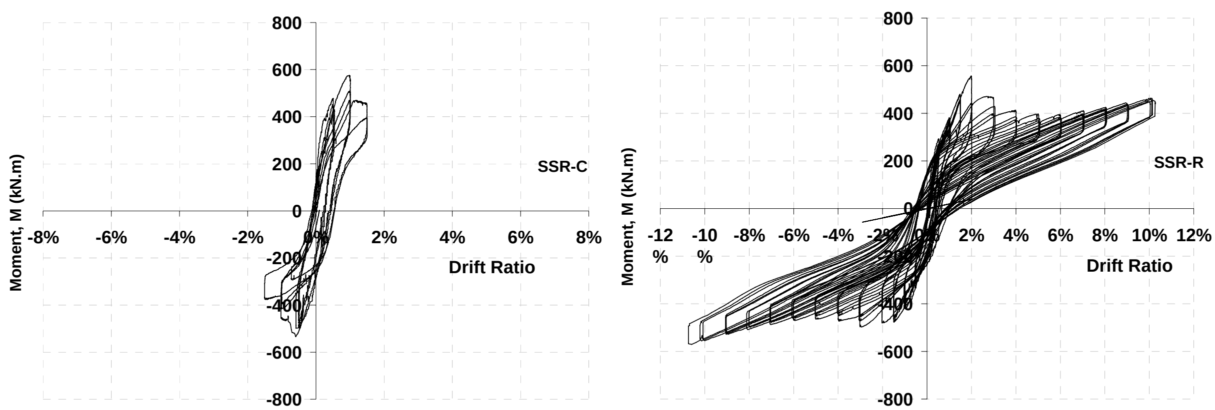
Figure 3 The application of RetroBelt repair technique to two columns tested in the experimental program

2.2. Square Column Tests

A square column labeled SSR-C, with a 500 mm square cross-section and a 1220 mm height (with an effective shear span of 1500 mm) was tested, damaged, repaired and re-tested. The column was reinforced with 12- 19.5 mm diameter deformed longitudinal reinforcement, spliced in the potential hinging region with a splice length of 20 times the bar diameter. The ties consisted of 6.35 mm diameter smooth reinforcement placed at 300 mm spacing. SSR-C was the control column which reflected non-seismic design practices utilized in existing older bridge columns. The column was subjected to 15% of its concentric capacity as axial compression. Lateral deformation reversals were applied as cycles of three at each of the progressively increasing deformation levels. Flexural cracks occurred after the first cycle of loading at 0.5% lateral drift ratio on north and south faces within the lower 700 mm segment of column. Further cycling at this deformation level increased the number of cracks and lengthened the cracks to the sides of column with a declining angle. When the load was increased to 1% lateral drift ratio, the flexural cracks propagated more towards the sides, in the form of inclined shear cracks, and opened up to a crack width of approximately 1.0 mm. The column reached its peak load resistance of 370kN at this load stage, corresponding to peak flexural resistance of 575 kN.m. Pinching of hysteresis loops was observed, which was indicative of the combination of shear response and slippage of spliced reinforcement. Vertical cracks formed within the splice region. The strain data indicated that most of the bars did not reach their yield capacity but instead slipped, except for one which did show yielding. Because the width of diagonal crack at this load stage was not indicative of significant shear damage, the deformation was increased to 1.5% drift level. Spalling and crushing of concrete was observed near the base within the bottom 75 mm segment of column. Further cycling resulted in the decay of strength. Moment resistance in the direction of first load excursion dropped by approximately 30% at the end of the second cycle of 1.5% drift ratio. This level of strength drop was considered to be significant enough to label the column drift capacity to be 1% (deformation level prior to 20% strength decay). During the 1.5% drift cycles the cracks widened within the lower 500 mm segment, as well as at the column-footing interface. Reinforcement slippage could be observed in the pictures taken.

Figure 4(a) illustrates experimentally recorded moment-lateral drift hysteretic relationship. The moment values plotted were computed from recorded horizontal forces and the horizontal and vertical components of axial loads including the P-Δ effect. It is clear from the hysteretic relationship that the column experienced severe strength degradation immediately after the cycles at 1% lateral drift. The hysteresis loops show pinching, signifying shear dominant response and slippage due to insufficient splice length. The reduction in load resistance was attributed essentially to insufficient transverse reinforcement against diagonal tension as evidenced by wide diagonal cracks that have formed, indicating the yielding of transverse reinforcement, which was confirmed by strain gauge readings.

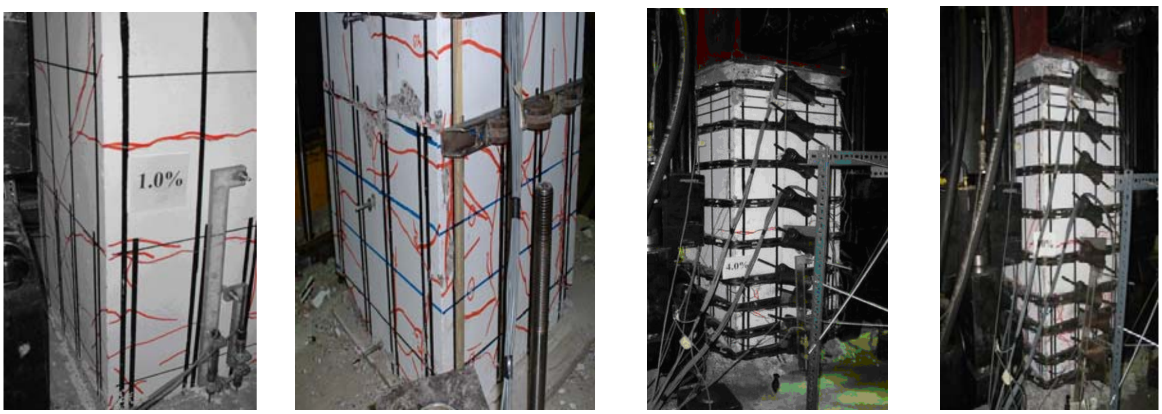
The damaged column (SSR-C) was repaired by using external transverse prestressing. The repaired column was labeled as SSR-R. The transverse prestressing was applied by using the hardware illustrated in Figure 2. A few small pieces of cover concrete that had become loose during previous loading were removed and the column was patched with fresh concrete in these areas in an effort to prepare the surface for external prestressing. Raiser frames were nailed on the surface. Seven-wire strands with 9.53 mm diameter were placed on the raiser frames. The spacing of strands was 100 mm within the splice region and was increased to 150 mm above this region. The intended level of prestressing was 50% f_{pu} (1050 MPa) for each strand. This level of prestressing was found to be adequate to improve the performance of the splice region in earlier tests, and was used throughout the column to close diagonal tension cracks as much as possible. This level also allowed further stretching (stressing) during testing, prior to reaching the rupturing strain. The same loading scheme that was used for the as-built column was also used for the repaired column. No additional damage was observed during the 0.5% drift cycles. The chipping of the patched cover concrete at the column-footing interface was observed at 1% drift level. Additional flexural cracks formed and the existing crack between the first 2 strands started opening up to 2.0 mm. The crack at column-footing interface became wider with a crack width of approximately 4 mm at 1.5% drift ratio, indicating the slippage of column bars in the splice region. More chipping of the repaired cover concrete was observed at the column footing interface. The cycles at 2% drift ratio resulted in additional widening of the flexural cracks on north and south faces when the maximum lateral force was at 344 kN. New hairline diagonal shear cracks were observed during 3% drift cycles, however the cracks were well under control due to external prestressing. During 4% drift and subsequent drift levels, the interface crack kept on widening and the column maintained its strength until 10% lateral drift. The column showed a partial rocking mode about the base as the longitudinal bars continued slipping. However the external prestressing helped maintain a significant shear force resistance until the end of testing. The test was stopped at the end of this drift level due to the shortage of stroke in the horizontal actuator. Some strength decay was experienced up to 6% lateral drift and a longitudinal bar rupture was observed at this deformation level while there was no concrete cover left below the first strand (75 mm from the column footing).



a) As built square column (Column SSR-C)   b) Repaired square column (Column SSR-R)

Figure 4 Hysteretic relationships for the square column tested

Figure 4(b) shows the experimentally recorded hysteretic moment-lateral drift relationships for repaired column, exhibiting stable loops until 10% lateral drift. The failure mechanism for each column was very different. The as-built column (SSR-C) exhibited limited deformability with a maximum drift capacity of 1% followed by a drop in load resistance. The failure of the repaired/retrofitted specimen (SSR-R) was ductile and much more gradual. Although the strength of SSR-R did not improve over the capacity experienced prior to repair, it did maintain this capacity with a gradual reduction in strength, which never dropped below about 70% of the initial resistance. The eventual column deformability, with some strength decay, was much higher than the control column. The damage observed in the repaired column at the end of testing was almost the same as the damage observed in the as-built column except for the column-footing interface which was damaged extensively due to the slippage of longitudinal reinforcement. When the moment-deformation hysteretic relationships are compared, it can be seen that column SSR-R with external prestressing was able to sustain more than 5 times the lateral drift sustained by the control column, although it sustained up to 30% strength decay. Figure 5 illustrates damage observed in the column before and after repair.



a) SSR-C at 1% drift b) SSR-C at 1.5% drift c) SSR-R at 4% drift d)SSR-R at 10% drift

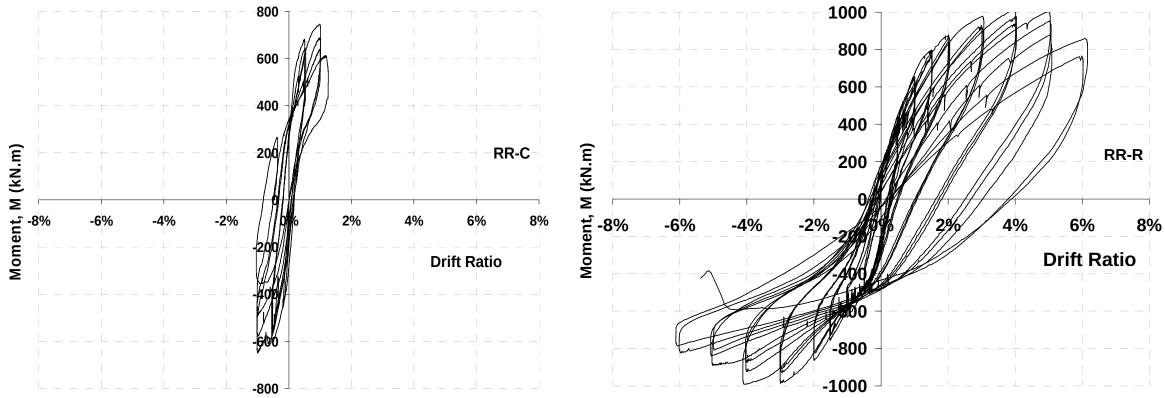
Figure 5 Damage in square column before and after repair

2.3. Rectangular Column Tests

A rectangular concrete column with 700 mm by 350 mm cross-sectional dimensions was designed, built and tested under the same loading regime as that used for the earlier square column tests. The column was reinforced with 12 – 19.5 mm deformed bars placed continuously without splicing. It had 1220 mm height (with an effective shear span of 1500 mm). **C**olumn RR-C was the control column, with shear deficiency. It was representative of a typical shear dominant bridge column with No.2 (6.3 mm diameter) perimeter ties at 300 mm spacing. The column was first subjected to a constant axial load of 15% of the column concentric capacity (1294 kN) to simulate typical gravity loading, and was subsequently subjected to incrementally increasing lateral deformation reversals.

The initial cycles at 0.5% drift ratio produced up to four flexural cracks, propagating towards the sides of the column with an inclined shear angle. The longitudinal bars generally reached their yield point during the first cycle at 0.5% drift and the cracks started widening indicating the yielding of transverse reinforcement. Increasing deformations to 1% drift ratio resulted in further propagation of cracks towards the sides with an increased width of approximately 5 mm. The crack that had formed at column footing interface became about 5 mm wide at this load stage. Spalling and crushing of concrete was observed near the base within the bottom 75 mm segment of the column. The previous shear cracks propagated further to column sides as new cracks also formed. Moment resistance in the direction of the first load excursion dropped by approximately 16% at the end of the third cycle. The column was then loaded to exceed 1% drift slightly (up to 1.2% drift ratio), but the test was stopped after one cycle at this deformation level since it was observed in earlier column tests that a companion column could not sustain three cycles at 1.5% drift ratio. It was decided that the observed level of damage with a 16% drop in strength was sufficient for the next stage of testing.

Figure 6(a) shows the experimentally recorded moment-lateral drift hysteretic relationship. It is clear from the hysteretic relationship that the column experienced strength degradation immediately after the cycles at 1% lateral drift. The hysteresis loops showed some pinching, signifying shear dominant response. The failure was triggered by insufficient transverse reinforcement against diagonal tension.



a) As built rectangular column (Column RR-C)   b) Repaired rectangular column (Column RR-R)

Figure 6 Hysteretic relationships for the rectangular column tested

The column was repaired by external transverse prestressing and labeled as RR-R. The level of prestressing applied was 50 % f_{pu} (1050 MPa) and it was tested following the same loading scheme as before. New flexural cracks were observed during the second cycle at 1% lateral drift and their number increased during subsequent cycles. A crack formed at the column-footing interface on the south side during the third cycle at 1% drift ratio. The first set of new shear cracks were observed on both side faces, during the 2nd cycle of 1.5% drift when the lateral force was at 590 kN. The first cycle at 2% drift resulted in additional hairline flexural cracks on the north and south faces and the crack at column-footing interface widened and became longer during the 2nd cycle at 2% drift level. Some crushing of cover concrete was observed near the base during the third cycle of 3% drift level while increased diagonal shear cracks were observed with widening of one of the cracks. However, the crack was well under control due to the external prestressing. The column maintained its strength until 4% lateral drift and experienced some strength decay beyond the 4% drift ratio. The hysteretic moment-lateral drift relationship plotted in Figure 6(b) show stable loops until after 4% lateral drift ratio.

The comparison of repaired and as-built columns clearly demonstrates the improvement attained in column deformability through external prestressing. The prestressing controlled diagonal tension cracks and served as additional shear reinforcement. This resulted in a significant increase in the load capacity of damaged column, from approximately 500 kN to 600 kN. The column deformability also improved substantially, demonstrating the effectiveness of transverse prestressing as a column repair technique. The hysteretic relationship for the repaired column showed asymmetric loops. This was attributed to a permanent damage caused in the control column, in one direction, prior to the repair work. Figure 7 illustrates damage sustained in the rectangular column before and after repair.

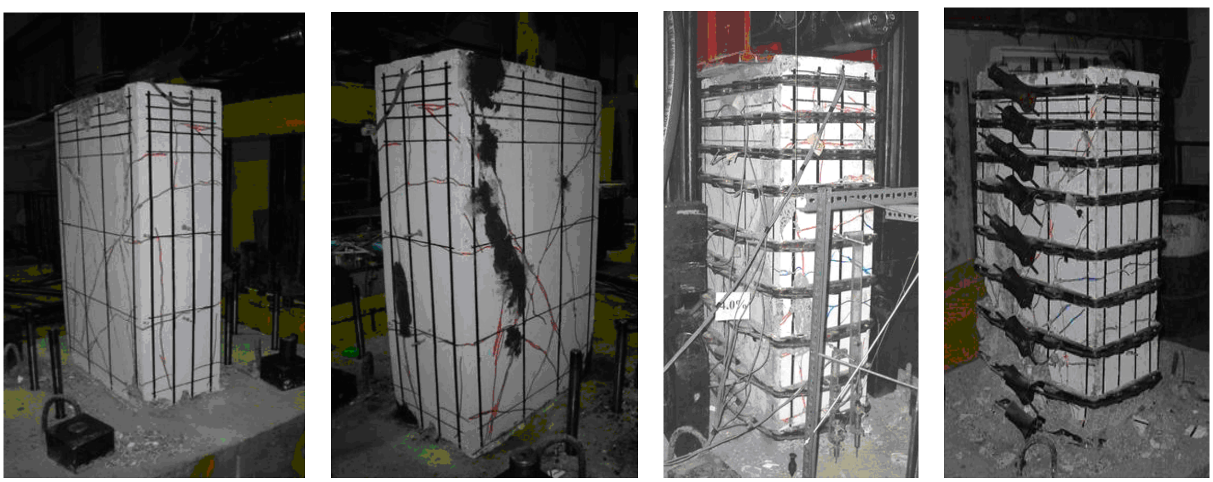
Considerable judgment needs to be exercised to assess whether the level of damage sustained by a column justifies its repair to reinstate full capacity. Tests have indicated that spalling of cover concrete and yielding of either longitudinal or transverse reinforcement should not discourage repair. However, if reinforcement has been fractured, buckled, or deformed significantly out of the straight, then column replacement should be considered as a serious option.

3. CONCLUSION

The following conclusions can be drawn from the experimental investigation presented in this paper:

- The Retro-belt technique described in the paper can be employed to repair shear-damaged concrete columns. Column tests indicate that improvements in lateral drift capacity, from 1% in shear-deficient columns to up to 4% in repaired columns, can be obtained.

- Considerable judgment needs to be exercised to assess whether the level of damage sustained by a column justifies its repair to achieve full restoration of its strength. Tests have indicated that spalling of cover concrete and yielding of either longitudinal or transverse reinforcement should not discourage repair. However, if the longitudinal reinforcement has been fractured, buckled, or deformed significantly out of the straight and/or the diagonal cracks widened significantly to damage the core concrete beyond repair, then column replacement should be considered as a serious option.
- The test results indicated that repairing a column that has experienced significant slippage of longitudinal reinforcement within the splice region may not be possible through RetroBelt technology. Though some improvement may be attained, restoring the original strength of the column may not be possible. More research is needed before a RetroBelt design strategy can be suggested as a repair technique for splice-deficient columns.



a) RR-C at 1% drift b) RR-C after concrete repair c) RR-R at 4% drift d) RR-R at 6% drift

Figure 7 Damage in rectangular column before and after repair

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