# Seismic Retrofit Of RC Columns With Inadequate Lap-Splice Length By External Post-Tensioned High-Strength Strips

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**SUMMARY:**
This paper presents the results of an experimental study on the application of a new technique for retrofitting RC columns with short lap-splice length of the longitudinal rebars. The applied retrofit technique was external confinement of columns by post-tensioned high strength alloy steel strips. Four 2/3 scale RC columns with circular sections were made and tested. The length of the lap-splice of longitudinal rebars of these specimens was twenty times their diameter. The column specimens were tested under constant axial load level of 0.38f'c Ag and cyclic lateral displacement reversals. The control specimen failed to achieve its theoretically estimated lateral strength and its ultimate drift ratio was 0.015. All of the retrofitted columns could achieve their theoretical strengths and both of their longitudinal and transverse reinforcements were yielded. The effects of the volumetric ratio of confining strips as well as the post-tensioning force of the strip were studied.

*Keywords: Reinforced concrete , lap-splice , seismic retrofit, Column , Displacement capacity*

## 1. INTRODUCTION:

Several reinforced concrete structures have been designed and constructed according to the old seismic codes, in which the required length for the lap-splice was being calculated based on the requirements of compressive elements. Therefore, during a seismic event the lap splice is not adequate to develop yielding in longitudinal rebars in tension. This results in premature loss of the lateral strength of concrete column and less displacement capacity. According to the codes prior to 1973, this compressive lap-length is about 20 times the diameters of the spliced rebar. Poor behavior of such structures during previous earthquakes implies the necessity of development of efficient retrofit techniques.

Melek et al (2003) reviewed several experimental studies previously conducted on the cyclic lateral behavior of RC columns with short lap-splice length. They also performed such tests on 6 large-scale RC columns with a splice length of $20d_b$. The fiber renforced polymers have been applied in several studies to compensate such a deficiency in existing RC columns, such as Ma et al (2000), Bousias et al (2004) and schlick and Brena (2004).

One of the relatively newer techniques for retrofit of RC columns is its external post-tensioning with high-strength metal strips. Post-tensioning the strips provides active external confinement that can effectively act before dilation of concrete. The technique was introduced and applied by Frangou and Pilakoutas (1995) in strengthening the shear critical RC beams. This technique was also successfully applied for enhancing the compressive behavior of small scale concrete columns with various shapes and sizes by Moghaddam et al. (2010). It could also increase the compressive strength and ductility of spirally reinforced cylindrical specimens (Moghaddam and Samadi (2008)). It could also successfully improve the lateral behavior of square-sectioned RC columns with inadequate transverse reinforcements (Moghaddam et al. (2010))

This paper presents the results of an experimental study on the application of this technique, that is called PMS hereafter. In the experiments reported in this paper, four 2/3 scale RC columns with circular sections were made and tested.

## 2. DETAILS OF THE TESTED COLUMN SPECIMENS

In order to study the capability of the PMS technique in enhancement of the lateral behavior of the RC columns with short lap-splice lengths, four column specimens were deliberately designed and made with such a deficiency. The columns were tested under constant axial load and cyclic lateral displacement reversals. The scale of the specimens was about 2/3 of the columns of conventional RC building. They were 100 cm high and the diameter of their section was 25 cm. The columns were reinforced with 8 longitudinal rebars with diameter of 12 mm. Circular hoops with diameter of 6mm were applied as their transverse reinforcement at spacings of 15cm along the column height. The length of the lap-splice of the longitudinal rebars was 24 cm that equals the 20$d_b$. In figure 1 details of the geometry and reinforcement of the tested column specimens are shown.

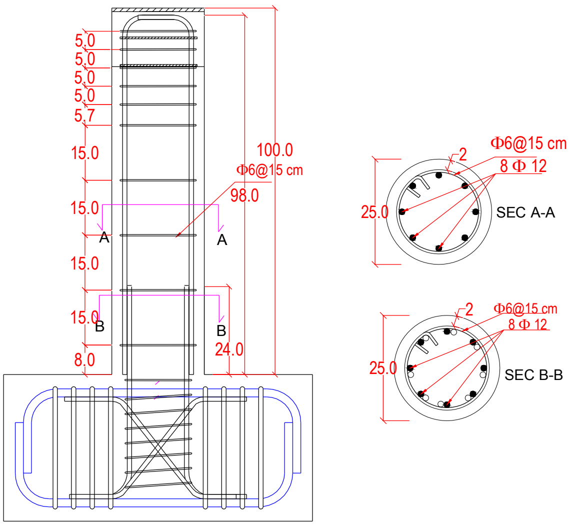



**Figure1**. Geometry and details of reinforcements of the tested column specimens

Tension tests were conducted to obtain the yield strength of the applied rebars. The yield strengths of longitudinal and transverse bars were 550 MPa and 320 MPa, respectively. The average strength of concrete was 21 MPa.

The specimens were tested under constant axial load of 365 kN that is equivalent with 0.19f'cAg and 0.38 f'cAg.. The column specimens were so designated that the ratio of the plastic shear to the shear capacity become 0.48. On this basis, according to ASCE/SEI 41-06 (2007), the column failure mode must be flexural, in which flexural yielding occurs without shear failure. This mode was selected to remove the effects of shear.

On the other hand the volumetric ratio of internal transverse reinforcements of the tested columns was 0.0025 that is too low when comparing with the amount of the confinement volumetric ratio required by the recent codes for ductile columns. One of such requirements is the equation 1, i.e. presented in ACI318-2008, that necessitates a volumetric ratio of transverse reinforcement of about 0.008 for these column specimens.

$$\rho_s = 0.12\, f_c'/f_{yh} \qquad (2.1)$$

Analysis of the section by using the fiber element was conducted to calculate the theoretical moment capacity of the designed column. In this analysis the Mander et al. (1988) confinement model was applied to obtain the stress-strain of core concrete of the columns and the measured stress-strain curves of the longitudinal reinforcements from tension coupon tests formerly conducted. The obtained capacity curve of the columns of this study is shown in figure 2. As can be seen in this figure, by applying an axial force of 365kN, i.e. the force applied in the tests of this study, the column must suffer a moment of about 4.8 t.m..

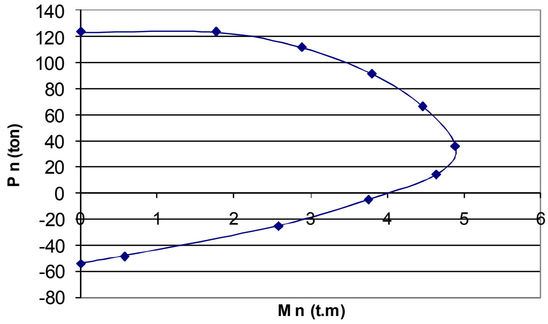



**Figure2**. the force-moment interaction diagram of the studied columns

## 3. RETROFIT DETAILS

The retrofit technique that was applied in this study involves strapping the concrete columns with high strength metal strips. The strips are tensioned with a pneumatic tensioner and then the both ends of the strip are locked in a seal by means of a sealer. Calibration tests were initially conducted and a linear relationship was obtained between the applied air pressure to the pneumatic tensioner and tensioning force in the strip. This linear relationship was then used in retrofit of RC columns. The technique has been introduced in more details by Moghaddam et al.(2010). The applied strips in the experiments had a width of 32 mm and thickness of 0.8 mm. Their yield and ultimate strengths were 850 and 950 MPa, respectively. The elastic modulus of the strips was 200 GPa and their rupture strain was 0.065.

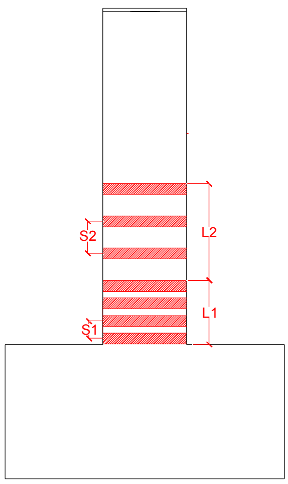



**Figure 3.** Schematic definition of the parameters of retrofit layout

The columns were tested under constant axial load cyclic lateral displacement reversals, that both were applied by means of hydraulic jacks. Details of retrofit of tested columns are presented in table 1. Two different amounts of strips were applied along the height of columns. As shown in figure 3, the column height was divided into two different regions of L1 and L2. Generally more confinement was provided in the first region.

**Table1** . Details of retrofit layouts applied for column specimens

| Specimen | Axial load | Retrofit layout | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | L1 (mm) | Number of strip layers | S1 (mm) | L2 (mm) | Number of strip layers | S2 (mm) | |
| CS0 | 0.35 Ag. f'c | Control specimen | | | | | | |
| CS-S64-A | 0.35 Ag. f'c | 224 | 2 | 64 | 192 | 1 | 64 | Active confinement |
| CS-S64-P | 0.35 Ag. f'c | 224 | 2 | 64 | 192 | 1 | 64 | passive confinement |
| CS-S32-A | 0.35 Ag. f'c | 263 | 2 | 32 | 195 | 1 | 64 | Active confinement |

A control specimen, i.e. column specimen CS0, was tested without any retrofit as the basis for quantification of the improvement developed due to strapping the column.

As shown in table 1, the column specimens CS-S64-A and CS-S64-P were retrofitted with the same amount of confining strips. The only difference between these two specimens was the level of the post-tensioning force in their confining strips. In the former specimen, the post-tensioning strain of the strips was about 1200 microstrain, while in the latter specimen the strips were tensioned just to 200 microstrain. Such a difference in the post-tensioning force of the strips was considered to compare the capabilities of the active versus passive external confinements. In the passive confinement, the application of the lateral confining pressure depends on the dilation of the concrete while in the active confinement, the lateral pressure is applied prior to load application.

The fourth specimen ,i.e. CS-S32-A was fully jacketed with strips at 1 mm spacing. The strips of this specimen were post-tensioned to about 1200 microstrain to actively apply the lateral pressure to concrete.

## 4. TEST SETUP AND INSTRUMENTATION

The column stubs were fastened to the strong floor with eight high-strength rods, and each rod was pre-stressed to 200 KN to prevent slip and overturning under large lateral load. A vertical hydraulic jack was used to apply the constant axial load (that was continuously monitored by a load cell and was held constant during the test). The effect of earthquake on the column specimens was simulated by reversed cyclic loading. Two hydraulic jacks in the test setup were used to displace the top of the columns to achieve a predetermined displacement level. Then the loading direction was reversed to achieve the same displacement level in the opposite direction. Test set up is shown in figure 4.

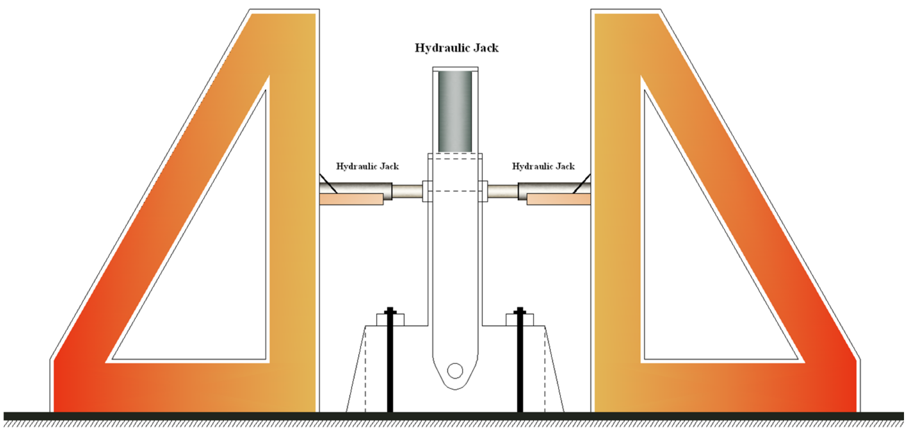



**Figure4.** The schematic depiction of the test setup

The lateral force was applied in the displacement control mode, consisting of three successive cycles of lateral displacement at drift ratio levels of 0.5, 1.0, 1.5, 2.0 and 2.5% and then one cycle at drift ratio levels of 3, 4, 5, 6 %, etc., until the load resistance dropped by 30%. The applied displacement history is shown in figure 5.

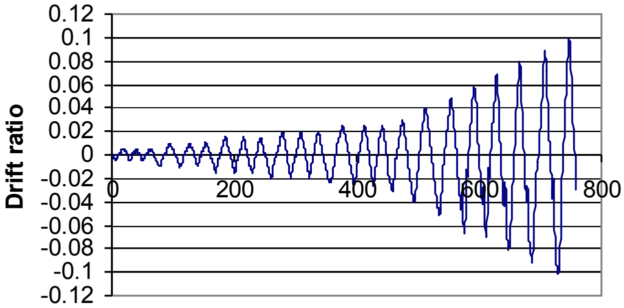



**Figure 5**. The applied displacement protocol

Six vertical LVDTs and four horizontal LVDTs were used to measure the columns curvature and lateral displacement, respectively. In addition, four LVDTs were used to measure the possible vertical and horizontal movements of the column stub. Ten Electrical resistance strain gages were glued to longitudinal and transverse reinforcements. In the retrofitted specimens ten strain gauges were attached to the external strips.

## 5. TEST RESULTS AND OBSERVATIONS

### 5.1. Control Specimen

The first test was conducted on the control specimen. At the drift ratio level of 0.5%, a horizontal crack formed just above the root reinforcement. At 1.5% drift ratio, several cracks was observed over the lap-length. After spalling of the cover concrete at 3% drift ratio, the sliding of the column rebar was apparently observed. Figure 6 shows the diagram of the base moment versus drift ratio of the control specimen. As can be seen in this figure, the maximum moment strength of this column is 41kN.m that is less than the theoretically obtained value of 4.8 t.m described in section 2. In addition it is obvious that the ultimate displacement capacity of this column after which the lateral strength starts its significant decay is the drift ratio of 1.5%.

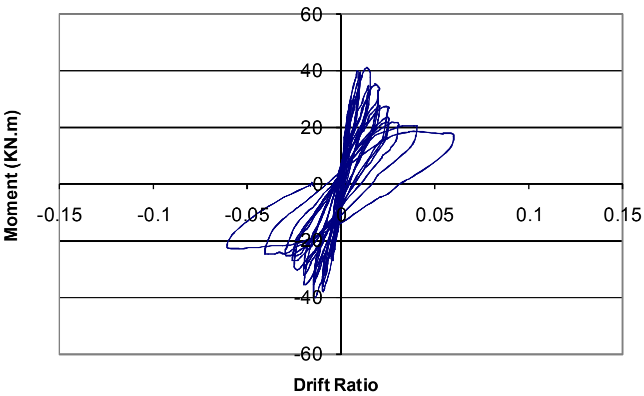



**Figure6.** The measured moment vs. drift ratio of the column specimenCS0

In figure 7 the variations of the strain values measured on the base of the root rebar is shown. It should be explained that these results correspond to the toe rebar that experiences the highest tensile and compressive strains. As can be seen, this rebar has not achieved its yield strength that implied its premature slippage during the lateral displacements of the column. Similar results were observed from the strain gauges attached to various points on the spliced rebar of the column as well as other points on the root rebar.

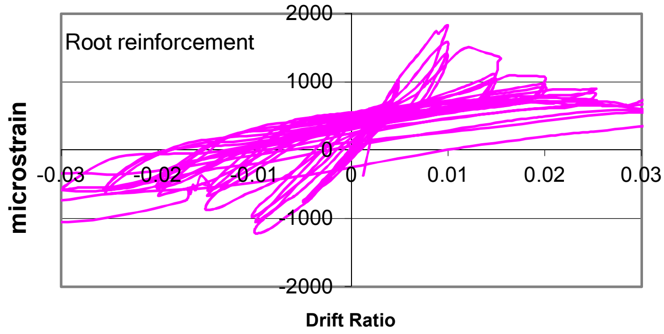



**Figure7.** Variations of the strain on root rebar of the column specimen CS0

### 5.2. The Specimen Actively Confined With Less Confinement Ratio of Strips

The second column specimen, i.e. CS-S64-A was actively confined with external strips. As depicted in figure8, this specimen could have suffered great lateral displacements with minor damages. None of the strips have ruptured even at the end of the tests. The damage at the 3% drift ratio is just some hair cracks between the strips. At 12% lateral drift ratio the cracks are really widened and some crushing between downer strips is observed. At this great level of lateral displacement, although the concrete crushing is observed but due to the effective lateral pressure applied by the external strips, the slippage of the longitudinal reinforcements along the short lap-splice has been prevented or at least controlled.

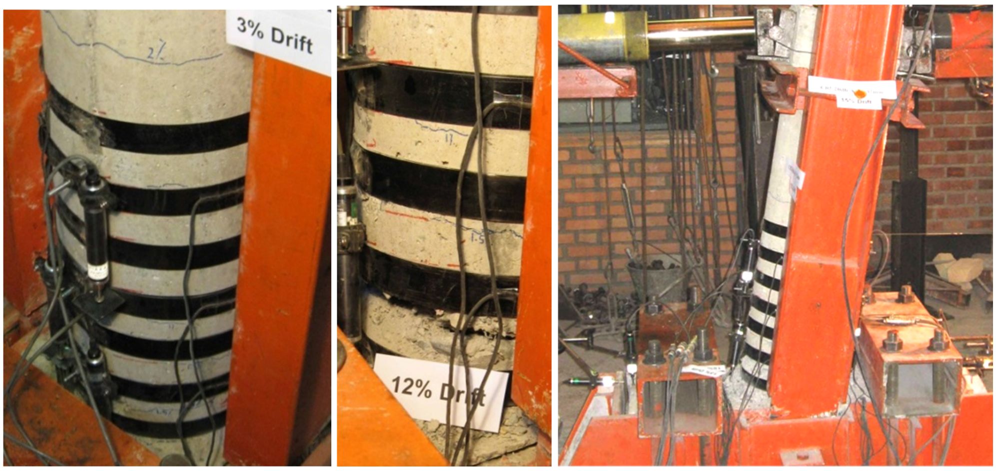



**Figure 8.** The observed behaviour of the column specimen CS-S64-A at various levels of lateral displacement

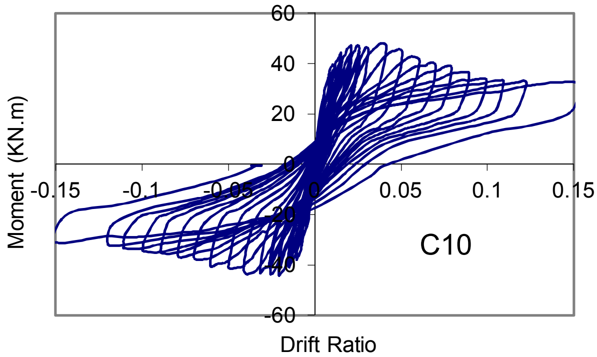
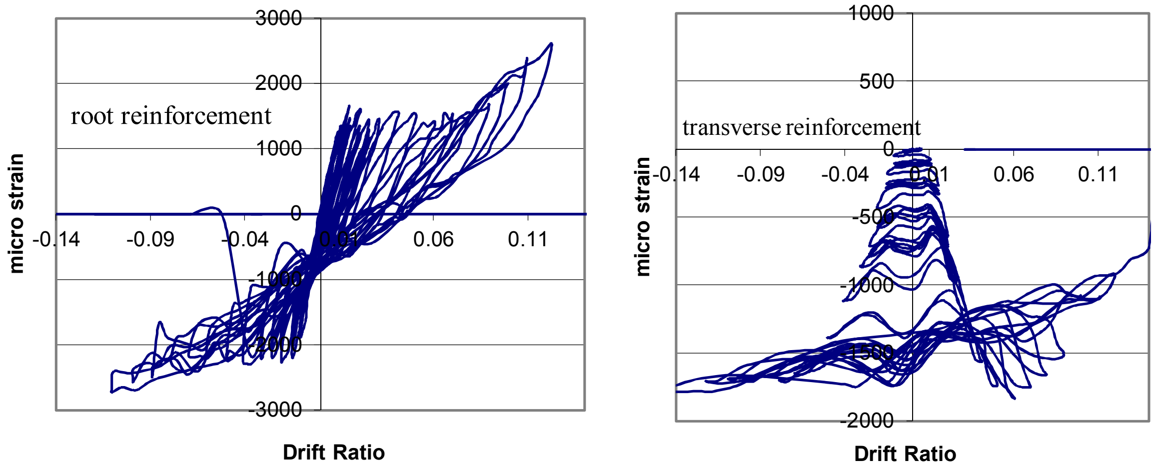



**Figure9.** The measured moment vs. drift ratio of the column specimen CS-S64-A

Figure 9 shows the capacity curve of this column specimen. It is obvious that the maximum moment strength of this column is 48 kN.m that is close to the theoretically estimated value. This implies that the yield strength of the longitudinal reinforcements has been utilized. The ultimate displacement capacity of this column is 0.09 in terms of the lateral drift ratio. At this point, the moment suffered by the column decreases to 80 percent of its peak lateral strength.

The yielding of the longitudinal reinforcements is further studied by studying the variations of the strain of the longitudinal rebars. Figure 10 shows the variations of the strain recorded on the root of the longitudinal reinforcement as well as on the transverse reinforcement. It is obvious that in contrast with the control specimen, the strain of the root reinforcement of the retrofitted column continuously evolves during the lateral displacement of the columns even under the high levels of the lateral displacement. This implies that the rebar has not slipped up to 11% lateral drift ratio and after this level the strain gauge has been damaged. On the other hand, results of the strain gauge mounted on the transverse reinforcement in figure 8b shows that this rebars has yielded at the drift ratio level of about 5% .




(a) (b)

**Figure10.** Variations of the strain on reinforcements of the column specimen CS-S64-A a) On root rebar b) On transverse rebar

## 5.3. The Specimen Passively Confined With Less Confinement Ratio of Strips

The third specimen, i.e. CS-S64-P was retrofitted with the same retrofit layout as the second specimen but with negligible post-tensioning force in the strips. The damage pattern observed in this column was very similar to that of its actively confined counterpart. The cracks formed between the strips and under 7% drift ratio, the only observable damage to the column was cracks between the strip on the tensile side and crushing along the edges of these cracks on the compressive side, as shown in figure11. None of the strips ruptured by the end of the test, that means a drift ratio level in excess of 12%. The gravitational load carrying capacity of the column was maintained by the end of the test.


**Figure 11.** The state of damage to the column specimen CS-S64-P at 10% drift ratio

Figure 12 shows the capacity diagram of this column. As can be seen the general behavior of this column is as appropriate as the column specimen CS-S64-A. It could have reached the nominal strength of the column. The post-peak behavior of this column is acceptable with minor degradation. The ultimate displacement capacity of this column (based on 20% loss of the peak strength) is the drift ratio of 7% that is considerable. It should be noted that in contrast to the control specimen, the degradation of this retrofitted specimen is really gradual. Results obtained from the strain gauges attached on the root and main reinforcements of this column specimen showed that these rebars have yielded at about 1.5% drift ratio.

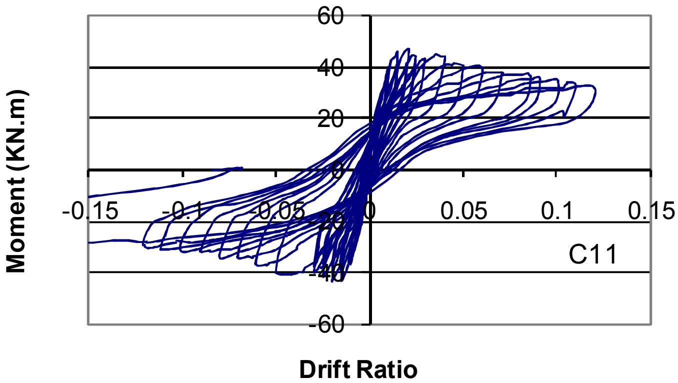
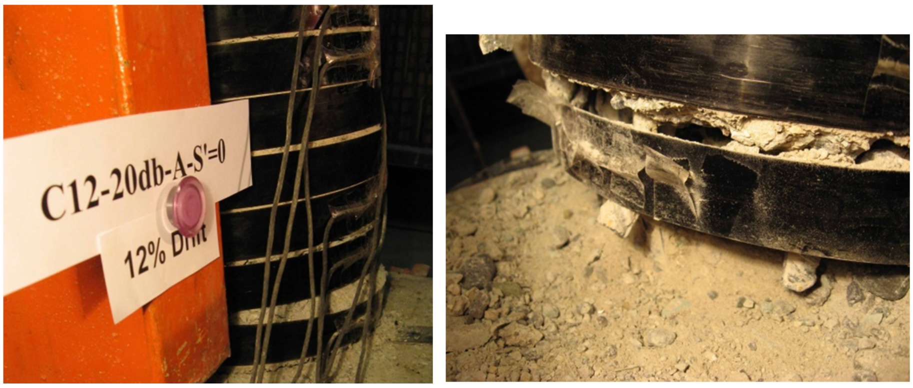



**Figure 12.** The moment-drift ratio capacity curve of the column specimen CS-S64-P

### 5.4. The Specimen Actively Confined With More Confinement Ratio of Strips

The last column specimen, i.e. CS-S32-A, was retrofitted by higher volumetric ratio of confining strips. As shown in table 1, along the height of the lap-splice, the column was fully jacketed with strips at zero spacings. At low levels of the lateral displacement, up to 6 % of drift ratio, the only observable damage to the columns is the completely horizontal cracks between the strips. At 7% drift ratio, the edges of these cracks are crushed in each half-cycle on the compressive sides. At very high levels of the lateral drift ratio (12%), the crushed concrete was observed to fall out from the strip jacketing as shown in figure 13. This must result in the loss of the bond between the spliced rebars due to the removal of their surrounding concrete. However, the effective lateral pressure applied by the strips at these stages of the lateral displacement (that severe damage has been imposed to the concrete of the column), successfully prevented the slippage of the spliced reinforcements. None of the strips ruptured by the end of the test and the column was able to maintain the gravitational load by the end of the test.




(a) (b)

**Figure13**. The state of damage observed in the column specimen CS-S32-A at a) 12%drift ratio and b) the end of the test

The hysteretic behavior of moment versus drift ratio of this column specimen is shown in figure 14. It is noticeable that this column could have achieved higher moment strength, even larger than its theoretically estimated nominal strength that was achieved by the previous retrofitted specimens. By assuming the conventional point of the 20% loss of the peak strength as the ultimate displacement capacity of this column, in terms of the drift ratio, is 7%. However, it should be noted that at the ultimate point of this column, the residual moment strength is 47 kN.m that equals with the peak strength of the control un-retrofitted specimen. On the other hand the residual strength of the retrofitted column specimens CS-S64-A and CS-S64-P at their ultimate displacement point (based on the 20% loss convention) was just 37 kN.m. this shows that the generally applied convention of the 20% loss of the peak strength is not an adequate measure for determining the ultimate displacement capacity of retrofitted columns.

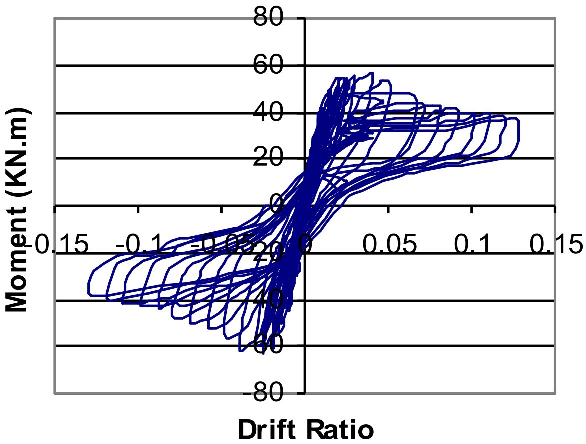



**Figure 14.** The hysteretic behaviour of the column specimen CS-S32-A

## 6. CONCLUSION

In this paper, the results of an experimental study on the application of the post-tensioned metal strips in retrofit of the circular-sectioned RC columns with short lap-splice of the longitudinal reinforcement are presented. It was observed that the technique is capable to improve this deficiency successfully. In contrast to the control specimen that did not achieve its theoretically estimated nominal strength, the peak moment strengths of all retrofitted columns were in excess of the nominal strength. The premature slippage that was the failure mode of the control specimen was fully prevented in the retrofitted specimen and the reinforcements were yielded. All of the specimens could support the gravitational load by the end of the tests. The retrofitted columns showed great capacity of lateral displacement in excess of 7%. The active confinement with the strips works better than the passive one by providing higher strength and ultimate displacement capacity. The specimen retrofitted with higher confining strips achieved higher peak and residual strengths.

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