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EXPERIMENTAL STUDY ON THE BEHAVIOR OF ECCENTRICALLY COMPRESSED REINFORCED CONCRETE COLUMNS STRENGTHENED WITH CFRP COMPOSITE SHEETS

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Abstract

Strengthening of reinforced concrete (RC) columns is needed when the actual load-carrying capacity of the columns does not reach the required level due to either structural deterioration or increasing acting loads. This experimental study aims to evaluate the strengthening effect on the eccentrically-compressed RC columns using Carbon fiber reinforced polymer (CFRP) sheets, that confine around the column cross-section. Three RC column specimens with the same geometrical dimensions, reinforcement detailing, and concrete compressive strength were cast and tested in the current experimental investigation. One RC column without being strengthened is referred as the control specimen whereas two other RC columns were partially strengthened by CFRP sheets. All three RC columns were axially loaded with the same initial eccentricity e_0 of 80 mm. Based on the test results such as the ultimate load-carrying capacity, the load-rotation relationship, and load-curvature at the middle of column height, the effectiveness of the strengthening technique is discussed.

Keywords: CFRP sheets; confinement; eccentricity; curvature; ductility.

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1. Introduction

The reduction of the actual load-bearing capacity of existing RC columns due to structural deterioration or increasing acting loads on existing buildings due to the change of building functionality addresses the need for structural strengthening. Fig. 1 shows the RC columns whose middle section has been environmentally deteriorated. Besides traditional strengthening methods such as widening cross-sections, using post-tensioned reinforcement, and adding steel section, using Fiber-reinforced polymer (FRP) in enhancing the structural performance of supporting columns has been more and more common in recent years. One of the composite materials that has been commonly used for strengthening purposes is Carbon fiber reinforced polymer (CFRP) due to its superior characteristics such as high compressive strength, high elastic modulus, lightweight, and not to be corroded [1–6]. In addition to the advantages of mechanical characteristics, CFRP strengthening technique is

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often simpler to be applied in a short period of construction time [7]. Furthermore, CFRP sheets can be easily wrapped around the column section using high-strength adhesive to provide confinement effects, resulting in increased load-carrying capacity [8–17].

In recent years, there have been a number of studies to investigate FRP confining effects on RC columns subjected to concentrical loads. Hadi and Li [8] tested a series of FRP-wrapped RC columns with a circular section subjected to different levels of eccentric loading conditions. The effects of the concrete strength, internal steel reinforcement, wrap types, and eccentricity were investigated. In a study performed by Parvin and Wang [9], a series of scaled RC columns with square cross-section were strengthened with varying layers of carbon fiber reinforced polymer (CFRP) composites that have been tested to failure using statically axially loading conditions with different eccentricities. Yuan et al. [10], Hassan et al. [14] performed a comparative study of concrete stress-strain models and applied these models for FRP confined RC columns under combined bending and compression and axial load-bending moment (P-M) interaction curve were presented.

Figure 1. Deterioration of RC column

Although the previous studies provide significant insights into the strengthening effects on eccentrically compressed RC columns, there have been a limited experimental evidence for either RC columns with rectangular section or those partially strengthened with CFRP materials. The experimental investigation presented herein aims to provide such lacked information based on the test on three CFRP strengthened RC columns that are eccentrically loaded. The findings of this study will be of interest for engineers those are involved in retrofitting and strengthening of RC structures with CFRP materials. The experimental research has been carried out in the Laboratory of Construction Testing and Inspection, Hanoi University of Civil Engineering (HUCE).

2. Experimental study

2.1. Test specimens and materials

The experimental program consisted of three RC columns under combined axial-flexural loading conditions. All test specimens had the same rectangular section of 150 × 200 mm, with two end corbels with a cross-section of 150 × 400 mm and a length of 400 mm. The overall length of the test specimens was 1600 mm. All column specimens were reinforced longitudinally in the test region with four deformed rebars with 14 mm diameter which corresponded to a steel reinforcement ratio of 2.05%. The transverse reinforcement consisted of deformed rebars with 6 mm diameter, spaced at 100 mm from center to center. The clear concrete cover was 20 mm. The corners of the cross-section were rounded to a radius of 15 mm. To ensure that failure would occur in the test region, the end corbels were designed to have sufficient flexural and shear strengths that are well beyond the anticipated failure load of the column section in the test region. The dimensions of the test columns and details of steel reinforcement are shown in Fig. 2.

Among the column specimens, one un-strengthened column, named C-0, was used as a reference specimen. Two other column specimens, named C-S-3 and C-S-4, were strengthened using CFRP sheets. Partial CFRP wrapping schemes were used in this study (Fig. 2). One layer of CFRP, with the fibers oriented in a transverse direction, were partially wrapped around the column's section in the test region. All CFRP strips were 100 mm wide at a spacing of 175 mm (center to center). The strengthening procedure for C-S-3 and C-S-4 specimens consist of four main steps, including: prepare the bottom face of the columns, apply epoxy to the prepared surface, install the CFRP sheets, and allow the epoxy to cure in 48 hours. The cleanness and smoothness of the column's bottom surface in the preparation process is the key step in this procedure that allow the CFRP sheets to develop their full strength when the columns are loaded.

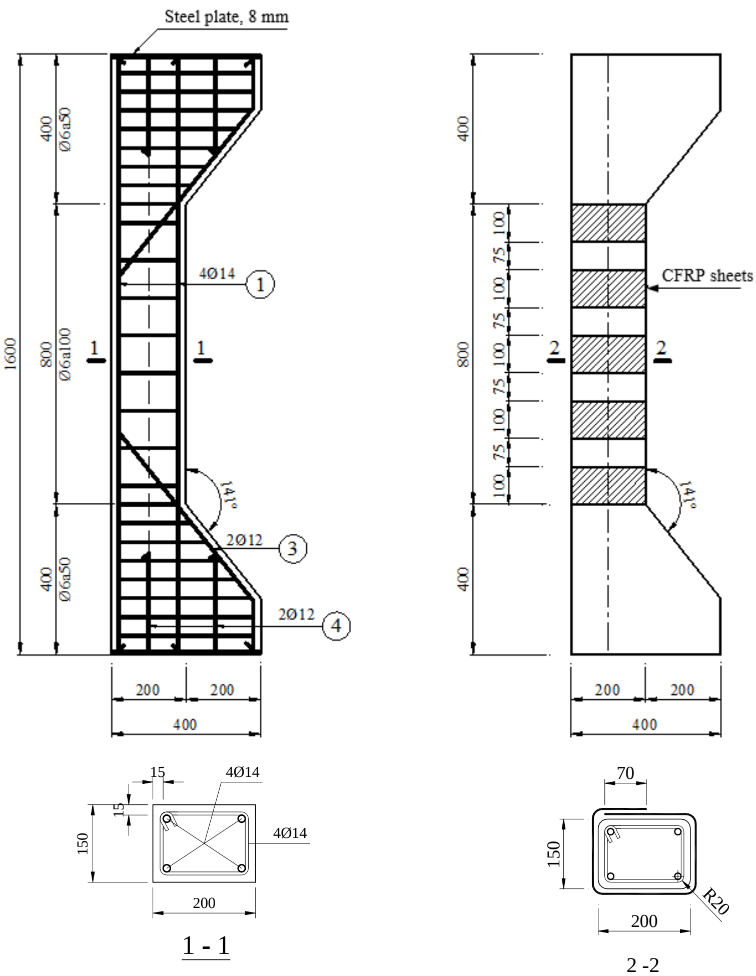


Figure 2. Details of test specimens and CFRP wrapping schemes

Table 1. Mixture proportions for 1 m^3 of concrete (kg/m^3)

Cement PCB40	Sand	Coarse aggregate	Water	Average cylinder strength R28 (MPa)
365	680	1260	175	23.5

All column specimens were cast in the same batch with the concrete mix ratio shown in Table 1. The average cylinder compressive strength measured at the age of 28 days is 23.5 MPa. Yield strengths of longitudinal and transversal reinforcing bars were 330 MPa and 490 MPa, respectively.

The CFRP sheets used in this study were unidirectional and manufactured by Toray Carbon Co. Ltd (Japan). Table 2 presents the mechanical properties of the CFRP sheets provided by the manufacturers.

Table 2. Mechanical properties for CFRP sheets

Thickness (mm)	Modulus of elasticity (GPa)	Ultimate tensile strength (MPa)	Ultimate tensile elongation (%)
0.111	245	3400	1.6

2.2. Test setup and instrumentations

Fig. 3 illustrates the typical test setup for the current experimental investigation and Fig. 4 shows a test in progress. All specimens were tested under monotonically increasing eccentric loading. A hydraulic actuator was used to apply the axial load to the columns. The upper ends of the column specimens were attached to the actuator, while the lower ends were supported on the steel reaction frame. Both end supports were designed as hinged connections with the initial eccentricity e_0 of 80 mm. This eccentricity is equal to the distance between the applying load and the centroid of the column's cross-section in the test region. The lateral stability of each specimen in and out of the plane was maintained by appropriate steel support as shown in Fig. 3.

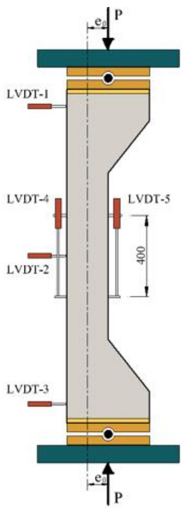


Figure 3. Test setup and instrumentation


Figure 4. Test in progress

Three Linear Variable Differential Transducers LVDT-1, LVDT-2, LVDT-3 were used to measure transversal displacements which were placed with a space of 750 mm along the column length (LVDT-1 and LVDT-3 are next to the hinged supports). The lateral displacement of the columns is used to construct the load-displacement curves can be calculated by the following formula:

$$f = f_2 - 0.5\,(f_1 + f_3) \tag{1}$$

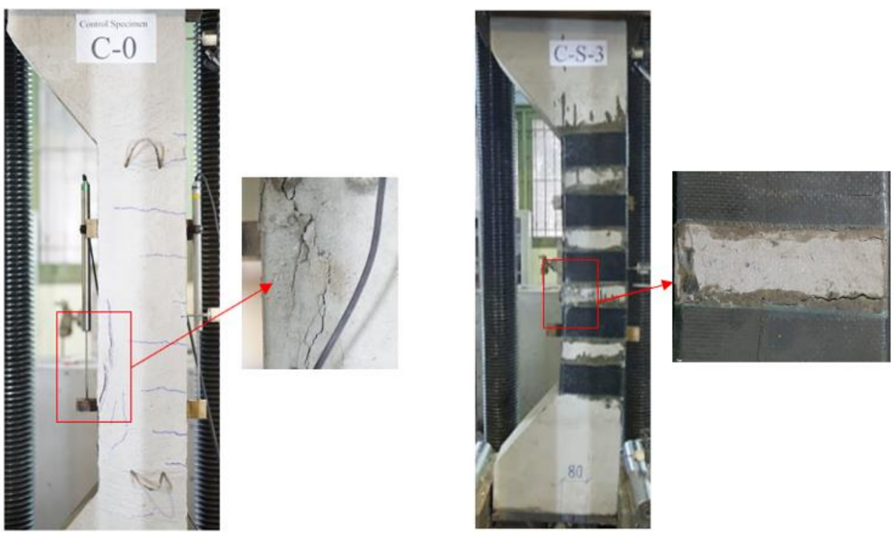
where f_1, f_2, and f_3 are the reading values of LVDT-1, LVDT-2, and LVDT-3, respectively.

LVDT-4 and LVDT-5 were mounted on the concrete surface in the longitudinal direction at the tension and compression side, to measure the longitudinal displacement over a 400 mm gauge length. During the test, load, transversal and longitudinal displacements were monitored by a digital data logger system TDS-530 (Tokyo Sokky). The tests were performed up to the failure of the specimens. The test was stopped when the concrete was crushed on the compression face for the unstrengthened column or when the CFRP failed on the tension face for the strengthened specimens.

3. Test results and discussions

3.1. Overall behavior and failure mode

Fig. 5 shows the photos of failure and the failure region of all tested specimens. It can be seen that the overall behavior of the unstrengthened and strengthened specimens was typical. Tensile cracks appeared on the tension face at the early stages of loading and propagated with increasing of the applying load. The cracks in the mid-height region of the specimen were opened extensively when the tensile stress of the longitudinal steel bars reached yield stress. The applying load dropped when the concrete on the compression face at the mid-height region was crushed and the compressive longitudinal steel bars buckled. For strengthened specimens, C-S-3 and C-S-4, the crushing of concrete happened at the unconfined zone between two adjacent strips of CFRP. Before the failure of all strengthened specimens, the maximum lateral displacement was almost seen at the mid-height of the specimens and the curvature was visible. There is no debonding between the CFRP layer and the concrete during the test. These results show the role of CFRP sheets in limiting the failure area of concrete in the compressive zone and in preventing the buckling of longitudinal compressive reinforcements. The overall behavior of the strengthened specimens shows the contribution of CFRP-partially wrapped rectangular concrete columns under eccentric loading for increasing the load-bearing capacity and post-peak behavior of strengthened specimens.



(a) C-0 specimen

(b) C-S-3 specimen

Figure 5. Failure of unstrengthened and strengthened specimens

3.2. Load – lateral displacement relationship

The load versus lateral mid-height displacement curves with 80 mm eccentricity for the unstrengthened and strengthened columns are shown in Fig. 6. The summary of the ultimate load and the corresponding lateral mid-height displacement is given in Table 3.

It can be seen that before the fracture of testing specimens, the lateral displacement of the unstrengthened and strengthened columns is almost identical. The unstrengthened specimen C-0 was failure at the ultimate load of 420 kN. Two strengthened specimens C-S-3 and C-S-4 were failures at 440 kN and 445 kN, respectively. The mean increasing of load-bearing capacity is about 6% for the strengthened columns. After the failure, the applying eccentric load was significantly decreased for the C-0 specimen, and for the strengthened specimens, the residual eccentric loads were maintained. These obtained results show that the contribution of CFRP wraps to limit the crushing of concrete in the compressive side and the buckling of longitudinal steel bars.

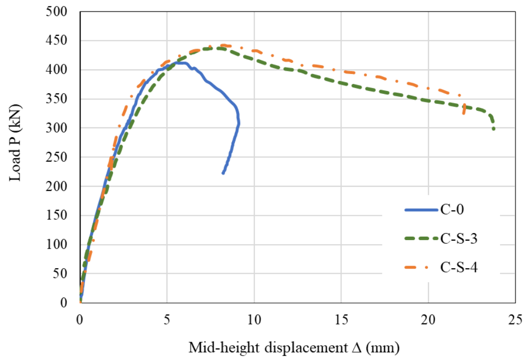


Figure 6. Load-lateral displacement relationship

Table 3. Ultimate axial load and corresponding lateral displacement

Specimens	Ultimate load P_{ul} (kN)	Corresponding lateral displacement (mm)
C-0	420	5.3
C-S-3	440	7.7
C-S-4	445	8.5

3.3. Moment - curvature relationship

The moment-curvature behaviors of the tested specimens at the mid-height of the test length are shown in Fig. 7. The bending moment M was calculated by multiplying the applying load P by actual eccentricity as shown in Eq. (2). At each load step, the actual eccentricity was determined by the sum of the initial eccentricity e_0 and mid-height displacement f at the previous load step. In this way, the bending moments were evaluated considering second-order effects.

$$M = P\left(e_0 + f\right) \tag{2}$$

The curvature of the columns, φ, was obtained using the differential longitudinal strain on the tensile face and compressive face of the mid-height section as follows:

$$\varphi = \frac{\varepsilon_{L,T} - \varepsilon_{L,C}}{h} \tag{3}$$

where $\varepsilon_{L,T}$ and $\varepsilon_{L,C}$ are the longitudinal strain of the tensile and compressive face, respectively (they are the reading values of LVDT-4 and LVDT-5), h is the height of the section (i.e, 200 mm).

The moment-curvature relations are dependent on the stress-strain characteristics of the reinforcing steel and the compressive strength of concrete. It can be seen that the bending-curvature behavior is similar to load-lateral displacement behavior for all test specimens. The CFRP partially wrapped significantly improved the curvature capacity of the specimen but the flexural stiffness is not affected. In this case, after the peak, the curvature capacity of two strengthened specimens has been significantly observed. These obtained results show the contribution of CFRP, by confining the compressed concrete, to improve the ductility of strengthened column specimens.

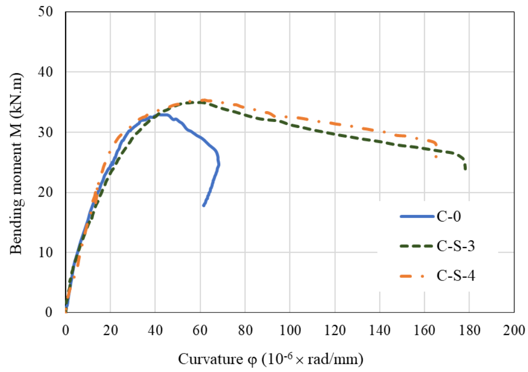


Figure 7. Moment-curvature relationship of tested specimens

3.4. *Curvature ductility factor*

The moment-curvature analyses can be used to determine the curvature ductility of structural concretes. The curvature ductility factors μ can be calculated by the following formula:

$$\mu = \frac{\varphi_{max}}{\varphi_y} \tag{4}$$

where φ_y is the corresponding curvature at the yield of the longitudinal reinforcing steel and $\varphi_{\max}$ is the maximum curvature. The alternative definitions which have been used to estimate the yield and maximum curvature of RC columns are illustrated in Fig. 8 [18]. The yield curvature φ_y was found as the secant bending stiffness at 75% of the ultimate bending moment.

The curvature ductility factor values in Table 4 show that the CFRP wrapped significantly contributes to increasing the ductility of the column. Partial CFRP wrapping is effective in the strengthening of RC structures working in earthquake areas, in order to limit the sudden collapse of the structural members.

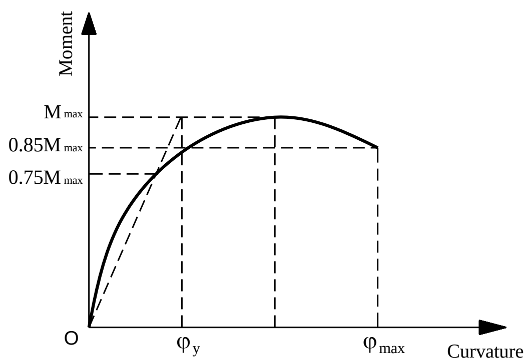


Figure 8. Determination of yield and maximum curvature of RC columns

Table 4. Curvature ductility factor

Specimens	φ_y ($10^{-6}\times$ rad/m)	$\varphi_{\max}$ ($10^{-6}\times$ rad/m)	$\mu = \frac{\varphi_{\max}}{\varphi_y}$
C-0	28.5	61.5	2.2
C-S-3	30.8	121.5	4.0
C-S-4	31.5	143.3	4.5

3.5. Comparison between analytical predictions and experimental results

In the case of RC columns with rectangular cross-section, according to ACI 440.2R-17 [1] and *fib* 14 [2], the maximum confined concrete compressive strength, f'_{cc}, and the maximum confinement pressure f_l are calculated using Eq. (5) and (6), respectively, with the inclusion of an additional reduction factor ψ_f equals to 0.95.

$$f'_{cc} = f'_c + \psi_f 3.3\kappa_a f_l \tag{5}$$

$$f_l = \frac{2nE_f t_f \varepsilon_{fe}}{D}\kappa_e \tag{6}$$

In Eq. (5), κ_a is the efficiency factor accounts for the geometry of the section. In Eq. (6), n is the number of CFRP plies, t_f is the thickness per ply, E_f is the modulus of elasticity of CFRP material, ε_{fe} is the effective strain in FRP at failure that equals $0.586\varepsilon_{fu}$ (ε_{fu} is the design rupture strain of FRP), D is the diameter of equivalent circular column, κ_e is the confinement effectiveness coefficient accounts for the influence of partial wrapping [2].

The factor κ_a can be calculated as follow:

$$\kappa_a = \frac{A_e}{A_c}\left(\frac{b}{h}\right)^2 \tag{7}$$

$$\frac{A_e}{A_c} = \frac{1 - \dfrac{\left[\left(\dfrac{b}{h}\right)(h-2r_c)^2 + \left(\dfrac{h}{b}\right)(b-2r_c)^2\right]}{3A_g} - \rho_g}{1-\rho_g} \tag{8}$$

where A_c and A_e are the cross-sectional area and the effective cross-section area, respectively (Fig. 9), A_g is the gross cross-sectional area, r_c is the radius of the corner, ρ_g is the longitudinal steel reinforcement ratio.

The diameter of equivalent circular cross-section D can be calculated as the diagonal of the rectangular cross-section:

$$D = \sqrt{b^2 + h^2} \tag{9}$$

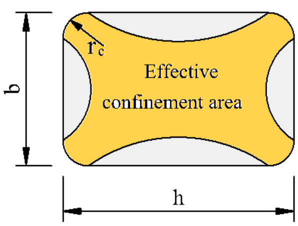


Figure 9. Confinement effectiveness cross-sectional area

To take into account the effectiveness of this strengthening method, in this research, it is proposed using coefficient κ_e ($\kappa_e < 1$) in calculating the maximum confinement pressure in Formulation (5). The coefficient κ_e is determined based on *fib* 14 [2], where a column rectangular section is replaced by a column circular section with an equivalent diameter shown in (9), and given as:

$$\kappa_e = \left(1 - \frac{s'}{2D}\right)^2 = \left(1 - \frac{s'}{2\sqrt{b^2+h^2}}\right)^2 \tag{10}$$

where s' is the clear spacing between the FRP wraps. In this study s' is 75 mm (Fig. 2).

The above-mentioned equations were used to determine the maximum confinement concrete compressive strength. The summary of the calculated parameters for strengthened columns C-S-3 and C-S-4 is given in Table 5.

According to the guideline of ACI 440.2R-17 [1], the axial load-moment ($P - M$) interaction diagrams for the un-strengthened and strengthened columns were constructed and presented in Fig. 10. It can be seen that the prediction results were suitable in comparison with experimental results.

Table 5. Summary of calculation parameters

κ_a	κ_e	f_l	f'_c	f'_{cc}
0.30	0.72	1.47	23.5	24.9

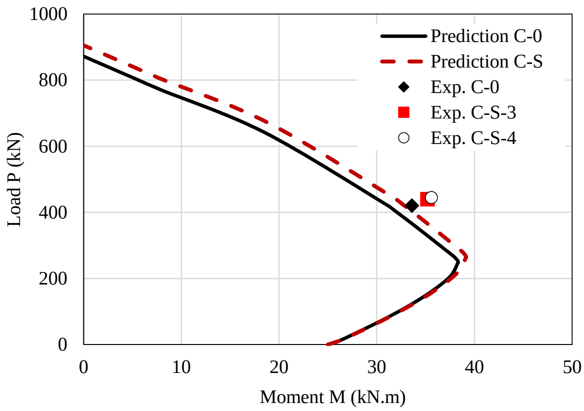


Figure 10. $P-M$ interaction diagrams

4. Conclusions

This paper presents an experimental investigation on the CFRP strengthening effects on eccentrically compressed RC columns with rectangular cross-section. Three specimens, one is un-strengthened while two others are partially strengthened, have been tested to failure. Based on the obtained test results, several conclusions can be drawn as follows:

- The behavior of strengthened columns with CFRP partially wrapped was typical with the same compression-controlled failure mode which is characterized by yielding of tensile longitudinal steel bars and crushing of compressive concrete on the compression face.

- It has been shown that the CFRP partial wrapping has significantly improved the curvature capacity of the column specimens. However, the flexural stiffness of the strengthened columns is not affected.

- The contribution of CFRP wrapped was also shown for the post-peak response of the strengthened columns. The CFRP sheets were effectively activated to limit the stiffness degradation and to increase the ductility of the strengthened columns.

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