Seismic Jacketing of RC Columns for Enhanced Axial Load Carrying Performance

by K.-C. Tsai and M.-L. Lin

Synopsis:

Axial compression test results for square RC columns incorporating Taiwanese construction practice in the placement of stirrups and various kinds of jacketing schemes are presented. The jacketing schemes include circular, octagonal and square shapes. The jacketing materials vary from steel plate to carbon fiber reinforced polymer (CFRP) composites. It is found from the monotonic axial load test results that the failure mode of the benchmark non-retrofitted specimen is identical to that observed in real damage cases subsequent to the 1999 Chi-Chi Taiwan earthquake. The benchmark specimen developed its design strength but a non-ductile failure mode occurred soon after the peak load was reached. Among the retrofitted specimens, the steel jacketed specimens exhibit not only greatly enhanced load carrying capacity but also excellent ductility performance. Test results show that CFRP sheets are effective in increasing the column axial strength, but the sheets could fracture suddenly in high strain conditions due to their brittle material characteristics. Test results indicate that CFRP sheet wrapping in general is not as effective as steel jacketing in improving the axial ductility capacity of RC columns. However, the proposed octagon-shaped CFRP wrapping scheme exhibits an improved performance compared to rectangular-wrapped columns using the same layers of CFRP sheets. Tests confirm that all octagonal steel or CFRP jacketed specimens have axial load capacities more than 2 times the nominal capacity.

Keywords: CFRP jacketing; octagon shape; RC columns; steel jacketing

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INTRODUCTION

Lessons learned from the 1999 Chi-Chi Taiwan earthquake indicate that inadequate axial load carrying and axial ductility capacities of the columns, among many other problems, are key factors responsible for the collapse of many reinforced concrete buildings. As shown in Photo 1, commonly encountered were columns with splices having inadequate development length or located in the hinge region, or stirrups with 90 degree hooks, or widely spaced stirrups resulting in unconfined plastic hinge zones. Strong-beam weak-column systems were apparently common, which might have resulted in numerous story collapses, following excessive column compressive load induced by large overturning moments. In order to gain insights into the compression load carry characteristics and the effectiveness of various kinds of seismic jacketing schemes on the aforementioned deficient rectangular reinforced concrete columns, an experimental test program was launched in the National Taiwan University (1). In a recent study on the seismic retrofit of rectangular RC bridge columns (2-3), the use of octagonal-shaped steel jacketing has been proposed and extensively tested for bridge columns subjected to low axial compressive stress but very severe cyclic flexural or shear demands. These test results have confirmed that properly proportioned octagonal steel jackets can improve the cyclic strength and ductility performance of bridge columns deficient in flexural or shear strength. Research results also indicate that rectangular steel jacketing cannot effectively provide lateral confinement due to the bulging out of the jacket (2, 4-5). This study focuses on investigating the effectiveness of steel plate and carbon fiber reinforced plastic (CFRP) jacketing schemes in improving the axial strength and axial ductility performance of existing rectangular RC building columns subjected to high axial loads. A total of 12 square RC column specimens, using transverse reinforcing tie details commonly found in Taiwan,

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were tested. The external jackets adopted in these specimens were configured in circular, square and octagonal shapes.

RETROFIT DESIGN

The design of octagonal steel jacketing is introduced herein. In the seismic retrofit of rectangular RC bridge columns, elliptical steel jacketing has been found effective (5). The ellipse circumscribes the rectangle while the octagon can be conveniently defined based on the circumscribing ellipse and the original rectangle as shown in Fig. 1. The dimensions of the ellipse can be expressed as:

$$\frac{X^2}{X_2^{\,2}} + \frac{Y^2}{Y_2^{\,2}} = 1 \tag{1}$$

where X_2 and Y_2 are the long and short axes of the ellipse, respectively.
Assumig

$$X_2 = KY_2 \tag{2}$$

and substituting Eq. 2 and (X_1, Y_1) into Eq.1 yields:

$$Y_2 = \sqrt{\left(\frac{X_1}{K}\right)^2 + Y_1^2} \tag{3}$$

Applying the rule of minimum elliptical area:

$$Min\ f\,(X_2, Y_2) = Min\ f(\pi X_2 Y_2) \tag{4}$$

and substituting Eqs. 2 and 3 into Eq. 4, and taking variation yields:

$$K = \frac{X_1}{Y_1} \tag{5}$$

Thus, X_2 and Y_2 can be expressed as:

$$X_2 = \sqrt{2}X_1 \tag{6}$$
$$Y_2 = \sqrt{2}Y_1 \tag{7}$$

The long and short axes of the ellipse can be determined using Eqs. 6 and 7, respectively. If the four corner points of the rectangle and the four intersecting points of the ellipse and the two axes are connected, these eight points define an

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octagon (Fig. 1), denoted the "Large Octagonal Shape". Both the elliptical and the associated octagonal retrofit schemes will increase the column cross section substantially. Therefore, for a case when a more compact scheme is desired, the reduced octagon shape has been proposed. If the dimension of X_2 is reduced to $X_1+(X_2-X_1)/2$, and one applies the same rule for points on the vertical axis, a small octagon can be defined by connecting these four new points on the axes and the same four corners of the rectangle (Fig. 1), denoted the "Small Octagonal Shape".

In the ACI seismic design provisions (6), the requirements for transverse reinforcement are prescribed as:

$$A_{sh} \geq 0.3\left(\frac{sh_c f'_c}{f_{yh}}\right)\left(\frac{A_g}{A_{ch}}-1\right) \tag{8}$$

$$A_{sh} \geq 0.09 sh_c \frac{f'_c}{f_{yh}} \tag{9}$$

where A_{sh} is the total transverse steel cross-sectional area within spacing s; h_c is the cross-section of the column core measured from center-to-center of the confining reinforcement; A_g is the gross area of the column section; A_{ch} is the cross sectional area of the column measured out-to-out of the transverse reinforcement; f'_c is the specified compressive strength of the concrete; and f_{yh} is the specified yield strength of the transverse reinforcement. From Eqs. 8 and 9, the equivalent transverse pressure of the concrete can be defined as:

$$\frac{A_{sh} f_{yh}}{sh_c} \geq 0.3 f'_c\left(\frac{A_g}{A_{ch}}-1\right) \tag{10}$$

$$\frac{A_{sh} f_{yh}}{sh_c} \geq 0.09 f'_c \tag{11}$$

If the amount of transverse reinforcement in the existing columns is not enough to satisfy the requirements prescribed in Eqs. 10 and 11, then additional confining pressure must be provided by external jacketing. The relationship between the additional lateral confinement and the tensile stress in the jacket can be evaluated using static equilibrium. As shown in Fig. 2, a free body diagram can be cut either from the centerline of the column section (Type I) or near the corners (Type II). The octagonal jacket is to prevent the outward bulging tendency of the rectangular section by mobilizing the tensile strength of the jacketing material. For a rectangular cross section oriented as shown in Fig. 1, it is found by examining typical values of $\sin\theta$ and $\cos\alpha$ in Figure 2, that, for the same demand of lateral confinement, the tensile stress in the jacket near the column corner (Type II) is much higher than that near the centerline of the section (Type I). Therefore, the Type II free body cut near the edge of the section

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is used in this research. Thus, the requirements for transverse pressure on the concrete can be expressed as:

$$\frac{2F\sin\theta}{B}+\frac{A_{sh}f_{yh}}{sh_c}\geq\left\{0.3f_c'\left(\frac{A_g}{A_{ch}}-1\right),0.09f_c'\right\}_{\max} \tag{12}$$

where B is the cross-section width of the column. In Fig. 2, the tensile strength provided by the octagonal steel jacketing for a unit length of the column is:

$$F=t_{sj}f_{ysj} \tag{13}$$

where t_{sj} is the thickness of the steel jacket; and f_{ysj} is the specified yield strength of the steel jacket. Thus, the required thickness of the octagonal steel jacket can be calculated as:

$$t_{sj}=\frac{B}{2\sin\theta f_{ysj}}\left\{\left\{0.3f_c'\left(\frac{A_g}{A_{ch}}-1\right),0.09f_c'\right\}_{\max}-\frac{A_{sh}f_{yh}}{sh_c}\right\} \tag{14}$$

For CFRP material, the tension strength for a unit length of the column can be expressed as:

$$F=t_{frp}f_{ufrp} \tag{15}$$

where t_{frp} is the total thickness of the CFRP sheets; and f_{ufrp} is the ultimate strength of the CFRP sheet. Thus, the required thickness of the CFRP sheets is:

$$t_{frp}=\frac{B}{2\sin\theta f_{ufrp}}\left\{\left\{0.3f_c'\left(\frac{A_g}{A_{ch}}-1\right),0.09f_c'\right\}_{\max}-\frac{A_{sh}f_{yh}}{sh_c}\right\} \tag{16}$$

EXPERIMENTAL PROGRAM

Test Matrix

A total of 12 specimens were constructed and tested under monotonically applied axial compression. One of the specimens is the benchmark, 7 specimens were retrofitted using steel jacketing, and 4 specimens using CFRP jacketing. The

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reinforcing details of the specimens are shown in Fig. 3. The height of the specimens is 1200 mm, and the cross section is 280 mm by 280 mm. The longitudinal reinforcements of the column specimens consists of 16-#5 (16mm diameter), uniformly distributed along the four sides of the column cross-section. The transverse reinforcement of the specimens are $\phi 6$ (6 mm diameter), spaced at 40 mm on center in the middle potential plastic hinge zone, and spaced at 80mm outside that region (Fig. 3). The Taiwanese building code requires that the 135 degree hook details be applied for column transverse reinforcement. However, Figure 4 shows typical transverse reinforcement details commonly found in Taiwan practice. The 90 degree, not 135 degree, non-ductile hook detail is believed one of the key factors responsible for many column failures observed after the 1999 Chi-Chi Taiwan Earthquake. Accordingly, this type of transverse reinforcement arrangement is adopted for all specimens. All of the specimens were constructed using the same reinforcing materials and concrete batches. The nominal and the measured strength of the materials are shown in Table 1. The CFRP sheets were provided by the Materials Research Laboratory of the Industrial Technology Research Institute. The material properties of the CFRP sheets are listed in Table 2. Non-shrink cement was used as infilling material between the square columns and the jackets.

Steel Jacketed Specimens

The dimensions of the steel jacketed specimens are shown in Fig. 5. The steel jacket tubing was prefabricated in the shop before delivery to the laboratory at the NCREE. The shapes of the steel jacket included circular, rectangular, large octagonal, and small, or reduced, octagonal. The thicknesses of the octagonal steel jackets were calculated based on the design criteria noted in Eq. 14. Specimens LOS23A and LOS23B were retrofitted using the large octagonal shape and the thickness of the steel jacket was 2.3mm. Specimens ROS45A and ROS45B were retrofitted using the reduced octagonal shape, and the thickness of the steel jacket was 4.5mm. Specimen CS23 was retrofitted by a circular jacket, and the thickness of the jacket was a 2.3 mm, the same as Specimen LOS23A. Specimen RS45 was retrofitted by a 4.5 mm rectangular jacket; the thickness is the same as in Specimen ROS45A for the purpose of comparison. Specimen ROS23 is a reduced octagonal jacketed specimen using a 2.3 mm thick jacket, just half the thickness of that in Specimen ROS45A, in order to see whether the design criteria noted above are conservative enough or not.

CFRP Jacketed Specimens

The shapes of the CFRP jackets include rectangular and reduced octagonal. In order to provide lateral confinement, continuous CFRP sheets were wrapped in

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the transverse direction of the columns. Specimen ROF2 and ROF3 were retrofitted, using the reduced octagonal scheme with 2 and 3 layers, respectively, of CFRP wrapping. The layers of CFRP were calculated by conservatively applying the design criteria noted in Eq. 16. It is worth noting that the assembling procedures for the reduced octagonal CFRP wrapping specimens are novel, as shown in Fig. 6. The octagonal shape was first formed using four 0.6 mm thick galvanized metal sheets that were bent into the specified shape before being attached to each other by screws. Then, CFRP wrapping was done after the metal surface was smoothed, as shown in Photo 2. The final procedure was infilling with non-shrink cement. The CFRP wrappings for Specimens RF2 and RF3 were 2 and 3 layers, respectively. They were rectangular, and the number of layers was the same as those in the reduced octagonal specimens for comparison purposes. The corner radius R is 30 mm according to the standard CFRP wrapping procedures.

Testing Method

As shown in Fig. 7, all specimens were loaded under monotonically increasing concentric compressive strains. At each end of the specimen, a steel square loading block was positioned in order to ensure that the axial load was applied only to the rectangular RC column section. As shown in Photos 3 and 4, the tests were conducted using NTU's Shimadzu 4900kN and Lien-Foo 58800kN universal testing machines with a 2.5×10^{-5} strain/sec (0.03 mm/sec) strain rate. Tests were stopped when severe damage occurred or the axial strain exceeded 5%.

The THS-1100 data logger and SHW-50D switch box made by TML were employed for data collection during the tests. External LVDTs were used for measuring the longitudinal and lateral deformations of the specimens. Strain gages were also aligned on the reinforcement and the jacket surfaces in each specimen for further data analysis.

EXPERIMENTAL RESULTS

Experimental results of axial loading tests are summarized in Table 3. The ratio between the peak axial strength and the nominal axial capacity (P_{max}/P_n) of each specimen is also given in the table. The nominal axial capacity is computed from $P_n = 0.85f'_cA_g+F_yA_s$, where f'_c is concrete compressive strength from cylinder tests, and F_y is the measured yielding stress of reinforcing steel. The axial load versus strain response relationships for the steel and CFRP jacketed specimens are shown in Figs. 8 and 9. The comparisons for the steel and CFRP jacketing are shown in Fig. 10. The failure modes of the specimens after the tests are shown in

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Photos 5 and 6.

Response of the Benchmark Specimen

The response of the benchmark specimen BM is shown in Fig. 8. The peak load is 2960 kN, which is very close to the nominal strength of 2862 kN. In the axial load versus strain response curve, it is evident that the strength degraded rapidly after the peak load was reached. Photo 5 shows evidence of open-up of the transverse reinforcement when loose concrete was removed after the test. This failure mode is very similar to that observed in the actual building damage shown in Photo 1. The non-ductile behavior of this type of transverse reinforcing detail has been confirmed in the column axial load versus strain response curve.

Response of the Steel Jacketed Specimens

The response curves of the steel jacketed specimens are shown in Fig. 8. Tests were stopped at about 5% axial strain for all specimens. Except for the rectangular steel jacketed Specimen RS45, all other circular or octagonal steel jacketed specimens exhibited excellent axial strength and axial ductility performance. Even at the peak 5% axial strain, their axial strengths sustained very well. Specimen RS45 was retrofitted using a 4.5 mm-thick rectangular steel jacket. Due to premature outward bulging at small axial strain, its improvements on column axial strength and axial ductility are much less pronounced than those of other steel jacketed specimens. Specimen CS23 had the highest axial strength, suggesting that the circular retrofit scheme has excellent performance in axial strength and axial ductility. It should be noted that Specimen LOS23A was tested again using the Lien-Foo 58800 kN machine due to the limited loading capacity of NTU's Shimadzu 4900 kN machine. Specimen LOS23A has higher strength performance than that of the same design Specimen LOS23B, possibly due to the recompression situation. Specimens LOS23B, ROS45A and ROS45B all have very similar axial load versus strain response curves, suggesting the assumptions and calculations made for the lateral confinement are reasonable. The peak axial strength of Specimen ROS23 is less than that of ROS45A, but Specimen ROS23 still exhibited excellent axial ductility performance, suggesting that the design criteria noted above is on the conservative side. The strength ratio P_{max}/P_n for circular jacketed specimen CS23 is 2.56, for rectangular steel jacketed specimen RS45 it is 1.49, and for other octagonal steel jacketed specimens it is equal to or greater than 2.0.

Response of the CFRP Jacketed Specimens

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The axial load versus strain response curves of the CFRP wrapped specimens are shown in Fig. 9. The general effects of the CFRP material can be observed as the column axial strength continued to rise until the CFRP ruptured as shown in Fig. 9. The final damage and ruptured positions of CFRP wrapped specimens are shown in Photo 6. The CFRP sheets ruptured in the middle of Specimen RF2 at an axial strain of 1.5%; the other three CFRP jacketed specimens started to rupture at a strain of about 2.5%. It is evident that the wrapping and the curing must be done very carefully or the CFRP may fracture prematurely. The outward bulging phenomenon observed in Specimen RF2 and RF3 was not as pronounced as that which occurred in RS45. It appears that well-smoothed corners prepared for the CFRP wrapping process have made the corners good places to develop confinement. The smoothened corners also reduce the unconfined width of the core concrete of these specimens. Tests also confirm that the octagonal scheme is more efficient than the rectangular scheme in developing the axial strength and axial ductility performance of CFRP jacketed columns. It is noted in Fig. 9 that the CFRP jacketed Specimens ROF2 and ROF3 wrapped with either 2 or 3 layers of CFRP sheets have very similar axial force versus deformation responses. This observation concurs with the findings in other tests (7), suggesting that the overall confining effects of the CFRP sheets are limited. If the confining limit is reached, the marginal effects of the additional layer are almost negligible.

The strength ratios P_{max}/P_n for rectangular CFRP jacketed specimens RF2 and RF3 are 1.33 and 1.56, respectively. These values are very close to the results of the rectangular steel jacketed specimen RS45 (P_{max}/P_n=1.49). For the octagonal CFRP jacketed specimens ROF2 and ROF3, the strength ratios are greater than 2.0.

DISCUSSION OF TEST RESULTS

In order to monitor the column lateral outward deformations, LVDTs were arranged on the two axes, 70 cm-high on the specimen, as shown in Fig. 11. Figures 12, 13 and 14 show the average lateral deformation response curves of all specimens. In Figs. 12 and 13, it can be seen that the lateral deformations of the rectangular jacketed specimens are larger than the circular or octagonal jacketed specimens. Steel or CFRP rectangular jackets have similar trends of lateral deformation. The lateral bulge out deformation is the primary reason why the rectangular jacketed specimens have a lower axial strength than the circular or octagonal jacketed specimens. It is evident that the rectangular jacket is not effective in providing lateral confinement except at the corners.

It can be seen from the material strengths listed in Tables 1 and 2 that the strength of 2 layers of CFRP sheets used in the tests is equivalent to a 2.8 mm thick layer of steel having 350 *MPa* yield strength. Similarly, the strength of 3

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layers of CFRP sheets is about the same as a 4.9 mm thick steel plate considering the yield strength of 294 *MPa*. Therefore, strictly speaking, results of steel jacketed specimens using the 2.3 mm (f_{ysj}=350 *MPa*) or the 4.5 mm (f_{ysj}=294 *MPa*) thick steel plate might not be suitable for direct comparison with the results of the 2 or 3 layer CFRP jacketed specimens. Nevertheless, judging the small differences in the corresponding designs (2.3 mm versus 2.8 mm or 4.5 mm versus 4.9 mm), test results of these steel jacketed specimens should provide a conservative basis for evaluating the effectiveness of the steel jackets in enhancing the column axial load carrying performance. From the axial load versus axial strain responses of steel and CFRP jacketed specimens given in Fig. 10, it is confirmed that both steel jacketed and CFRP jacketed specimens have similar trends in developing the axial load carry capacity. The peak axial strengths developed in Specimens ROS23 (steel jacketed) and ROF3 (CFRP wrapped) are very similar. It is based on this similarity in strength that the steel jacket appears to provide primarily lateral confinement as the fibers in the CFRP sheets are oriented in the transverse direction. The axial strength effects of the steel jacket on the column axial strength should be negligible.

For typical RC columns constructed with stirrups, the peak load is generally reached before 1% axial strain due to buckling of the longitudinal reinforcement (8-10). In this study, the axial strain at the peak load for the circular or octagonal jacketed specimens is greater than 2%. Buckling of the longitudinal reinforcement was essentially eliminated using the circular or octagonal jackets with continuous confining effects. Rapid degradation of strength could occur in the typical RC columns after peak strength is reached. However, test results confirm that octagonal steel jacketed specimens can maintain the axial load carrying capacity even under extremely large axial strain conditions.

Comparing the performance of steel and CFRP jacketed specimens, it is evident from Fig. 10 that the steel jacketing scheme can provide greater axial ductility than that of the CFRP jacket. The steel jackets were able to provide a stable lateral confinement even when a 5% axial strain was reached, but the CFRP jackets had already ruptured before 3% axial strain was reached. It is found that the strength of the specimens can be satisfactorily predicted in the analytical study of this research. Further analysis can be found elsewhere (1).

RESEARCH SIGNIFICANCE

Tests confirm that the octagon-shape steel jacketed RC column specimens exhibit not only greatly enhanced axial load carrying capacity but also excellent ductility performance. Test results indicate that CFRP sheet wrapping in general is not as effective as steel jacketing in improving the axial ductility capacity of RC columns. However, the proposed octagon-shaped CFRP wrapping scheme exhibits an improved performance compared to rectangular-wrapped columns using the same

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