Axial Performance of Various Strengthening Methods Applied on Full-scale Rectangular RC Columns

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Abstract. The performance of RC columns subjected to axial force is relative to the confinement. CFRP wrapping, a generally adopted retrofit method, was proved not to effectively provide confining force due to the bulging effect on the column face. Therefore, this paper is focused on the performance of the retrofitted full-scale rectangular RC columns using different retrofit schemes including the proposed CFRP wrapping conjugated with CFRP anchors method. A total of eleven rectangular RC columns with low transverse reinforcement ratio were constructed. Among them, one was tested as benchmark; one was purposely constructed with larger transverse reinforcement ratio; five were retrofitted by using CFRP wrapping and CFRP anchors; and the other four were retrofitted by using different shapes of steel jacketing alone or with adhesive anchors. All the specimens were subjected to monotonic incremental axial force until failure occurred. Experimental results demonstrated that the ductility of the specimens retrofitted by using CFRP wrapping with CFRP anchors was significantly improved compared with those retrofitted by using only CFRP wrapping. On the other hand, the specimen with octagonal steel jacketing performed better than all other specimens not only on ductility but also on strength. Finally, a novel numerical model considering the contribution of the retrofit material will be proposed and validated in the future.

Introduction

Seismic retrofit of reinforced concrete (RC) members has become an important research issue in Taiwan since a number of RC buildings were severely damaged or collapsed 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. As a result, a large number of tests have been conducted in National Center for Research on Earthquake Engineering (NCREE) in recent years to evaluate the effectiveness of various retrofit schemes on RC building columns, beams or walls.

Carbon fiber reinforced polymer (CFRP) wrapping has been widely used to retrofit the existing buildings because of its high tensile strength, slight weight, and convenient application. However, it was observed that external confinement provided by CFRP wrapping was ineffective due to the debonding between CFRP sheets and RC surfaces. Therefore, *CFRP wrapping conjugated with CFRP anchors* retrofit method was proposed and validated in the previous studies [1-3]. Experimental results demonstrated that the seismic performance of the rectangular RC columns and beams was improved significantly by this retrofit method. Further researches on RC components retrofitted by using CFRP wrapping and CFRP anchors are necessary to develop the theoretical model of retrofitted RC members. It is known that the relation between axial performance and confinement is the key factor to develop the numerical model of retrofitted RC members. Hence, a number of simple but representative axial tests for RC columns were conducted. In this paper, the axial performance of eleven RC columns retrofitted by using several different schemes is compared and discussed.

Specimen Design

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

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

$$\frac{A_{sh} f_{yh}}{s h_c} \geq 0.09 f_c' \tag{2}$$

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, Eq. 1, Eq. 2, can be written as:

$$t_f = \frac{B}{2\varepsilon_{jd} E_{jd}} \left\{ \left\{ 0.3 f_c' \left(\frac{A_g}{A_{ch}} - 1 \right), 0.09 f_c' \right\}_{\max} - \frac{A_{sh} f_{yh}}{s h_c} \right\} \tag{3}$$

Where, t_f is the required thickness of the external jacketing, B is the width of gross column, and ε_{jd} is the design strain of the external jacketing.

Since CFRP anchors are designed to provide additional confinement to satisfy the right-hand side requirement of Eq.1 and Eq.2; therefore, Eq.3 can be re-written as:

$$f_{an} = \left\{ 0.3 f_c' \left(\frac{A_g}{A_{ch}} - 1 \right), 0.09 f_c' \right\}_{\max} - \frac{A_{sh} f_{yh}}{s h_c} - \frac{2 f_{jd} t_f}{B} \tag{4}$$

Where, f_{an} is the confinement stress provided by CFRP anchors, f_{jd} is the design stress of CFRP. The design procedure of CFRP anchors are documented in [2].

Specimen Detail. In many existing RC buildings, the details of 90° 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 eleven specimens were designed based on the non-ductile reinforcement detail. Among them, one was purposely constructed with larger transverse reinforcement ratio and named R09TS8. The details of the other columns are identical with Specimen R09BM, the benchmark specimen, consisting of 12-22mm diameter vertical bars. The spacing of 10mm-diameter stirrups is 250mm. The column height is 1600mm, including the test region of 1000mm and two stiffened regions of 300mm at the bottom and the top of the column. The stiffened region is for transferring the axial force to the test region without causing any failure at the end; as a result, the transverse reinforcement ratio of the stiffened region was designed larger than that of the test region. The column cross section is 450mm x 450mm. The tensile test results of reinforcements and the compressive test results of concrete cylinders are shown in Table 1.

The above-mentioned ten RC columns with the same reinforcement detail were retrofitted by using different schemes. Among them, five were retrofitted by using CFRP wrapping and CFRP anchors. Specimens R09F2 and R09F4 were retrofitted by using only CFRP wrapping with two and four wrapping layers, respectively. Specimens R09FA2, R09FA4 and R09FA8 were retrofitted by using two layers of CFRP wrapping conjugated with two, four and eight CFRP anchors on each side of the column, correspondingly. The diameter of the fiber bolt was 20mm and the length was 170mm. The radius of the spread tail was 170mm.The remainder four specimens were retrofitted by using steel jackets. The steel thickness of Specimen R09S3 and R09S6 were 3mm and 6mm respectively. Specimen R09SA4 was retrofitted by using 3mm-thick steel with 16mm-diameter adhesive anchors.

Specimen R09OS3 was retrofitted by using 3mm-thick octagonal steel jacket. After the steel jackets were welded, non-shrinkage grout was filled into the gaps between the steel jackets and the column faces. Figure 1 illustrates the above-mentioned detail of each specimen, and each specimen was listed with a brief instruction in Table 2.

Table 1 Material test results

Concrete 28-day compressive strength [MPa]	22.1
D-10 rebar yield strength [MPa]	368
D-22 rebar yield strength [MPa]	478
Tensile modulus of CFRP [GPa]	279
A-36 steel plate yield strength [MPa]	252

Table 2 Instruction of the tested specimens

Specimen	Retrofit schemes
R09BM	Benchmark specimen
R09TS8	high transverse reinforcement ratio
R09F2	2 layers of CFRP wrapping
R09F4	4 layers of CFRP wrapping
R09FA2	2 layers of CFRP wrapping with CFRP anchors of 500mm spacing
R09FA4	2 layers of CFRP wrapping with CFRP anchors of 250mm spacing
R09FA8	2 layers of CFRP wrapping with CFRP anchors of 250mm spacing
R09S3	3mm-thick steel jacket
R09S6	6mm-thick steel jacket
R09SA4	3mm-thick steel jacket with adhesive anchors of 250mm spacing
R09OS3	3mm-thick octagonal steel jacket

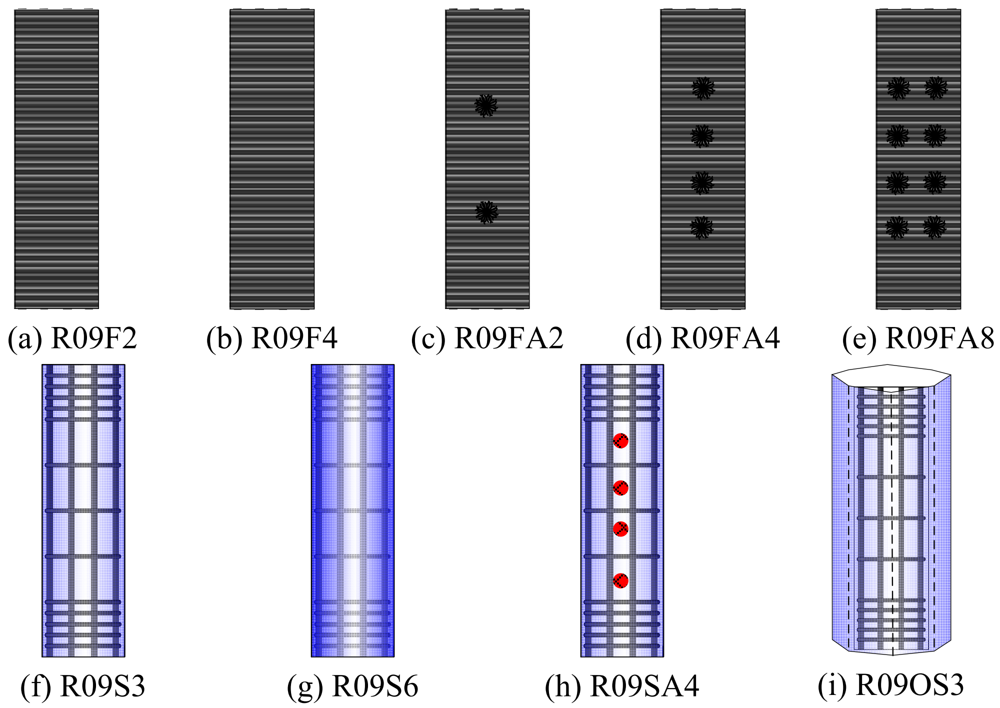

Fig. 1 Illustration of retrofitted specimens

Test Setup

All the specimens were tested on the 6-DOF testing system, MATS [4]. It was constructed in NCREE in 2008. The specimen can be anchored between the top cross beam and the bottom platen within a 5-meter clear space. There are built-in tie-down holes through the cross beam to allow anchoring RC or steel shim blocks for meeting the specimen height. In this study, four high performance concrete (HPC) blocks were installed between the cross beam and the specimens. A rigid universal joint was fixed on the HPC blocks to transfer the axial force to the specimens without carrying any bending moment. Figure 2 shows the overview of the test setup. The axial displacement loading rate was 0.05mm/sec. The test ended once the strength of the specimen became lower than 70% of its ultimate strength.

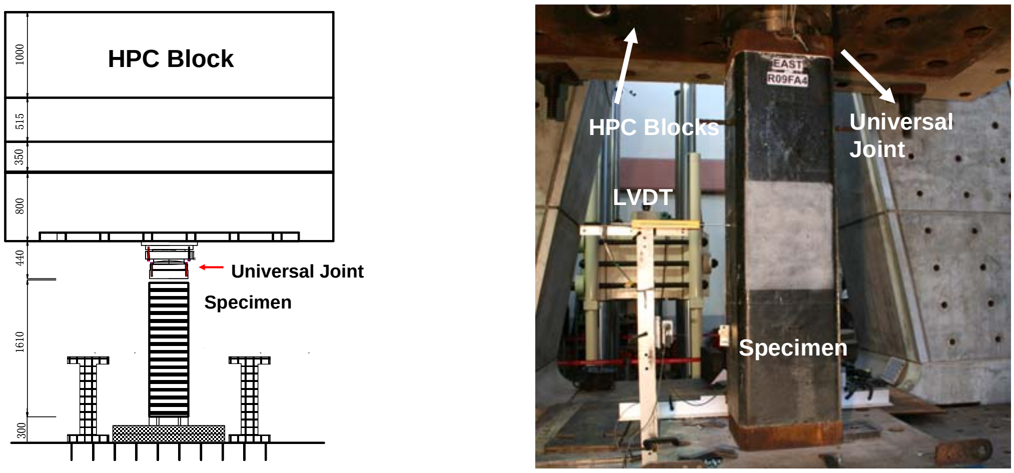

Fig. 2 Test setup

Experimental Results

Specimens R09BM and R09TS8 performed similarly. The concrete cover bulged and broke immediately after the peak axial strength was reached. The strength of Specimen R09BM and Specimen R09TS8 was 6191kN and 6692kN, respectively. On the other hand, the ultimate axial deformation of Specimen R09BM and Specimen R09TS8 was 12.1mm and 13.8mm. The strength of Specimen R09TS8 was slightly higher than that of Specimen R09BM; however, the ultimate deformation of the two specimens was almost identical. It indicates that the effect of higher transverse reinforcement ratio was not significant.

For the specimens retrofitted by using CFRP wrapping, the axial strength of Specimen R09F2 and Specimen R09F4 was 7189kN and 7260kN, respectively. The ultimate axial deformation of the two specimens was 14.2mm and 22.3mm. Comparing the two specimens with Specimen R09BM, both the axial strength and deformation capacity were improved. However, more CFRP layers did not remarkably improve the deformation capacity because the CFRP was broken and debonded at the corner due to concrete crush. It is concluded that if the CFRP is not well-anchored with the column face, more layers of CFRP wrapping is not able to increase the confinement efficiently.

For the specimens retrofitted by using CFRP wrapping and CFRP anchors, the axial strength of Specimen R09FA2, Specimen R09FA4 and Specimen R09FA8 was 7117kN, 7219kN, and 6855kN respectively. The ultimate axial deformation of the three specimens was 17.2mm, 18.9mm and 17.4mm. The axial strength of these three specimens was close to that of Specimen R09F2; nevertheless, the deformation capacity of these three specimens was improved. The response of each CFRP wrapped specimen subjected to monotonic axial loading is shown in Fig.3. Among the responses, it is evident that the more amounts of CFRP anchors, the better deformation capacity (except for Specimen R09FA8 because it was unexpectedly damaged during the installation before testing).

For the specimens retrofitted by using rectangular steel jacketing, the axial strength of Specimen R09S3 and Specimen R09S6 was 8641kN and 8805kN, respectively. Comparing the two specimens with Specimen R09BM, the extraordinary increase of axial strength was due to the enlarged cross section after the non-shrinkage grout was filled in. On the other hand, the thickness of the steel jacket resulted in slight difference of axial strength observed from the two specimens. The ultimate axial deformation of Specimen R09S3 and Specimen R09S6 was 26.8mm and 32.4mm, respectively. The steel jacket of Specimen R09S3 ruptured at the welding region whereas it tore at the corner on Specimen R09S6.

For the specimen retrofitted by using rectangular steel jacketing and adhesive anchors, the axial strength and ultimate deformation of Specimen R09SA4 were 8004kN and 20.6mm. Comparing Specimen R09SA4 and Specimen R09S3, neither the strength nor the deformation capacity was improved by the application of adhesive anchors. On the other hand, the specimen retrofitted by using octagonal steel jacketing, Specimen R09OS3, exhibited the best performance among all the retrofitted specimens. The axial strength and ultimate deformation of Specimen R09OS3 were 10664kN and 40.9mm. The response of each steel jacketed specimen subjected to monotonic axial loading is shown in Fig.4.

In order to specify the effectiveness of each retrofit scheme, a confining ratio index, R, is defined as the equivalent confinement stress divided by the required confinement stress as shown in Eq. 5.

$$R = \frac{f_{ts} + f_{an} + f_{rf}}{\left\{0.3 f_c'\left(\frac{A_g}{A_{ch}} - 1\right),\ 0.09 f_c'\right\}_{\max}} \tag{5}$$

Where f_{ts} , f_{an} , and f_{rf} are the equivalent confinement stress provided by transverse reinforcement, anchors, and external jacketing, respectively.

Moreover, the axial ductility μ was defined as $\Delta u / \Delta y$, where Δy is the axial deformation of specimen while the first longitudinal reinforcement yields, and Δu is the axial deformation of specimen while the strength of the specimen is lower than 70% of its ultimate strength. Table 3 shows the above-mentioned indices of each specimen. Apparently, the ductility of Specimen R09FA2, Specimen R09FA4 and Specimen R09FA8 is better than that of Specimen R09F2 due to the use of the CFRP anchors. Also, Specimen R09OS3 performed the best among all the retrofitted specimens. Finally, the relationship between the confining ratio and the ultimate strain of each specimen is shown in Fig.5. It demonstrates that the ultimate strain is proportional to the confining ratio on the premise that the same cross section area is considered (removing the steel jacketed specimens).

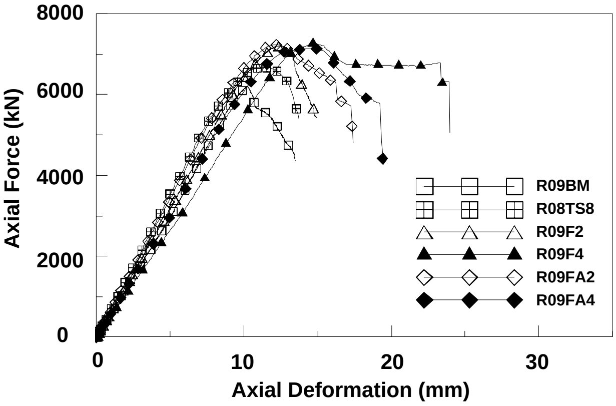

Fig. 3 Responses of CFRP wrapped specimens

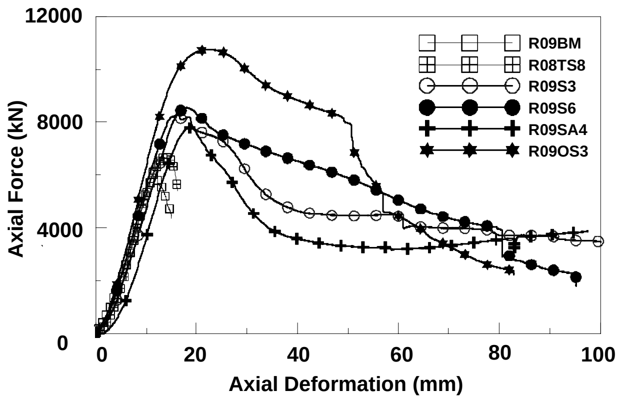

Fig. 4 Responses of steel jacketed specimens

Table 3 Experimental indices of the specimens

Specimen	Δy [mm]	Δu [mm]	R	μ
R09BM	10.4	12.1	0.20	1.2
R09TS8	11.0	13.9	0.63	1.3
R09F2	9.4	14.2	0.55	1.5
R09F4	11.8	22.3	0.90	1.9
R09FA2	9.4	17.2	0.64	1.8
R09FA4	9.3	18.9	0.75	2.0
R09FA8	8.0	16.1	0.95	2.0
R09S3	12.4	26.8	1.15	2.2
R09S6	12.0	32.4	2.08	2.7
R09SA4	12.0	20.6	1.35	1.7
R09OS3	12.1	40.9	1.15	3.4

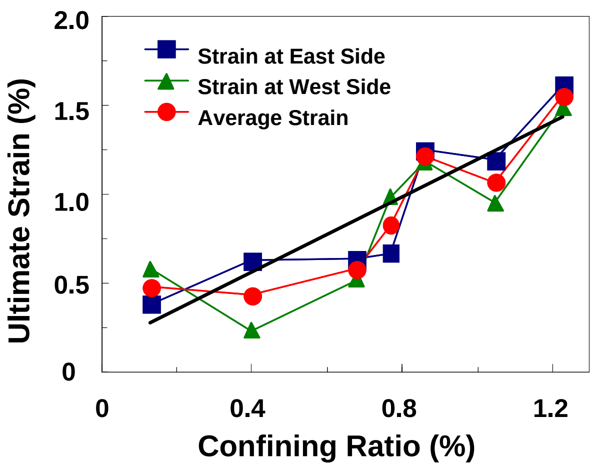

Fig. 5 Confining ratio versus ultimate strain relationship

Conclusions

Eleven full-scale RC columns with different retrofit schemes have been tested in this research. The results are helpful to develop the numerical model based on the contribution of confinement. Conclusions for this paper are:

1. The proposed CFRP anchors provide additional confinement to improve the axial strength and ductility of the RC columns. All the three retrofitted specimens exhibited better performance than the benchmark specimen.
2. The octagonal steel jacketing used in Specimen R09OS3 performed the best among all the retrofitted specimens. It is evident that the octagonal steel jacketing scheme can effectively provide lateral confinement.
3. The ultimate strain is proportional to the confining ratio if the cross sectional area remains the same after retrofitting. The numerical model considering the confinement needs to be developed and validated.

Further researches on RC components retrofitted by using CFRP wrapping and CFRP anchors will be continued to develop the mechanical theorem and modified design criteria of CFRP anchors.

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