**Ninth Canadian Conference on Earthquake Engineering**
**Ottawa, Ontario, Canada**
**26-29 June 2007**

# IMPROVING STRENGTH AND DUCTILITY OF REINFORCED CONCRETE COLUMNS USING CARBON FIBER REINFORCED POLYMER (CFRP)

O. Ozcan[1], G. Ozcebe[2], B. Binici[3]

## ABSTRACT

Reinforced concrete columns lacking sufficient transverse reinforcing steel do not possess the necessary ductility to dissipate seismic energy during a major earthquake. The study reported herein investigates the use of carbon fiber-reinforced polymer (CFRP) wrapping as a method of retrofitting non-ductile rectangular reinforced concrete columns with low strength concrete ($f_c$'≈15MPa) and plain bars. Five specimens representative of transverse steel deficient columns in existing buildings were tested. Each specimen was tested under lateral cyclic displacement excursions under constant axial load (approximately 35% of axial load carrying capacity) to simulate the seismic demand. The main parameters under investigation were the number of layers of CFRP wrap and presence and absence of the axial load on the column during strengthening. It was observed that ultimate drift ratio at the onset of strength degradation was about 2.5% for the as built column and about 40% of the deformations were due to bar slip. On the other hand, upon wrapping the plastic hinge regions of the columns with two layers of CFRP ultimate drift ratio was about 7% at CFRP rupture. Interestingly, about 80% of the deformation was due to bar slip. This shows that upon CFRP retrofit, deficient columns with plain bars can undergo larger deformation demands without strength degradation compared to those with deformed bars.

## Introduction

Recent earthquakes occurred in Turkey (Kocaeli 1999, Duzce 1999, Bingol 2003) revealed that inadequate strength and ductility of reinforced concrete columns due to poor detailing of transverse reinforcement can cause extensive damage in buildings. There is an urgent need to understand the behavior of low strength reinforced columns (10 to 15 MPa concrete compressive strength) having plain bars and insufficient confining steel in typical deficient buildings of Turkey. Furthermore, rapid retrofit methods need to be established and presented to the service of engineers.

Previous research on strengthening and repairing methods emphasized that composite column jacket retrofit systems can be as effective as conventional steel jacketing in improving the seismic response characteristics of reinforced concrete columns (Seible et. al. 1997, Sheikh and Yau 2000, Iacobucci et. al. 2003). In all the tests presented in these studies, properly designed continuous CFRP jackets met or exceeded deformation capacities obtained for comparable behavior obtained for code compliant

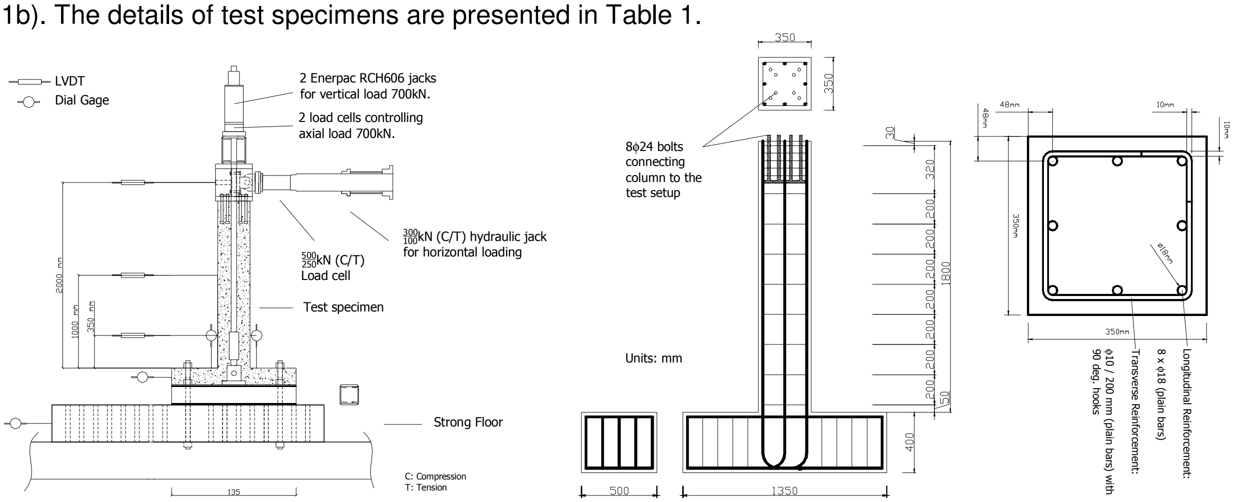
[1]Research Assistant, Dept. of Civil Engineering, Akdeniz University, Antalya, Turkey, 07058 (Currently on leave at the Middle East Technical University for graduate study)
[2]Professor, Dept. of Civil Engineering, Middle East Technical University, Ankara, Turkey, 06531
[3]Associate Professor, Dept. of Civil Engineering, Middle East Technical University, Ankara, Turkey, 06531

transverse reinforcement design. Test results showed that seismic resistance of FRP retrofitted columns improved significantly as a result of confining the entire column section and eliminating premature bar buckling. It was concluded that FRP composites were very effective for both the rehabilitation and repair of existing columns. However, none of the details of the columns tested in the literature can successfully simulate the typical deficiencies and construction practice encountered in Turkey (i.e. plain bars, 90 degree hooks, and low strength concrete). Hence, a new experimental program is conducted and results of the first phase of these experiments are reported herein. The primary objectives of this experimental study are: 1) to investigate the effectiveness of CFRP wrapping of potential plastic hinge regions of reinforced concrete columns made of low strength concrete and plain bars with inadequate transverse reinforcement detailing, 2) to investigate the effect of presence of axial load during strengthening process and number of CFRP wraps.

## Experimental Program

### Test Specimens

The test specimens had dimensions of 350 x 350 x 2000 mm that were connected to a column stub of 1350 x 500 x 400 mm. The details of the specimens are shown in Fig. 1. The column and the stub of the specimens were cast vertically at the same time in order to simulate the actual casting conditions. The longitudinal reinforcement consisted of eight 18 mm diameter plain bars ($\rho_l$=1.66%) and the lateral reinforcement consisted of 10 mm diameter plain bars with a spacing of 200 mm with 90 degree hooks details to simulate the common deficient detailing practice in Turkey. The total embedment length of longitudinal reinforcement was 1160 mm that consisted of 370 mm of straight portion and 90 degree hooked extension of 790 mm for side bars. The 90 degree hooks used in the footing represent a typical column stub reinforcement connection that simulates the actual case in building column foundations (Fig. 1b). The details of test specimens are presented in Table 1.




a) Test Setup b) Specimen details c) Section details

Figure 1. Test setup and specimen details.

### Concrete and Steel

Each specimen was cast particularly with 3 batches of concrete with the cement mixer. Portland cement and maximum 15 mm size gravel were used in each batch in order to achieve nominal 28-day target strength of 15 MPa. The specimens were cast vertically and vibrators were used to prevent segregation at the test region. The concrete strengths of the specimens were listed in Table 1. The plain bars which were used to form the specimens, had 293 MPa yield stress, $f_y$, and 420 MPa ultimate stress, $f_u$. The stub' s reinforcing cage was formed with four 16mm bars at top and bottom with 8 mm bars for transverse reinforcement in order to prevent a failure of the specimen away from the test region.

### CFRP Application

The specimens were strengthened by using carbon-fiber wrapping system. The CFRP plies had 0.165 mm thickness and an elasticity modulus of 230000 MPa with a rupture strain of 0.015 according to the data reported by the manufacturer. At the first phase of the implementation, the corners of each column were rounded to a radius of 30 mm. The undercoat was applied on the test region of the column using a brush after the rounding process. After rounding off the corners, epoxy based mortar was applied at the designated length of the potential plastic hinge region (500 mm) and finally FRP sheet was wrapped around the test region of the column (500 mm) starting from 15 mm above the column-stub interface. 3 CFRP anchorages were present along the test region at heights of 50, 250, 450 mm. These anchorages were inserted 80 mm into the column and excessive 50 mm of the anchorages were bonded to the confining CFRP sheets (Fig. 2). The anchorages were placed to prevent debonding of the overlap section of the CFRP sheet during the test. The strengthened specimens were ready for the test after duration of one week.

Table 1. Details of test specimens.

| Specimen | Specimen Properties | | | | Longitudinal Steel Ratio | Axial load level, $P/P_0$*** | CFRP Implementation | |
|---|---|---|---|---|---|---|---|---|
| | $f_c'$ | $f_y$ | Reinforcement | | | | | |
| | *(MPa)* | *(MPa)* | **Longitudinal** | **Transverse** | *(%)* | *(%)* | **Ply No** | **Strengthening** |
| S-L-0-00 | 14.0 | | | | | 34 | 0 | Reference |
| S-L-1-00 | 19.4 | | | | | 27 | 1 | NL* |
| S-L-1-34 | 14.0 | 293 | 8 x 18mm (plain bars) | D=10mm at 200 (plain bars) | 1.66 | 34 | 1 | UL** |
| S-L-2-00 | 11.4 | | | | | 39 | 2 | NL |
| S-L-2-32 | 15.6 | | | | | 32 | 2 | UL |

* NL indicates strengthening intervention was made under no load.
** UL indicates strengthening intervention was made under axial load.
*** $P_o = 0.85 f_c' A_g + A_s f_y$

a. b. c. d. e.

Figure 2. CFRP Application: a) Rounding of corners and undercoat application, b) CFRP wrapping, c) Column after wrapping, d) Anchorage insertion, e) CFRP wrapped column with anchorages.

### Instrumentation and Testing

The specimens were carefully instrumented to obtain the required data at different drift levels. Linear Variable Differential Transducers (LVDTs) were used to measure horizontal deflections. Rotations at critical regions were measured by using eight dial gages. Eight electrical strain gages were placed on the longitudinal bars to record steel strains. The applied lateral and axial loads were measured by load cells. All specimens were instrumented to measure hinging region rotations both relative to the critical section and surface of the column-stub. The difference between the two readings was accepted as concentrated rotations due to the slip of the column reinforcement in the footing. Possible movement of the column footing relative to the laboratory strong floor was measured by using two additional dial gages. Columns were guided with 4 rollers between the guide rails to assure bending in the plane of loading. The details of the test setup and locations of the instruments installed are shown in Fig. 1.

The specimens were tested under constant axial load and cyclic lateral displacement excursions were imposed to simulate the seismic demand. The axial load had been applied on the specimen before lateral loading began. For specimens tested under load, CFRP wrapping was performed and axial load was maintained about one week on the specimen to ensure proper curing of epoxy resin. Then, the specimen was subjected to lateral cyclic displacement excursions. The drift levels were incremented by 0.5% until the drift level of 3%, for (three cycles for each drift level). Following displacement excursions beyond 3% drift level were incremented by 1% having two cycles at each drift level.

**Test Observations**

Responses of each specimen were obtained in the form of applied lateral load – column tip deflection ($P - \Delta$), and moment – curvature, ($M - K$), curves. The lateral deflection readings were taken from the LVDTs located at the tip of the column where the lateral load was applied. The curvature was computed by using the displacement readings of the dial gages located 350 and 50 mm away from the column-stub interface. The readings that were taken from 50 mm away from the interface were used to compute the displacements due to the slipping of the reinforcing bar. The $P - \Delta$ and $M - K$ responses of the specimens were shown and important events during testing such as cracking at the column-stub interface, debonding of CFRP sheet and fracture of the CFRP sheet were marked on the graphs that are shown in Fig. 3. In order to compare the specimens, normalization process was performed by dividing the force quantities by the yield values (moment, $M_y$ and lateral load, $P_y$) obtained using standard sectional analysis procedures at first longitudinal bar yielding of the reference specimen.

All of the test specimens experienced a similar failure mode in the column base as a result of column plastic hinging. In the first cycles of the lateral displacement excursions, flexural cracks were observed. The flexural cracks opened further and joined at both faces as the displacement excursions increased. The column-stub interface cracked at a drift level of about 1% and after that stage, rotations due to bar-slip increased as a result of widening of this interface crack. The yielding of the longitudinal reinforcement took place at a drift level of about 1%. The observed length of the plastic hinge was about the same size as the depth of the section, h. The strengthened specimens failed with a sudden explosion due to the rupture of the CFRP followed by debonding of the CFRP sheet. The test results are summarized in Table 2. Normalized load-deformation and moment curvature response (for the plastic hinge region) of the specimens including both the cyclic response and the envelope behavior are presented in Figs. 4 to 5.

Table 2. Test Results.

| Specimen | Yield | | | Ultimate | | $M_u/M_y$ | Interface cracking | CFRP | | 20% Capacity Drop |
|---|---|---|---|---|---|---|---|---|---|---|
| | $P_y$ | $M_y$ | $K_y$ | $P_u$ | $M_u$ | | | Swell | Rupture | |
| | *(kN)* | *(kNm)* | *(rad/km)* | *(kN)* | *(kNm)* | | *u, Drift (%)* | *u, Drift (%)* | *u, Drift (%)* | *$u_u$, Drift (%)* |
| S-L-0-00 | 61.8 | 123.6 | 10.85 | 67.4 | 134.8 | 1.09 | 0.5 | 1.50 *(crushing)* | | 2.5 |
| S-L-1-00 | 71.7 | 143.4 | 11.94 | 85.5 | 171.0 | 1.19 | 1.0 | 2.5 | 4.0 | 6.0 |
| S-L-1-34 | 61.8 | 123.6 | 10.85 | 75.2 | 150.4 | 1.22 | 1.0 | 2.5 | 5.0 | 6.0 |
| S-L-2-00 | 53.3 | 106.6 | 9.86 | 67.2 | 134.4 | 1.26 | 1.5 | 3.0 | 7.0 | 8.0 |
| S-L-2-32 | 66.9 | 133.8 | 11.94 | 83.6 | 167.2 | 1.25 | 1.5 | 3.0 | 6.0 | 8.0 |

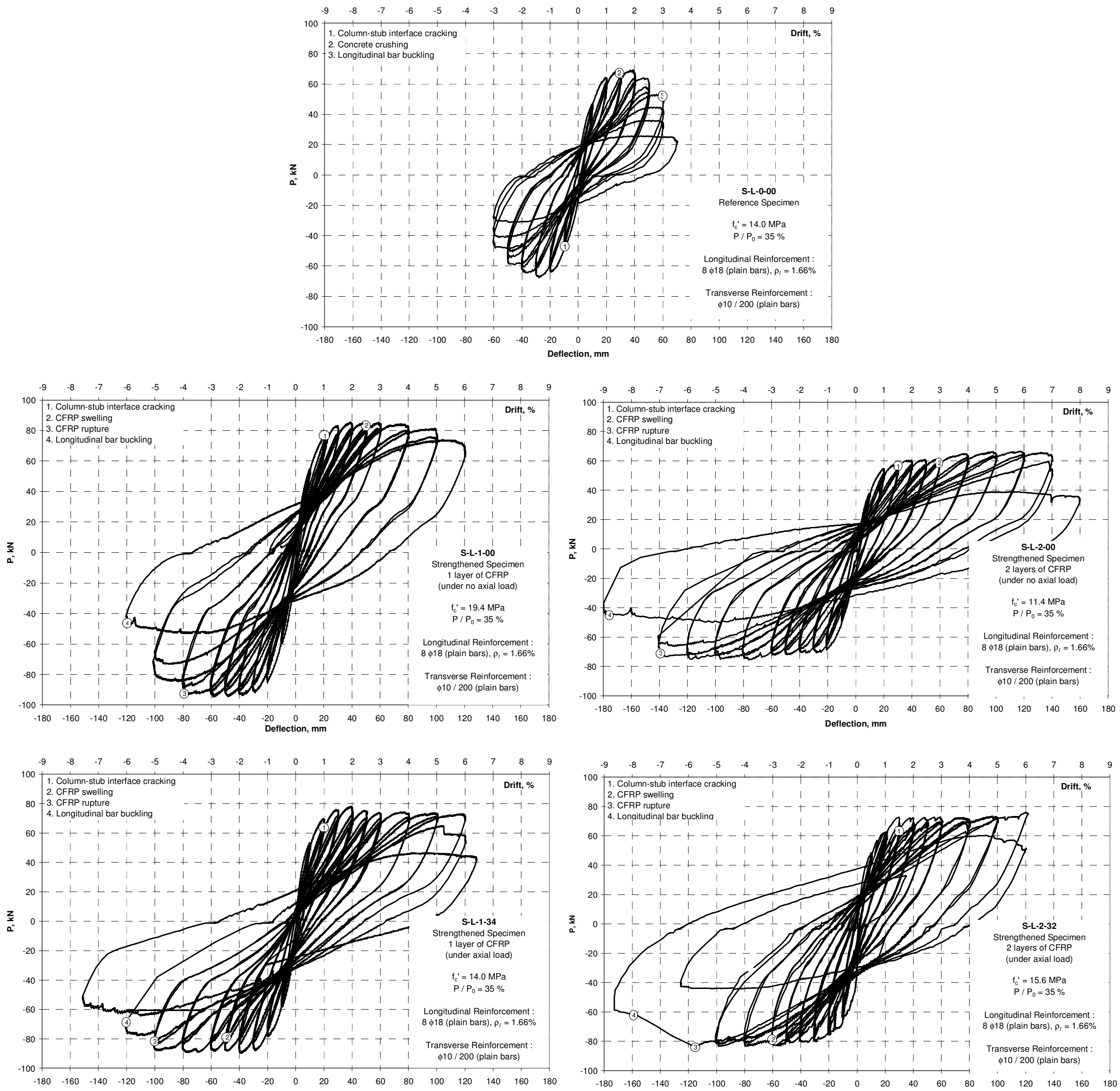



Figure 3. Load vs. deflection behavior of the specimens.

### ***Control Specimen, S-L-0-00***

In the reference specimen, S-L-0-00, evenly distributed horizontal flexural cracks developed at both faces of the column at heights of 200 to 1000 mm. The column-stub interface cracked at 0.5% drift and increasing load cycles made the column experience inelastic deformations and as a result of widening of the interface crack, slipping of the reinforcement increased. The lateral load resistance started degrading as a result of concrete crushing at the base at a height of approximately ‘h’ at 1.5% drift. Longitudinal bar buckling occurred at a drift of 2.5% the lateral loading capacity of the column decreased significantly (below 80% of ultimate).

### ***Strengthened Specimens, S-L-1-00, S-L-1-34***

The strengthened specimen, S-L-1-00, was wrapped with 1 ply of CFRP. Flexural cracks formed over the wrapped region at heights from 650 to 1000 mm in the first cycles of deformations. These cracks were closer to each other than those observed in the reference specimen. In the following cycles, the flexural cracks widened above the wrapped region and the column-stub interface cracked at about 1% drift. Keeping the lateral load resistance constant, the column deformed to higher drift values while widening the interface crack was observed. At 2.5% drift horizontal CFRP cracks occurred along a height of 350 mm from the column base and at the other side CFRP started to debond as a result of compression tension cycles imposed on it. The confining effect of the CFRP prevented the column bar buckling and increased the slipping of the reinforcement at the stub-column interface. First rupture in CFRP occurred at 4% drift and the lateral load resistance started to decrease. This degrading behavior was observed until 5% drift ratio followed by an explosive rupture at the CFRP at the end of the test resulting in significant reduction of lateral load. The companion specimen, S-L-1-34, also experienced a similar behavior. The drift levels at which interface cracking and CFRP debonding took place, were identical. The drift ratio, at which the CFRP sheet ruptured, was higher than the S-L-1-00 but this change did not affect the ultimate deflection of the column. Both specimens dropped below 80% of their lateral load capacities at 6% drift.

***Strengthened Specimens, S-L-2-00, S-L-2-32***

The specimen S-L-2-00, which was wrapped with 2 plies of CFRP, behaved in a similar manner with the specimen S-L-2-32. In the first cycles, flexural cracks were formed evenly between 500 to 1000 mm. The column-stub interface cracking and CFRP swelling occurred at 1.5% and 3% drifts respectively in both of the specimens. Wrapping the specimen with 2 plies of CFRP approximately doubled the drift capacity of the specimens compared to those wrapped with 1 ply of CFRP. Specimen S-L-2-32 had a very similar behavior by having similar crack locations and hinge length. CFRP rupture took place at drifts of 7% and 6% for S-L-2-00 and S-L-2-32, respectively. 20% drop of column capacity occurred at 8% for both of the specimens.

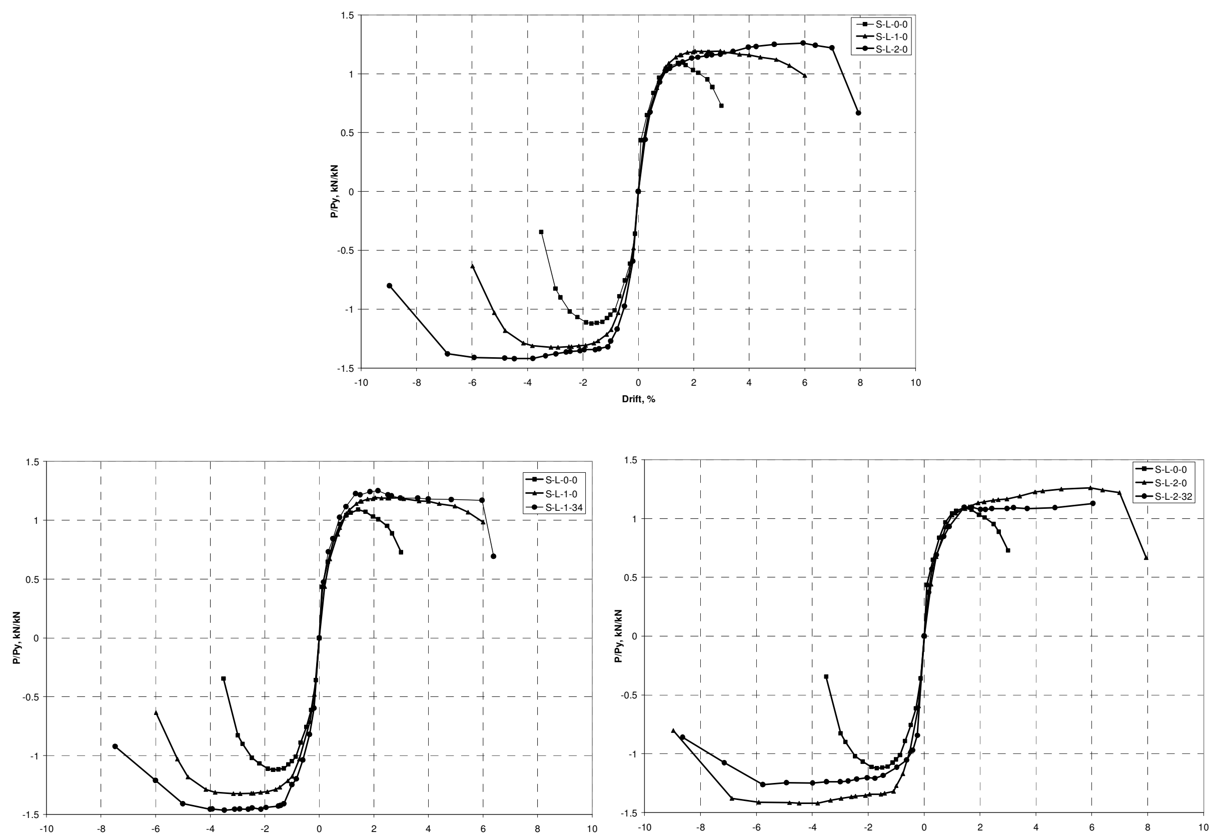



Figure 4. Envelope responses of normalized column shear versus drift ratio.

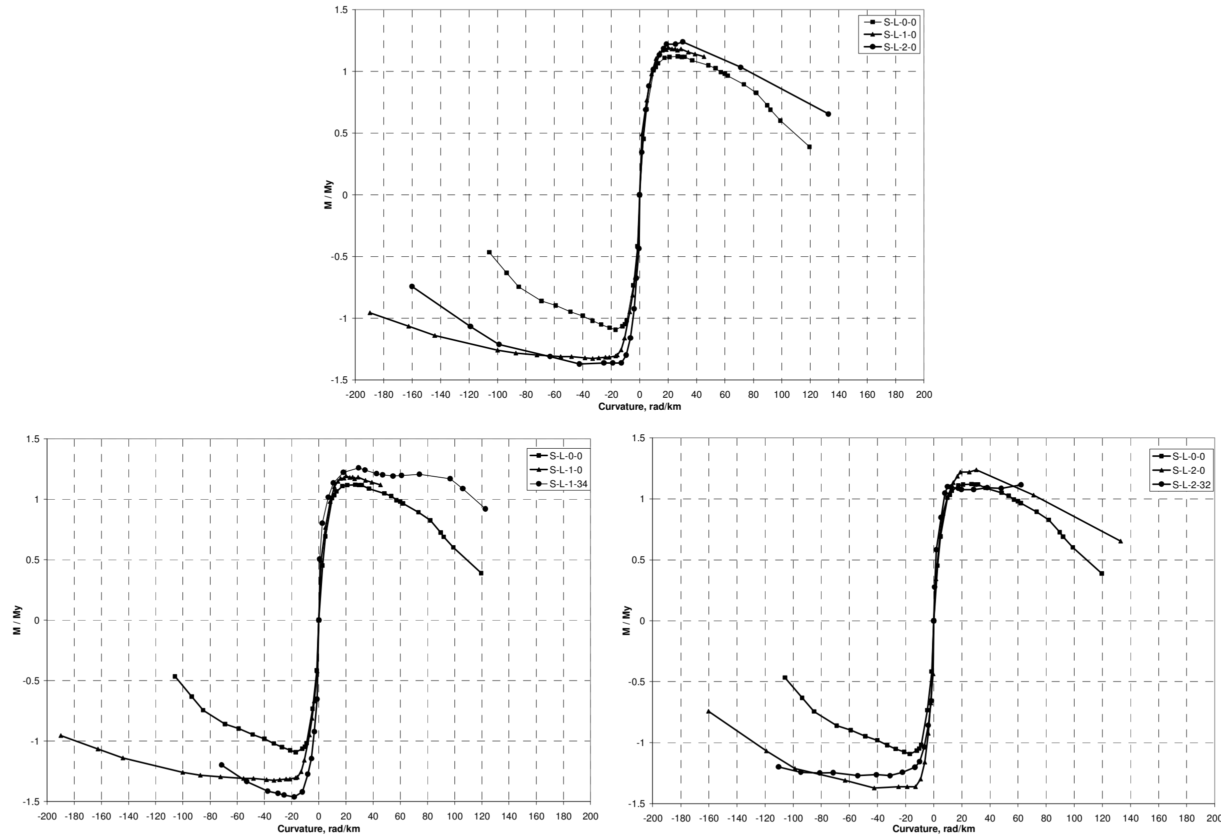



Figure 5. Envelope responses of normalized column moment versus curvature.

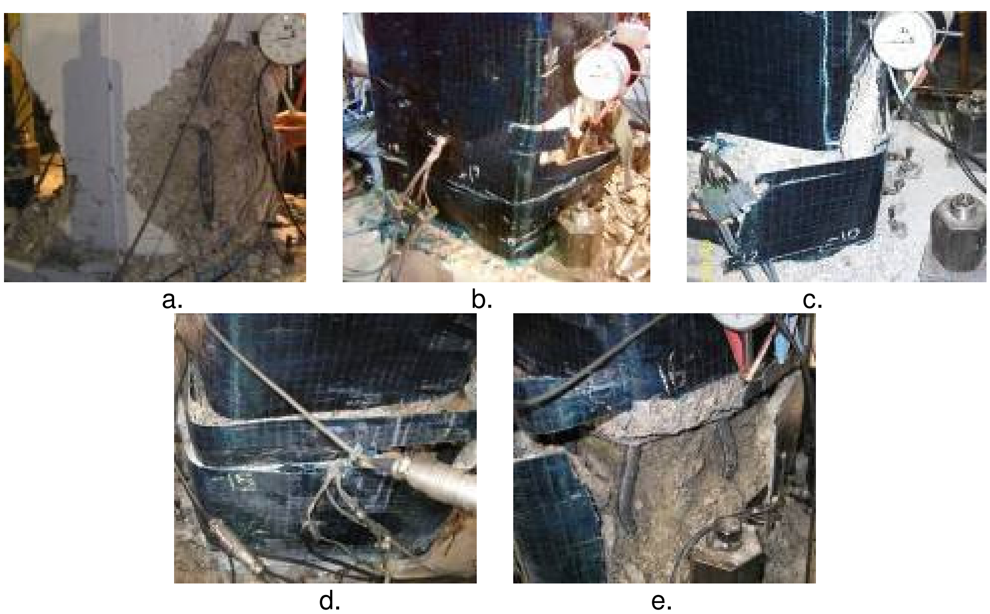



Figure 6. Columns at the end of testing. a) S-L-0-00, b) S-L-1-00, c) S-L-1-34, d) S-L-2-00, e)S-L-2-32.

## Discussions

### *Effect of CFRP layers*

Strengthening square columns with either 1 or 2 plies of CFRP sheets significantly improved the seismic performance (ductility and energy dissipation capacity) of the test specimens. The experiments showed that increasing the number of CFRP sheets wrapped around the column increased the displacement ductility of the specimens. However, negligible strength enhancement was observed (10 to 15%) compared to the control specimen, showing that FRP applications result in deformation capacity increase rather than strength increase. Interestingly, the enhancement in drift capacity at 20% strength drop was not in proportion to the amount of CFRP used. Wrapping 1 layer of CFRP sheet increased the ultimate drift ratio of the specimen S-L-1-34 by a factor of about 2.4 compared to the control specimen. On the other hand this ratio was about 3.2 for specimen S-L-2-32. This shows that doubling the amount of FRP does not translate itself to doubling the deformation capacity enhancement. Similar results can be observed upon comparing specimens S-L-1-00 and S-L-2-00.

### *Effect of strengthening under axial load*

The influence of strengthening under axial load was evaluated by comparing two sets of companion specimens that were wrapped by 1 ply and 2 plies of CFRP sheets. It can be observed that specimens S-L-1-00 and S-L-1-34 attained similar drift deformations. Although the axial load on specimen S-L-1-00 is slightly lower than that of specimen S-L-1-34 due to unexpected variation in concrete strength, it can be stated that effect of having the axial load during FRP wrapping has negligible influence on the ultimate drift ratios. Even the axial load levels were precisely the same; it is not unrealistic to expect a response from specimen SL-1-34 as good as if not better than specimen SL-1-00. A similar argument is also valid upon comparing specimens SL-2-00 and SL-2-32. It can be observed that effect of axial load during FRP application has again negligible influence. In this case, however, axial load variation of about 20% between the two specimens can be attributed to a better performance of specimen SL-2-00. However since drift levels of about 8%, which are well above expected drift demands for structural stability are of concern, it can easily be recognized that the effect of presence of axial load around 35% of the axial load carrying capacity does not significantly influence the deformation capacities of the retrofitted specimens.

### *Effect of plain bars*

The effect of plain bars can be examined by comparing the concentrated rotations that occurred within bottom 50 mm of the column (Fig. 7). In the reference specimen S-L-0-00 the column rotation due to bar-slip reached up to 40% of the ultimate drift ratio. Interestingly, wrapping 1 layer of CFRP sheet (S-L-1-00) increased the bar slip rotations to almost 65% of the total rotations in the plastic hinge region and the additional layer of CFRP in S-L-2-00 increased these rotations to a level of 80% as shown in Fig. 7. The specimens withstood larger drift demands without any strength degradation due to the confining effect of CFRP sheets preventing the buckling of the longitudinal bars and helping the specimen maintain its lateral load resistance. These experimental results revealed that upon CFRP retrofit, deficient columns with plain bars can undergo larger deformations compared to those with deformed bars as a result of increased bar-slip deformations. Hence, it is crucial to account for bar slip in seismic assessment and retrofit design of deficient reinforced concrete columns with plain bars.

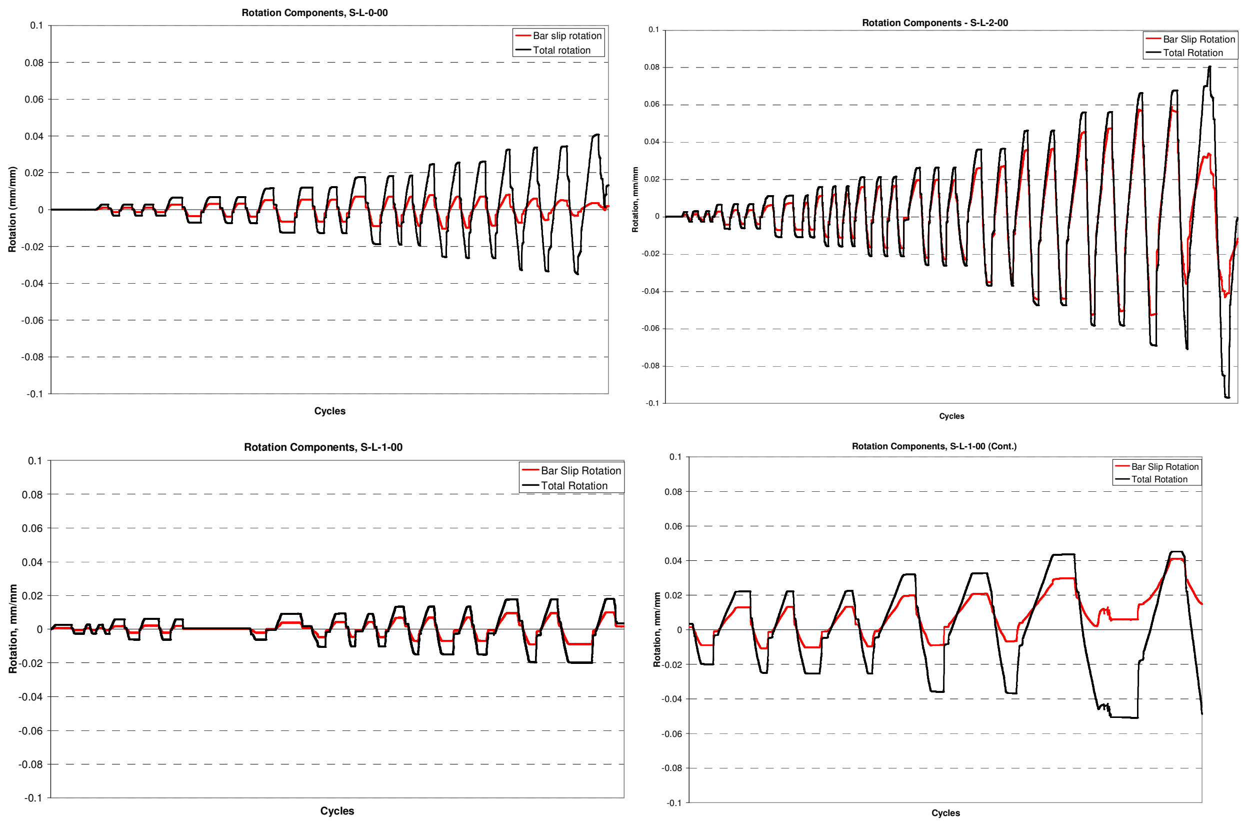



Figure 7. Rotation components at plastic hinge region of the specimens.

## Summary and Conclusions

Results from an experimental study, in which 5 column specimens were tested under constant axial load and cyclic lateral displacement excursions that simulated seismic forces, are presented in this study. Each specimen consisted of a 350 x 350 x 2000 mm column cast vertically together with a 1350 x 500 x 400 mm stub that represented a typical building column. 2 specimens were strengthened with 1 layer of CFRP sheet, 2 specimens were strengthened with 2 layers of CFRP sheets. Other remaining specimen was termed as reference specimen as it represented a deficient column that had insufficient transverse reinforcement and relatively low concrete compressive strength. The effect of CFRP confinement, presence of axial load during retrofit and plain bars were studied. The following conclusions can be drawn from this study:

1. The number of CFRP sheets used to confine plastic hinge regions of columns significantly improved the seismic behavior of the deficient columns. Although negligible lateral load carrying capacity enhancement was observed (~10-15%), significant increase in ultimate drift and ductility were obtained. While increasing the number of plies that were wrapped around the column improved the seismic performance (drift capacity), the improvement was not proportional to the increase in confinement provided by CFRP.

2. Wrapping the column critical region under an axial load level of about 35% of the axial capacity did not have a considerable influence on the behavior of the columns. The columns that were strengthened under this axial load level behaved similarly with the companion columns that were wrapped under no axial load. The experimental results revealed that lateral strains due to existing axial load on the column had no significant effect on the behavior of the strengthened columns. However, additional studies are needed to further support this result at higher axial load levels.

3. Use of plain bars can result in a higher contribution of bar-slip displacement to the total displacements. In the case of reference specimen, this contribution was about 40% maximum, whereas for strengthened specimens contribution of bar slip rotations was in the order of 65 to 80% of the total plastic hinge rotations. This shows that it is necessary to account for bar-slip induced displacements in the assessment and retrofit design of deficient RC columns.

## References


Iacobucci, R. D., Sheikh, S. A., Bayrak, O., 2003. Retrofit of Square Concrete Columns with Carbon-Fiber-Reinforced-Polymer for Seismic Resistance, *ACI Structural Journal,* 100-S81, 785-793.

Seible, F., Priestley, M. J. N., Hegemier, G. A., Innamorato, D., 1997. Seismic Retrofitting of RC Columns with Continuous Carbon Fiber Jackets, *Journal of Composites for Construction, May,* 52-62.

Sheikh, S. A., Yau, G., 2002. Seismic Behavior of Concrete Columns Confined with Steel and Fiber-Reinforced Polymers, *ACI Structural Journal,* 99-S8, 72-80.