Proceedings of the 9th U.S. National and 10th Canadian Conference on Earthquake Engineering
Compte Rendu de la 9ième Conférence Nationale Américaine et
10ième Conférence Canadienne de Génie Parasismique
July 25-29, 2010, Toronto, Ontario, Canada • Paper No 892

SEISMIC RETROFIT OF RECTANGULAR RC COLUMNS USING CFRP WRAPPING AND CFRP ANCHORS

Min-Lang Lin[1], Keh-Chyuan Tsai[2], Chih-Tsung Lin[3] , Pei-Ching Chen[4] and Ying-Han Wu[5]

ABSTRACT

Several buildings were severely damaged during the Chi-Chi earthquake in Taiwan in 1999. To improve the seismic performance of the existing buildings, researches on retrofit have been studied for several years. Research results showed that CFRP wrapping was ineffective due to the bulging effect on the column face. This paper is focused on the retrofit techniques for rectangular RC columns using the proposed CFRP wrapping conjugated with CFRP anchors. A total of five full-scale RC column specimens were constructed. One as-built benchmark specimen, and the other four specimens using CFRP wrapping and CFRP anchors are divided into two major groups: two specimens were shear capacity retrofitted and the other two were focused on flexural ductility. The specimens were subjected to constant axial force and reverse-curvature moment during the cyclic tests. The objectives of this study include: (1) deriving and introducing the design concept of the usage of CFRP anchors (2) evaluating the enhanced shear capacity and flexural ductility, and (3) comparing and analyzing the behavior of tested specimens. Experimental results demonstrated that the specimens retrofitted by CFRP wrapping with CFRP anchors improved the seismic behavior compared with the one retrofitted by CFRP wrapping only. The design procedures are proposed as well.

Introduction

A number of reinforced concrete (RC) buildings were severely damaged or collapsed in Taiwan during the 1999 Chi-Chi earthquake. It was observed that a lack of ductility capacity of the ground-floor columns was the key factor, among many others, responsible for the collapse of these buildings. In particular, numerous RC buildings were severely damaged due to the shear failure of columns. Since the occurrence of the Chi-Chi earthquake, the building codes were

[1]Associate Research Fellow, National Center for Research on Earthquake Engineering, Taipei, Taiwan
[2]Professor, Dept. of Civil Engineering, National Taiwan University, Taipei, Taiwan
[3]Associate Professor, Dept. of Civil Engineering, National Taipei University of Technology, Taipei, Taiwan
[4]Assistant Research Fellow, National Center for Research on Earthquake Engineering, Taipei, Taiwan
[5]Graduate Research Assistant, Dept. of Civil Engineering, National Taipei University of Technology, Taipei, Taiwan

modified. The demand of the design base shear has been increased. Nevertheless, there still exist a large number of RC buildings without sufficient column shear strength. Hence, seismic retrofitting to improve the columns' seismic strength and ductility has become an urgent research issue. A large number of tests have been conducted in National Center for Research on Earthquake Engineering (NCREE) in recent years (Tsai and Lin 2002) to evaluate the effectiveness of various retrofit schemes on RC building columns, walls or systems. It was observed that external confinement provided by CFRP wrapping was ineffective due to the debonding between CFRP sheets and column faces. In the preliminary study, test results demonstrated that the seismic performance of the rectangular RC columns was improved significantly by the CFRP wrapping and the CFRP anchors (Lin 2008). In this paper, seismic column retrofit result using the CFRP wrapping and the CFRP anchors is compared with the one without the CFRP anchors. The paper concludes with the key test results of the five specimens.

Design Criteria of CFRP wrapping and CFRP Anchors

Brief design criteria of CFRP wrapping and CFRP anchors are introduced in this chapter. All the specimens were designed based on the criteria. A CFRP anchor is made of a bolt rolled by CFRP sheet bonded with epoxy. The end of the CFRP anchor is cut to spread the fiber sheet evenly. Figure 1 shows the dimensional notation of a CFRP anchor.   is the width of the covering CFRP sheet,   is the length of the CFRP anchor, and   is the length of the spread tail.

Shear and Flexural Strength Retrofit

CFRP wrapping can be considered as continuous stirrups along the column. The shear strength provided by CFRP is:

$$V_j = 2\, t_j \varepsilon_{jd}\, d \cot\theta \tag{1}$$

Where, V_j is the shear strength provided by CFRP wrapping, t_j is the thickness of the CFRP layers, ε_{jd} is the design strain of CFRP, E_{jd} is the elastic modulus of CFRP, d is the effective depth of the column, and θ is the angle between shear cracks and the column face.

The flexural strength of the column can be obtained by sectional analysis. The following equilibrium equation must be satisfied:

$$P + \sum T + T_f = C_c + \sum C_s + C_f \tag{2}$$

Where, P is axial force, T is the tensile force provided by reinforcements, T_f is the tensile force provided by CFRP sheets, C_c is the compressive force provided by concrete, C_s is the compressive force provided by reinforcements, and C_f is the compressive force provided by CFRP sheets. C_f is assumed zero since CFRP sheet can hardly resist compressive force. T_f is obtained by the following equation:

$$T_f = t_j D \varepsilon_{jd} E_{jd} \tag{3}$$

Where D is the column depth.

Ductility Retrofit

Following the latest Taiwan Seismic Provisions for RC buildings, the equivalent transverse pressure can be expressed as:

$$\frac{A_{sh} f_{yh}}{s h_c} \geq 0.3 f_c^{'} \left(\frac{A_g}{A_{ch}} - 1 \right) \tag{4}$$

$$\frac{A_{sh} f_{yh}}{s h_c} \geq 0.09 f_c^{'} \tag{5}$$

Where, A_{sh} is the total area of transverse reinforcements, f_{yh} is the yield stress of transverse reinforcements, s is the spacing of transverse reinforcements, h_c is the center-to-center distance of the transverse reinforcements, A_g is the gross area of the column, A_{ch} is the area enclosed by the transverse reinforcements, and f'_c is the compressive strength of concrete. Considering the confinement provided by the external jacketing, Eq.(4) and Eq.(5) can be written as:

$$t_f = \frac{B}{2\varepsilon_{jd} E_{jd}} \left\{ \left\{ 0.3 f_c^{'} \left(\frac{A_g}{A_{ch}} - 1 \right), 0.09 f_c^{'} \right\}_{\max} - \frac{A_{sh} f_{yh}}{s h_c} \right\} \tag{6}$$

Where, t_f is the required thickness of the CFRP sheet, B is the width of the gross column. In this research, ε_{jd} is 0.004 for design. Since CFRP anchors are supposed to be applied with CFRP wrapping, the confinement provided by CFRP anchors should be taken into consideration. Eq.(6) can be re-written as:

$$f_{an} = \left\{ 0.3 f_c' \left(\frac{A_g}{A_{ch}} - 1 \right),\ 0.09 f_c' \right\}_{\max} - \frac{A_{sh} f_{yh}}{s\, h_c} - \frac{2 f_{jd} t_f}{B} \tag{7}$$

Where, f_{an} is the confinement stress provided by CFRP anchors, $f_{jd}=E_{jd}\varepsilon_{jd}$ is the design stress of CFRP.

Tensile and Bond Strength of CFRP Anchor

The tensile strength of CFRP anchor is provided by the covering CFRP sheet:

$$F_{an} = t_0 D_r f_{jd} \tag{8}$$

Where, F_{an} is the tensile strength of CFRP anchor, t_0 is the thickness of the covering CFRP sheet.

The bond strength of CFRP anchor is mostly controlled by the shear strength of the epoxy (τ_{ep}) filled between the CFRP sheet and the bolt. A reduction factor of 0.6 is preliminarily adopted for calculating the allowable bond strength of CFRP anchor:

$$U_{an} = 0.6\pi D_a L_a \tau_{ep} \tag{9}$$

Where, U_{an} is the bond strength of CFRP anchor, D_a is the diameter of the CFRP anchor. The designed bond strength should be larger than the tensile strength to prevent from bond failure. Hence, L_a and D_r can be obtained by combining Eq.(8) and Eq.(9). Figure 2 shows the corresponding notation of Eq.(8) and Eq.(9).

Anchorage Force of CFRP Anchor

The anchorage force of CFRP anchor is provided by the connection of the spread tail and epoxy. The mechanical behavior is complex on the interface of the tail and epoxy, therefore, a reduction factor 0.5 is adopted for calculating the anchorage strength of CFRP anchor:

$$0.5 \times 2\tau_{ep} A_{an} = F_{an} \tag{10}$$

Where, A_{an} is the required area of the spread tail. It is difficult to spread the tail perfectly such that a reduction factor of 0.5 is adopted for calculating the effective area of the spread tail:

$$A_{an} = 0.6\pi D_a L_r \tag{11}$$

By combing Eq.(10) and Eq.(11), the required tail length of CFRP anchor is obtained. The design parameters and procedures are described in detail in reference (Lin 2009).

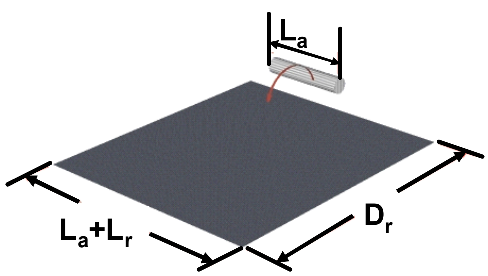


Figure 1. The dimensional notation of the covering CFRP sheet.

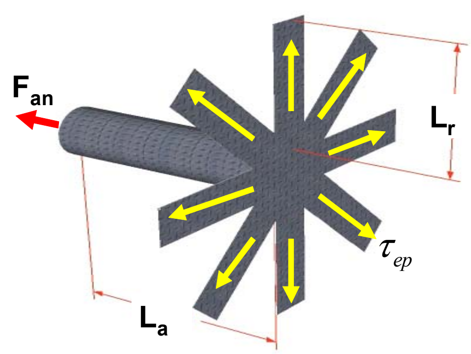


Figure 2. The dimensional notation of a CFRP anchor.

Specimen Design

In many existing RC buildings, the details of 90o hooked stirrups and without the use of cross ties in columns are non-ductile and not meeting the confinement requirements in current design provision. In this study, a total of five specimens were designed based on reinforcing details commonly found in the old existing RC buildings in Taiwan. The column reinforcing details of the five columns are identical, consisting of 12-22mm diameter vertical bars. The spacing of 10mm diameter stirrups is 250mm. The column height is 2250mm and the cross section is 450mm x 450mm. They were expected to have flexural-shear failure without retrofitting. The crosshead and the foundation of each specimen were designed to have sufficient strength to resist the lateral and vertical loads without any failure occur. The fabrication details of the specimens are shown in Fig.3. The tension test results of reinforcements are shown in Table 1. The compression test results of concrete cylinders are shown in Table 2.

Table 1 Tensile test results of reinforcements

Bar Diameter (mm)	**Nominal Strength (MPa)**	**Yield Strength (MPa)**	**Ultimate Strength (MPa)**
10	280	354	580
16	280	368	521
22	420	491	658
25	420	423	664

Table 2 Compression test results of cylinders

Events	**Nominal Strength (MPa)**	**Compression Strength (MPa)**
Foundation	21	25.0
Column	21	22.3

Table 3 Instruction of tested specimens

<table>
<tr><th colspan="2">Specimen</th><th>Retrofit Target</th><th>Retrofit Scheme</th></tr>
<tr><td colspan="2">R08BM</td><td>benchmark</td><td>—</td></tr>
<tr><td rowspan="2">Group1</td><td>R08RF1</td><td>shear strength
ductility</td><td>CFRP</td></tr>
<tr><td>R08RF2</td><td>shear strength
ductility</td><td>CFRP &
CFRP anchors</td></tr>
<tr><td rowspan="2">Group2</td><td>R08RF3</td><td>shear strength
flexural strength
ductility</td><td>CFRP &
CFRP anchors</td></tr>
<tr><td>R08RF4</td><td>shear strength
flexural strength
ductility</td><td>CFRP &
CFRP anchors</td></tr>
</table>

After the construction was completed, the specimens were retrofitted with four different schemes using CFRP wrapping and CFRP anchors. The retrofitted specimens can be divided into two groups based on its respective retrofit target. Specimen R08BM is a benchmark to be compared with the other four retrofitted specimens. Two specimens, Specimen R08RF1 and Specimen R08RF2, were retrofitted for increasing the shear capacity and were denominated as Group1. They were both wrapped by three layers of CFRP sheets in transverse direction. In addition, the CFRP anchors were used in Specimen R08RF2. The other two specimens, Specimen R08RF3 and Specimen R08RF4, were for enhancing the flexural strength and ductility and were denominated as Group2. Both of them were wrapped by two layers of CFRP sheets in transverse direction and two additional layers of CFRP sheets in longitudinal direction to retrofit the flexural strength. CFRP anchors were used on both specimens, however, with different link mechanisms between the foundation and the CFRP sheets as shown in Fig. 4. In the preliminary research (Lin 2008), the column surface was slightly bulgy after CFRP anchors were applied due to the thickness of the tail of CFRP anchors. In this paper, it was improved by removing some concrete skin of column before CFRP was wrapped on the specimen. Figure 5 shows the surface of CFRP wrapping with CFRP anchors after the retrofit was completed. Each specimen was named as described in Table 3.

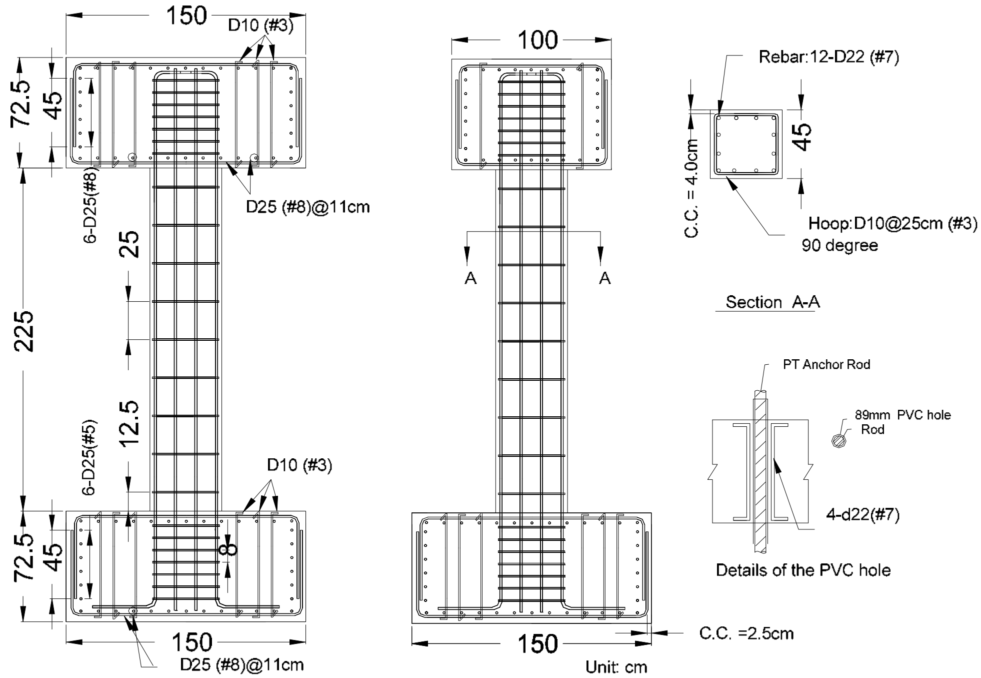


Figure 3. Design details of the specimens.

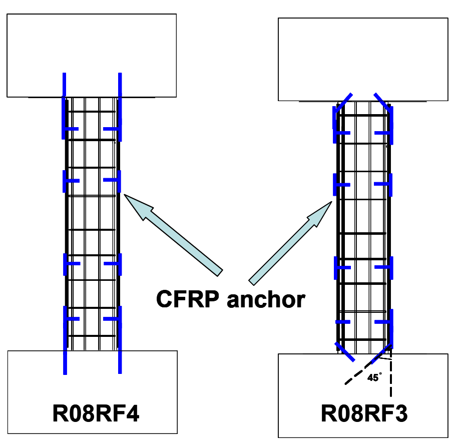


Figure 4. Illustration of link mechanisms of Specimen R08RF3 and Specimen R08RF4.

Figure 5. Illustration of the specimen surface after retrofitting.

Test Setup and Experimental Results

It is intended to have the test specimens be subjected to high axial forces and reverse-curvature moments to reflect the real conditions of RC columns. Therefore, an L-shaped test frame was designed accordingly to meet the requirement. Test setup is shown in Fig.6. Total four servo-controlled hydraulic actuators were used in the test. Two horizontal hydraulic actuators provided lateral force and the other two vertical hydraulic actuators supplied axial loads. Among the two horizontal actuators, one was displacement-controlled by the external transducer and the other one was slaved to have the same force as the displacement-controlled one. On the other hand, one of the two vertical actuators was force-controlled and the other one was slaved to have the same displacement as the force-controlled one. This control algorithm made the lateral force passing through the middle height of the column, where the bending moment is zero during the test. Moreover, the two vertical actuators were kept in a same stroke during the test to make the L-shaped frame move back and forth horizontally. Hence, the specimens were subject to constant total axial force without rotation on the top of the crosshead. The lateral displacement time history is shown in Fig.7. The test ended once the strength of the specimen became lower than 80% of its ultimate strength.

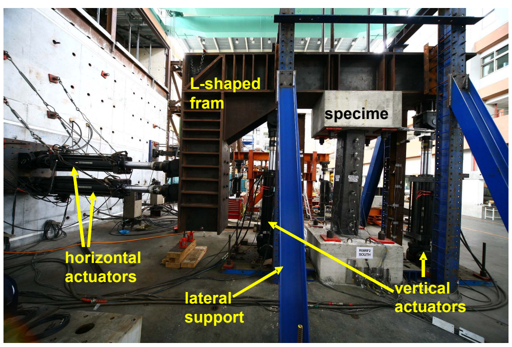


Figure 6. Test setup.

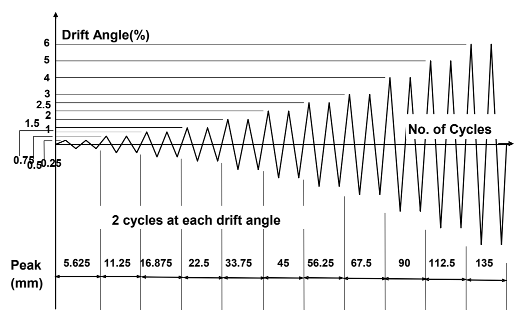


Figure 7. Time history loading protocol.

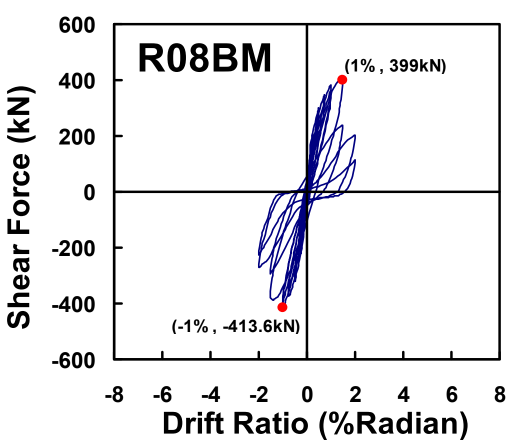


Figure 8. Hysteresis loop of R08BM

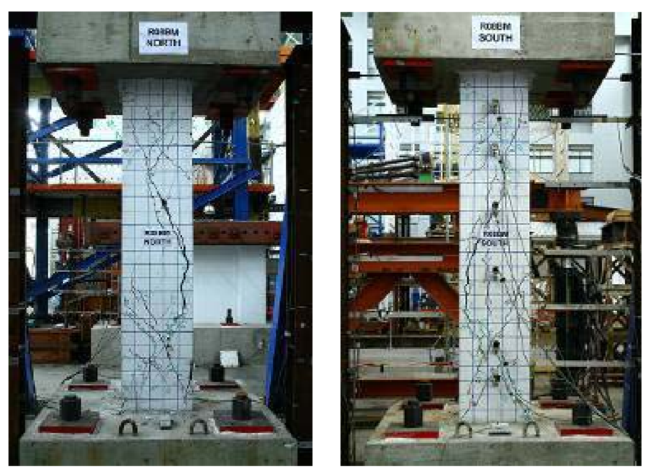
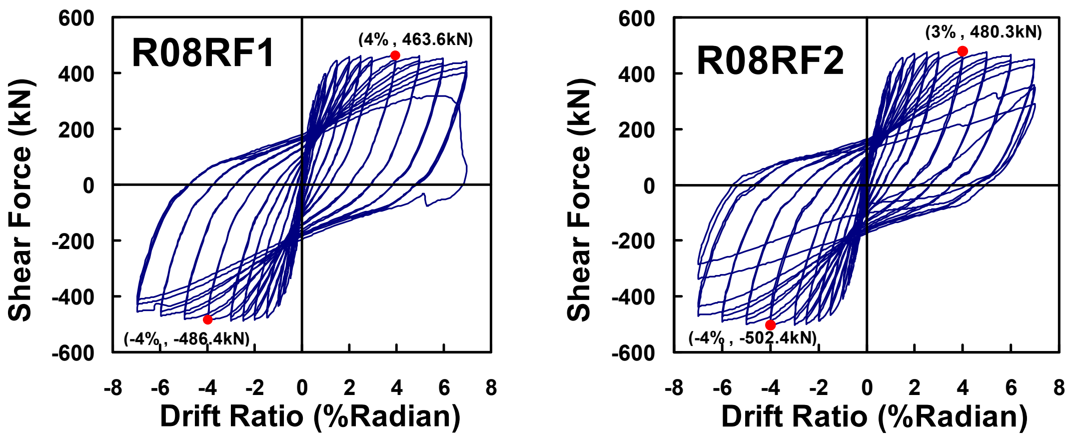


Figure 9. Failure of R08BM

Specimen R08BM was designed to have flexural-shear failure mode. When the drift ratio reached 0.75% radian, shear cracks occurred at the top and bottom of the column. Meanwhile, the shear force was still increasing. When the drift ratio reached 1.5% radian, the strength of the specimen decayed and shear failure occurred. Figure 8 shows the hysteresis loop of Specimen R08BM. The ultimate moment caused by the maximum shear force was close to the plastic moment capacity. It was demonstrated that the specimen behaved as it was expected. Figure 9 shows the failure mode of Specimen R08BM.

Group 1: Both two specimens reached 7.0% radian drift ratio without loss of strength. The behaviors of the two specimens were almost the same. Larger displacement was not available due to the stroke limit of the lateral actuators. Hence, repeated cyclic loading with drift ratio of 7.0% radian was applied on the two specimens until the CFRP wrapping broke. For specimens R08RF1, the maximum lateral load was 486.4kN (pulling) developed in the first cycle of the 4% radians lateral drift angle. For R08RF2, the maximum lateral load was 502.4kN (pulling) in the first cycle of the 4% radians lateral drift angle. Specimen R08RF1 failed due to the fracture of the CFRP at the bottom of the column in the 3rd cycle. However, Specimen R08RF2 failed in the 5th cycle due to the low cycle fatigue of the reinforcements. The CFRP sheets were still bonded to the column face. Obviously, the usage of CFRP anchors delayed the fracture time of CFRP sheets and changed the failure mode from brittle failure of the CFRP sheets to flexural failure of the reinforcements. Figure 10 shows the hysteresis loops of the specimens in Group1. To compare with Specimen R08BM, both the ductility and the strength were enhanced significantly. Figure 11 shows the failure modes of the specimens in Group 1.



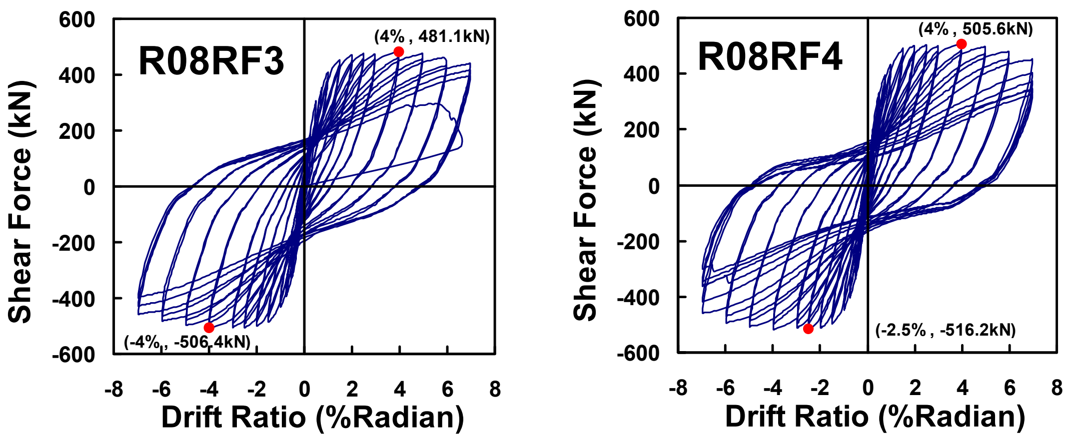
(a) (b)

Figure 10. Hysteresis loops of the specimens in Group 1 (a) R08RF1 (b) R08RF2

(a) (b)

Figure 11. Failure modes of the specimens in Group 1 (a) R08RF1 (b) R08RF2

Group 2: Both two specimens reached 7.0% radian drift ratio without loss of strength. Again, repeated cyclic loading with drift ratio of 7.0% radian was applied on the two specimens until the fracture occurred. For specimens R08RF3, the maximum lateral load was 506.4kN (pulling) developed in the first cycle of the 4% radians lateral drift angle. For R08RF4, the maximum lateral load was 516.2kN (pulling) in the first cycle of the 2.5% radians lateral drift angle. The CFRP anchors linked the longitudinal CFRP sheets and the foundation by plugging the CFRP anchors with the angle of 45° into the foundation in Specimen R08RF3. However, the CFRP anchors were plugged into the foundation vertically in Specimen R08RF4. It was expected to develop larger flexural strength by wrapping the CFRP sheets in longitudinal direction and the linking systems. Unfortunately, the links of both specimens broke under large deformation. Figure 12 shows the hysteresis loops of the specimens in Group 2. The initial stiffness of the two specimens increase slightly, but neither of the moment capacities increased evidently. Figure 13 shows the failure modes of the specimens in Group 2.



(a) (b)

Figure 12. Hysteresis loops of the specimens in Group 2 (a) R08RF3 (b) R08RF4

(a) (b)

Figure 13. Failure modes of the specimens in Group 2 (a) R08RF3 (b) R08RF4

Conclusions

Four different retrofit schemes have been tested in this research. The results can provide practical applications in the field. Conclusions for this paper are:

1. The breaks of the CFRP caused the failure of Specimen R08RF1 and Specimen R08RF2. However, the ductility of Specimen R08RF2 was better than that of Specimen R08RF1 due to the usage of CFRP anchors.
2. The link mechanisms of Specimen R08RF3 and Specimen R08RF4 were not practical. The moment capacity was not enhanced evidently. Further link mechanisms are necessary to be developed to retrofit the flexural strength by CFRP wrapping and CFRP anchors in the future.
3. Further researches on different structural components such as RC walls and RC beams are necessary to evaluate the performance of those retrofitted by CFRP wrapping and CFRP anchors.

References

Tsai, K. C., and Lin, M.L., 2002. Steel Jacket Retrofitting of Rectangular RC Bridge Columns to Prevent Lap Splice and Shear Failures, *Report No. NCREE-02-015*, National Center for Research on Earthquake Engineering.

Tsai, K. C., and Lin, M.L., 2002. Seismic Jacketing of RC Columns for Enhanced Axial Load Carrying Performances, *Report No. NCREE-02-016*, National Center for Research on Earthquake Engineering.

Lin, M.L., Chen, P.C., Tsai, K. C., and Wu, Y.H., 2008. Retrofit Tests on RC Columns Subjected to High Axial Force and Reverse-Curvature Moment, *Report No. NCREE-08-025*, National Center for Research on Earthquake Engineering.

Lin, M.L., Lin, C.T., Chen, P.C., Tsai, K.C., and Wu, Y.H., 2009. Seismic Retrofit of Rectangle RC Columns Using CFRP Wrapping and CFRP Anchors, *Report No. NCREE-09-014*, National Center for Research on Earthquake Engineering.