CYCLIC PERFORMANCE OF FULL-SCALE RC COLUMNS RETROFITTED USING EXTERNAL JACKETING METHODS

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ABSTRACT :

A total of seven full-scale specimens were constructed and tested at the Center for Research on Earthquake Engineering (NCREE) in Taiwan: one as-built benchmark specimen and the other six specimens were retrofitted using various methods. Using a stiff frame, reinforced concrete column specimens were subjected to high axial forces and cyclic reverse-curvature moments. A companion paper describing the emergency retrofit technology for improving the column load carrying capacity is to be presented by the Japanese collaborators in the 14WCEE. This paper presents the retrofit techniques for rectangular RC columns using three retrofit schemes. The objectives of this study include: (1) validating existing retrofit schemes using steel jacketing and CFRP wrapping (2) evaluating the CFRP retrofit schemes using the CFRP anchors conveniently made by hands, and (3) analyzing the responses of the tested specimens. Experimental results demonstrated that the seismic performance of the stated rectangular RC columns can be significantly enhanced by properly-constructed octagonal steel jacket. Comparing with the one retrofitted by CFRP wrapping only, the cyclic load carrying performance of the specimen was significantly improved by using the CFRP wrapping and the proposed CFRP anchors.

KEYWORDS: Seismic retrofit, Octagonal steel jacket, CFRP wrapping, CFRP anchors

1. 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. In order to improve the seismic performance of existing RC buildings, a Taiwan-Japan Cooperative Research Program on investigating the effective retrofit methods for reinforced concrete columns was launched at the Center for Research on Earthquake Engineering (NCREE) in 2006. Since the occurrence of the Chi-Chi earthquake, the building codes were 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. In fact, a large number of tests have been conducted in NCREE in recent years to evaluate the effectiveness of various retrofit schemes on RC building columns, walls or systems. Some of the retrofit methods have been adopted in the construction sites. For example, carbon fiber reinforced polymer (CFRP) wrapping, enlarged RC columns, and external steel jacketing are common. In this paper, seismic column retrofit result using the CFRP jacketing and the CFRP anchors is compared with the one without the CFRP anchors. The paper concludes with the key test results of the four specimens.

2. SPEICMEN DESIGN

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

$$\frac{A_{sh} f_{yh}}{sh_c} \geq 0.3 f_c^{'} \left(\frac{A_g}{A_{ch}} - 1 \right) \tag{2.1}$$

$$\frac{A_{sh} f_{yh}}{sh_c} \geq 0.09 f_c^{'} \tag{2.2}$$

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, Eqn.2.1 and Eqn.2.2 can be written as:

$$t_{rf} = \frac{B}{2 f_{rf}} \left\{ \left\{ 0.3 f_c^{'} \left(\frac{A_g}{A_{ch}} - 1 \right), 0.09 f_c^{'} \right\}_{\max} - \frac{A_{sh} f_{yh}}{sh_c} \right\} \tag{2.3}$$

Where t_{rf} is the required thickness of the external jacket, B is the width of the gross column, f_{rf} is the strength of the external jacket. All the external jackets of the specimens were designed based on Eqn.2.3.

In many existing RC buildings, the details of 90^o hooked stirrups and without the use of cross ties in columns are non-ductile and not meeting the confinement requirements prescribed in Eqns. 2.1 and 2.2. In this study, a total of four specimens were designed based on reinforcing details commonly found in the existing RC buildings in Taiwan. As shown in Fig. 1, the column reinforcing details of the four columns are identical, consisting of 12-25mm diameter vertical bars. The spacing of 10mm diameter stirrups is 250mm. The column height is 1800mm and the cross section is 600mm x 600mm. The fabrication details of the specimens are shown in Fig.1. The tension test results of reinforcements are shown in Table 2.1. All four specimens were constructed in two steps: (1) the foundations were first poured before pouring the columns; and (2) the cross heads were poured after the strength of the foundation had reached up to 70% of the nominal strength. The compression test results of concrete cylinders are shown in Table 2.2. After the construction was completed, three different types of retrofit methods were applied to the specimens. Each specimen was named as that described in Table 2.3. Octagonal steel jacketing retrofit scheme was first evaluated in 2002 in Taiwan where test results showed that the performance of the column was significantly enhanced. The CFRP wrapping technique is also a common and practical retrofit method in Taiwan. The performance of CFRP wrapped columns with or without the use of CFRP anchors is examined in this paper. The three different retrofit schemes adopted in the research are shown in Fig.2.

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.3. Two horizontal hydraulic actuators provided the lateral forces and the other two vertical hydraulic actuators supplied axial loads. The two vertical actuators were kept in a fixed stroke during the test to make the L-shaped frame move back and forth horizontally. The imposed lateral displacement time history is shown in Fig.4. The test was stopped once the strength of the specimen became lower than 80% of its peak strength.

Table 2.1 Tension test results of reinforcements

Reinforcing Bar	Nominal Strength （MPa）	Yield Stress （MPa）	Tensile Strength （MPa）
#3 (D=10mm)	280	374	550
#5 (D=16mm)	420	437	654
#8 (D=25mm)	420	490	673
#9 (D-29mm)	420	489	672

Table 2.2 Compression test results of cylinders

Location	Nominal Strength (MPa)	Compressive Strength (MPa)
Foundation	20.60	17.95
Cross Head	20.60	24.01
Column	20.60	23.48

Table 2.3 ID of the specimens

Specimen	Retrofit Method
R06-BM	No retrofit (benchmark)
R06-RF1	rectangular carbon fiber
R06-RF2	rectangular carbon fiber with CFRP anchor bolts
R06-OS1	octagonal steel jacket

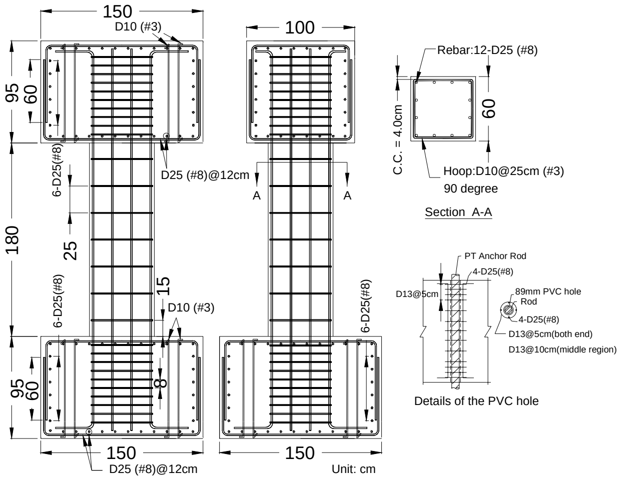
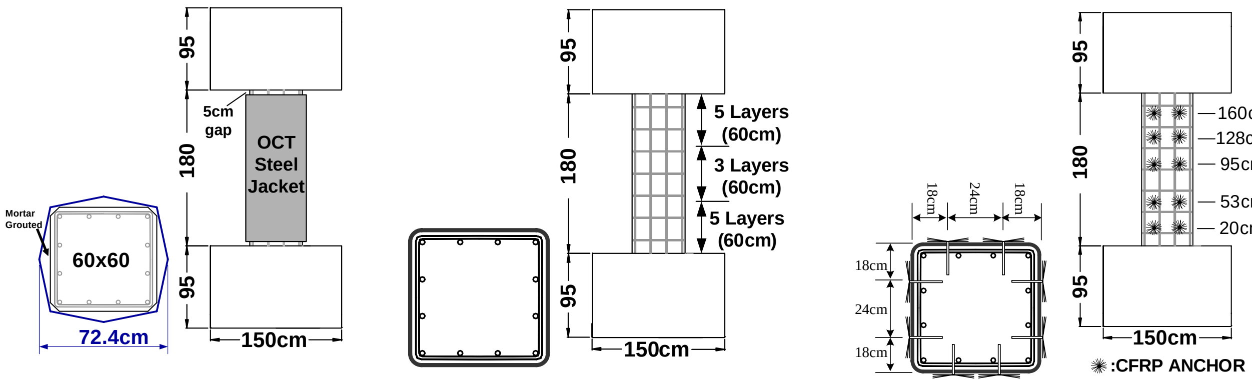


Figure 1 Design details of specimens



(a) R06-OS (b) R06-RF1 (c) R06-RF2

Figure 2 Retrofit schemes on specimens

Figure 3 Test setup

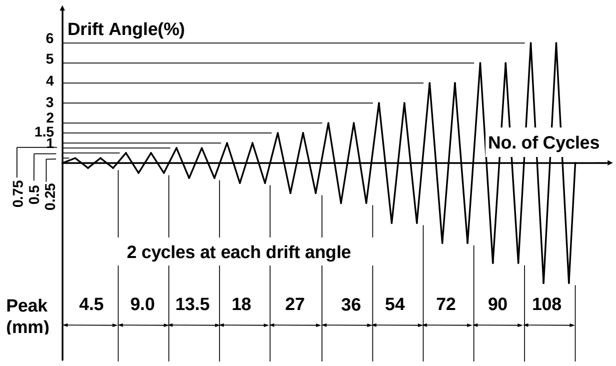


Figure 4 Displacement-controlled loading protocol

3. EXPERIMENTAL RESULTS

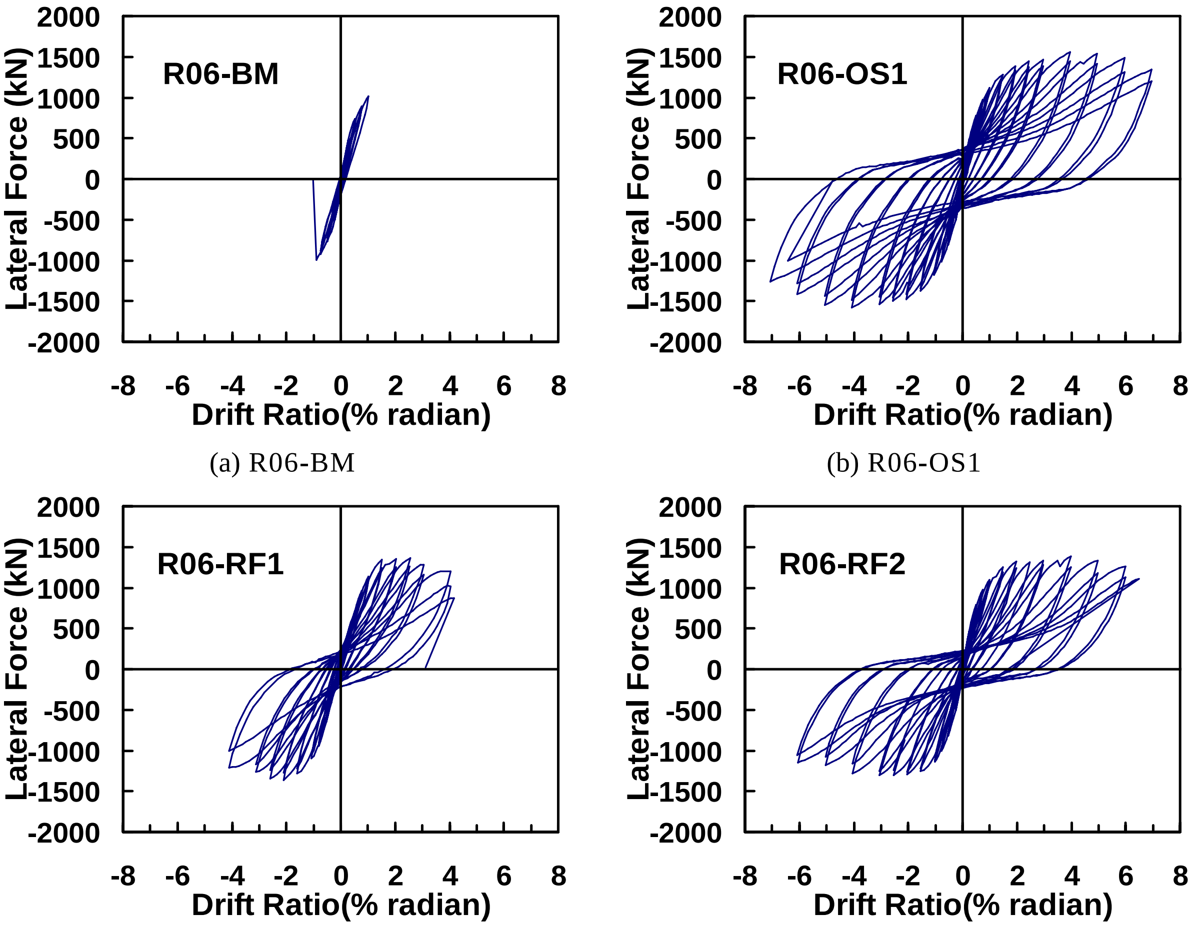
The benchmark specimen (R06-BM) was designed to fail in shear. When the drift angle reached the 1.0% radian, shear cracks occurred diagonally and the strength of the column decreased rapidly. The specimen retrofitted with the octagonal steel jacket, R06-OS1, had the reinforcements fractured due to the low cycle fatigue when the drift angle reached 7.0% radians. The strength and the ductility of the specimen were significantly enhanced with adequate confinement provided by the steel jacket. The failure mode was changed from shear failure to flexural failure. Specimens R06-RF1 and R06-RF2 both were wrapped with CFRP. In addition, forty CFRP anchors were applied on the four faces of the column of specimen R06-RF2. CFRP fracture occurred in both two specimens, but it was observed that the CFRP anchors delayed the fracture of the CFRP wrapping and improved the ductility of the column (increase the drift ratio from 4.0% radians to 6.0% radians). The specimen R06-OS1 exhibited the best performance among all the three retrofitted specimens. The failure modes of the specimens are shown in Fig.5. The lateral force versus the drift relationships of the four specimens are shown in Fig.6.

Comparing all the retrofit schemes, the response envelopes of all specimens are shown in Fig.7. It can be found that the performance of the retrofitted specimens was significantly improved. The peak shear strength and the maximum drift ratio of the four specimens are shown in Table 3.1. It is evident that all three retrofit schemes enhance the shear strength and ductility. Figure 8 shows the hoop strain readings found on the face of the octagonal steel jacket on R06-OS1 at a distance of 20cm from the top of the foundation. From all other strains found at different levels, it is confirmed that the steel jacket remained elastic during the entire cyclic loading test. Figure 9 shows the hoop strain comparisons of the two specimens using CFRP wrapping. The strain was more uniform on the specimen R06-RF2 from the readings of the strain gauges glued on the faces of CFRP. It can be found that the strain growth was smoother in R06-RF2 than in R06-RF1 as drift angle increased. It is clear that the CFRP anchors effectively reduce the hoop strain as the column lateral deformations increase. Evidently, the use of CFRP anchors effectively delayed the fracture of CFRP jacketing. Further studies on the detail responses of CFRP anchors are required in order to develop the design recommendations.

Four strain gauges were glued on the transverse reinforcements of the columns at each one of the four different levels (height=40cm, 90cm, 140cm, and 165cm). Figure 10 shows the strains (H=40cm) when the lateral actuators were pushing. It is obvious that the transverse reinforcements of R06-BM remained in elastic range even when shear failure occurred. The strain of the transverse reinforcements was very small on R06-OS1. This suggests that the steel jacket has provided sufficient confinement to the column and effectively decreased the demand on the transverse reinforcements. Specimens R06-RF1 and R06-RF2 had similar strain histories. The transverse reinforcements yielded when the drift ratio increased. It appears that the CFRP wrapping effectively make the transverse steel participating in resisting the applied loads. Moreover, the CFRP anchors delayed the fracture of the CFRP wrapping.

(a) R06-BM (b) R06-OS1 (c) R06-RF1 (d) R06-RF2

Figure 5 Failure modes of the specimens



(a) R06-BM (b) R06-OS1

(c) R06-RF1 (d) R06-RF2

Figure 6 Hysteresis loops of the specimens

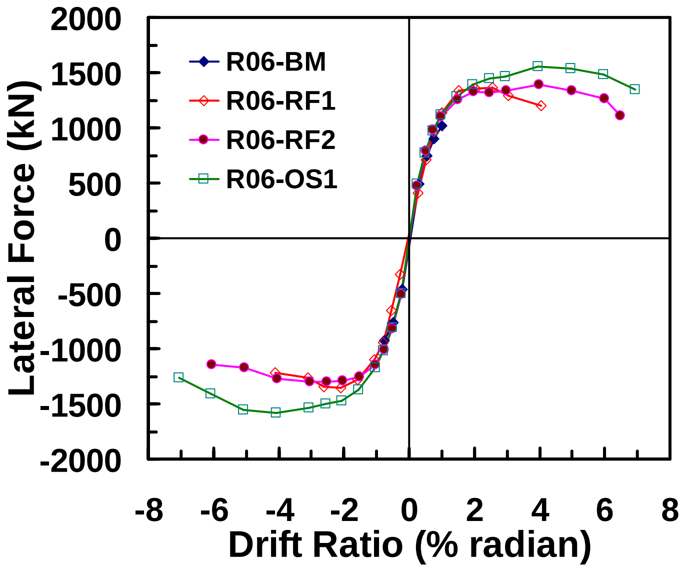
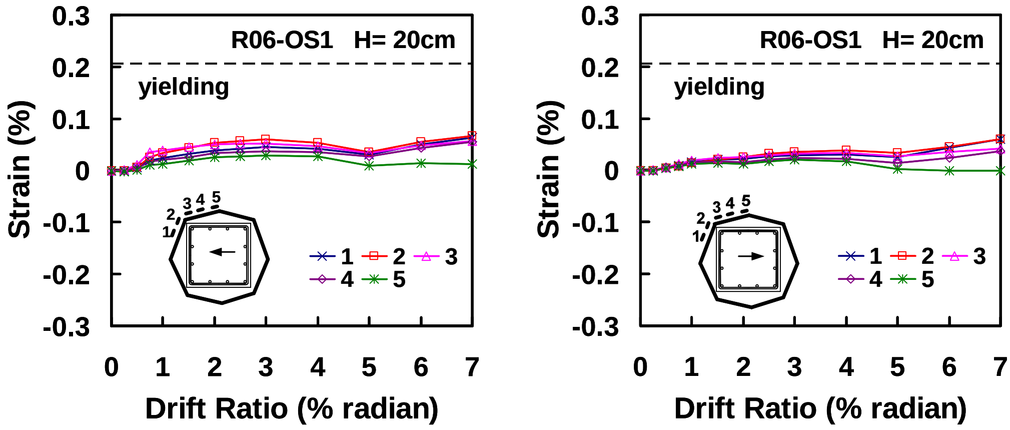


Figure 7 Response envelopes of the specimens

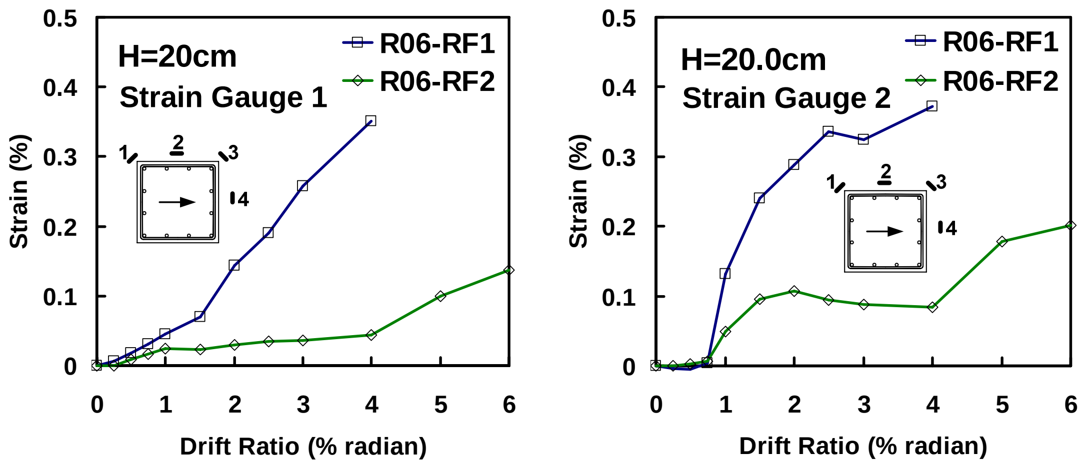
Table 3.1 Peak shear strength and maximum drift ratio of the specimens

Specimen	Shear Strength (kN)	Maximum Drift Ratio (% radian)
R06-BM	1015	1.0
R06-RF1	1359	4.0
R06-RF2	1389	6.0
R06-OS1	1583	7.0

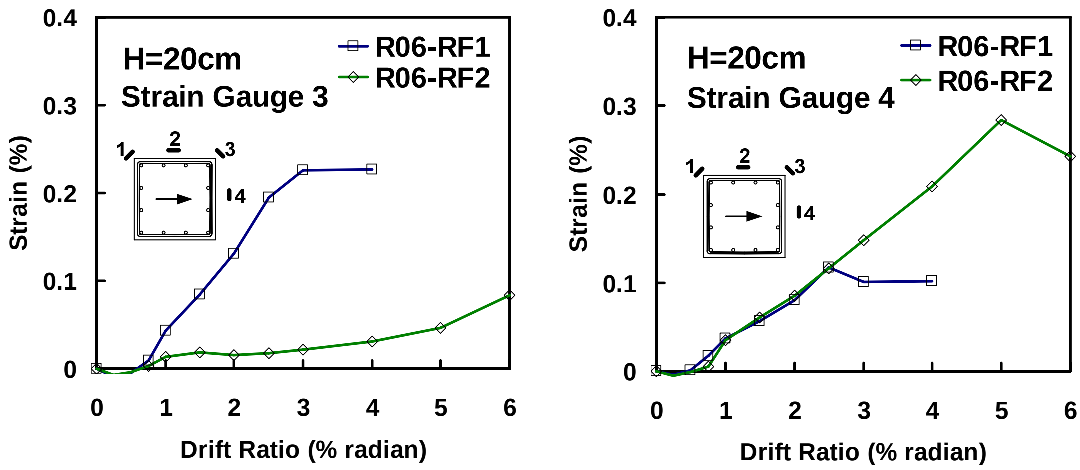


(a) (b)

Figure 8 Readings of strain gauges on the face of steel jacket: (a) pull (b) push

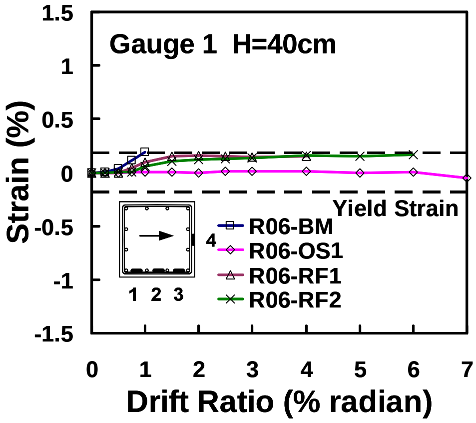


(a) Strain Gauge 1 (b) Strain Gauge 2

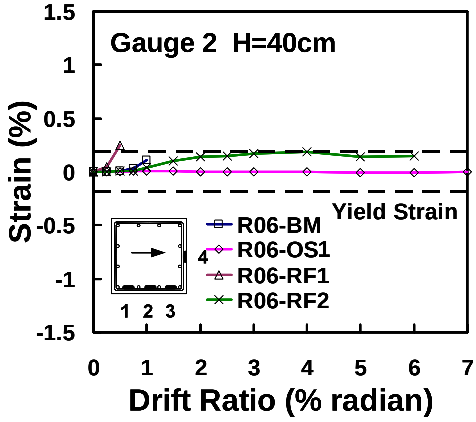


(c) Strain Gauge 3 (d) Strain Gauge 4

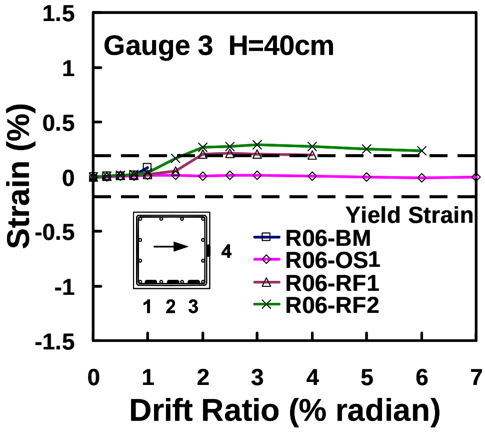
Figure 9 Comparison of strain gauge readings on the faces of CFRP



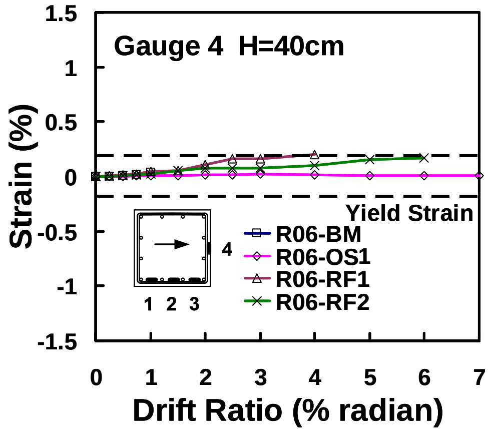
(a) Strain Gauge 1



(b) Strain Gauge2



(c) Strain Gauge 3



(d) Strain Gauge4

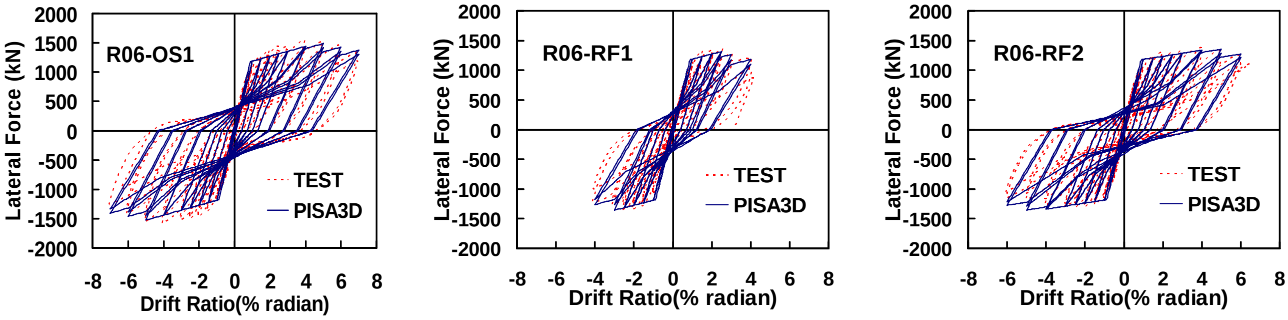
Figure 10 Comparison of strain gauge readings on the transverse reinforcements

4. NUMERICAL SIMULATION

PISA3D, developed at NCREE, is an useful structural analysis software. It is very convenient to build nonlinear numerical models for 3D structures using the material and element libraries provided in PISA3D. In this paper, beam-column elements with three parameters degrading rule were used to simulate the cyclic behavior of the specimens. The stated three degrading parameters include the stiffness degradation (S_1), strength deterioration (S_2), and for the simulation of pinching effects (S_3). Moreover, it is possible to input a second set of three parameters separated by a boundary value (BV). The BV is the ratio of the critical strain to the yield strain, to trigger the use of the second set of parameters. It could allow a more precise simulation of RC elements subjected to large strain reversals. The parameters adopted for the three specimens are shown in Table 4.1. The flexural capacity of the columns is based on the steel reinforcement coupon test results and confined concrete model. The simulation versus the test results of the three retrofitted specimens are shown in Fig.11. The cyclic responses of the specimens are well simulated using PISA3D.

Table 4.1 Input parameters to numerical models

Specimen		R06-OS1	R06-RF1	R06RF2
1st set of 3 parameters	S_1	2.2	2.2	2.2
	S_2	0.99	0.99	0.99
	S_3	0.6	0.6	0.6
BV		5.0	3.0	5.0
2nd set of 3 parameters	S_1	3.0	1.5	3.0
	S_2	0.95	0.93	0.95
	S_3	0.6	0.6	0.35



(a) R06-OS1 (b) R06-RF1 (c) R06-RF2

Figure 11 Numerical simulation results using PISA3D

5. CONCLUSIONS

Three different retrofit schemes have been tested in this research. The results can provide practical applications in the field. For the application of CFRP anchors, the design criterion needs to be developed. Conclusions for this paper are:

1. All the three retrofitted specimens exhibited better performance than the benchmark specimens not only on shear strength but also on ductility.
2. The fractures of the CFRP wrapping caused the failure of Specimens R06-RF1 and R06-RF2. However, the performance of R06-RF2 (peak drift ratio 6.0% radians) is better than R06-RF1 (peak drift ratio 4.0% radians) due to the use of the CFRP anchors.
3. The CFRP anchors effectively reduced the hoop strain and delayed the fracture of the CFRP jacketing.
4. The octagonal steel jacketing used in Specimen R06-OS1 performed the best among all the three retrofitted specimens. Although only a 6mm thick steel plate was used, the steel jacket remained elastic during large deformations of the column. It is evident that the octagonal steel jacketing scheme can effectively provide lateral confinement.
5. The cyclic responses of the three retrofitted specimens can be satisfactorily simulated using the PISA3D computer program.

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