BIAXIALLY LOADED CFRP-CONFINED RECTANGULAR RC COLUMNS

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ABSTRACT

This paper investigates the behavior of rectangular RC columns strengthened with carbon fiber-reinforced polymer (CFRP) composites under biaxial loading. A total of 4 wall-like RC columns are tested under biaxial loading up to failure. In this research, some parameters such as CFRP thickness and fiber orientations are studied. Their influence on the moment-curvature and load-deflection curves is concerned. Generally, longitudinal layers improve load carrying capacity and ductility of columns, but transverse layers plays a little role in increasing strength of specimens. The results show that using CFRP composites causes a great improvement on the strength and ductility of confined RC columns under axial loading and biaxial bending.

Keywords: Biaxial Bending, Rectangular RC Columns, Carbon Fiber-Reinforced Polymer, Strength, Ductility.

1. INTRODUCTION

In recent years, fiber reinforced polymers (FRPs) are increasingly being used for rehabilitating and strengthening of structural members due to their minimal aesthetic impact, corrosion resistance, no additional weigth, quick and easy implement (Teng et al. 2003; Xiao 2004). Many researchers studied the behavior of axially loaded FRP-confined RC columns, but less attention on the behavior of the confined columns under biaxial bending is reported in the literature (Zaki 2013; Gajdosova and Bilcik 2011)

Confining rectangular reinforced concrete (RC) columns increases their strength, ductility, and stiffness. The load carrying capacity of the biaxially loaded FRP-confined RC columns is a function of the column shape (circular, square, and rectangular), the cross-sectional aspect ratio, the height of column, the flexural and shear reinforcement ratio, the eccentricities, the mechanical properties of the FRP composite sheets, the FRP volume, and the compressive strength of concrete (Punurai et al. 2009; Hsu and Mirza 1973).

Punurai et al. presented experimental and numerical investigations on the behavior of CFRP-confined RC slender columns under axial load and biaxial bending. A total of five RC slender columns confined with CFRP composite sheets were tested under biaxial bending. The

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results showed that strengthening with CFRP composites increased load carrying capacity and ductility of the columns. In addition, the effects of the fiber orientation on the moment-curvature, transverse and longitudinal strains relationships were studied and the results indicated that the lateral deflection was reduced when FRP fabrics were oriented in the longitudinal direction. Moreover, the longitudinal fibers resulted in more flexural capacity and energy dissipation rather than transverse layers (Punurai et al. 2013).

Ozcan et al. tested five RC columns to investigate the application of FRP strengthening of non-ductile square reinforced concrete with low strength concrete and plain bars. They found that upon CFRP retrofit, deficient columns were able to withstand larger deformation demands without strength degradation (Ozcan et al. 2008).

Cao et al. expressed that load eccentricity affected the stress-strain relationship of biaxially loaded RC columns because eccentricity caused variation in transverse confinement pressure across the section leading to longitudinal stress. Moreover, the rectangularity of the cross-section reduced the CFRP efficiency in increasing the load carrying capacity and ductility of columns (Cao et al. 2006).

This paper presents the results of an experimental investigation on the behavior of rectangular RC columns strengthened with CFRP composites under axial load and biaxial bending. In this regard, four CFRP-confined wall-like rectangular RC columns are built and tested up to failure. The results show that using CFRP composites for strengthening of RC columns improves their compressive and flexural behavior and increases their strength and ductility.

2. EXPERIMENTAL PROGRAM

A total of 4 rectangular RC columns are tested under axial load and biaxial bending. The cross-sectional aspect ratio is 3 and the height of test section is 1500 mm. All columns' corners are chamfered to a radius of 15 mm and three of them are confined with CFRP composites. The geometry and detail of reinforcement are shown in Figure 1.

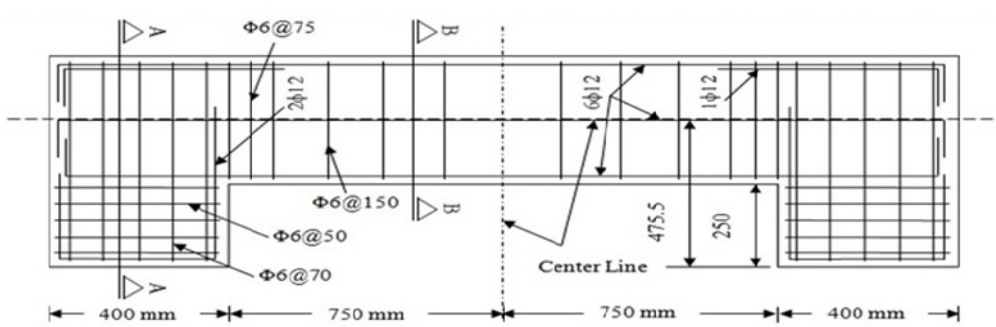

Figure 1: Geometry and reinforcements detail of columns (units in millimeters)

All columns are cast from a concrete with a compressive strength of f_c = 35 MPa. The longitudinal and tranverse steel reinforcements are 6 ϕ12 mm and ϕ6 @150 mm, respectively. The yield strength

of the longitudinal and tranverse steel reinforcements are 375 and 215 MPa, respectively. Additional reinforcements are embedded in the end brackets to prevent the local failures.

Unidirectional carbon fiber reinforced composites (CFRP) are used to strengthen the RC columns with an expoxy resin. A cured CFRP has a thickness of 0.5 mm, and a tensile strength of 336 MPa. The mechanical properties of CFRP are given in Table 1.

Table 1: Mechanical properties of CFRP

Test Direction	*Ultimate Strength (MPa)*	*Initial Modulus (MPa)*	*Ultimate Strain (mm/m)*	*CFRP Thickness (mm/layer)*	*Dry Thickness (mm/layer)*
Fiber Direction	336	39944	9.3	0.5	0.166
Matrix Direction	32	2338	9	0.5	0.166

In this paper, the effect of CFRP thickness and fiber orientations are studied. In this regard, three fiber orientations including 0˚, 90˚, and a combination of them are considered, where 90˚ refers to fibers orientation along the column axis and 0˚ refers to the orientation of fibers perpendicular to the column axis. The test program is summarized in Table 2, where the CFRP-confined and unstrengthened columns are labelled “S” and “U”, respectively. Two labels, “L” and “T”, are the representatives of fiber orientations of 0˚, and 90˚, respectively. In addition, a pair of eccentricity in two directions, 225 mm in Y-direction and 75 mm in X-direction, is selected and is constant during the test.

Table 2: Specimens’ details

Specimens	*Type*	*Number of Layers*	*Fiber Orientation*	*Eccentricity Y-Direction (mm)*	*Eccentricity X-Direction (mm)*
U-225-75	Unstrengthened	---	---	225	75
S-225-75-L	Strengthened	1	90˚	225	75
S-225-75-T	Strengthened	1	0˚	225	75
S-225-75-LT	Strengthened	2	90˚/0˚	225	75

The load is applied by a 1000 KN load capacity hydraulic jack. Two end hinge supports are designed to apply the load in the defined eccentricity. The lateral deflection in the direction of each principal axis is measured by means of four Linear Variable Displacement Transducers (LVDTs). The longitudinal and transverse strains are measured by forty foil strain gauges for each specimen. Totally, the specimens are tested under axial load and biaxial bending up to failure.

3. RESULTS AND DISCUSSION

3.1. Overall Behavior

The unstrengthened columns fail suddenly by crushing at the bottom of the load point and propagating tensile cracks on the tension sides. As the compressive load increases incrementally, the tensile cracks continue along two tension sides and a pyramid crushed zone is produced at the bottom of the load point. The total failure is accompanished with yielding and buckling of the

tensile and compressive steel reinforcements, respectively and finally the plastic hinge is produced in the middle of the columns.

The behavior of strengthened columns is similar to the unstrengthened specimens until the concrete reaches to its ultimate tensile strength and cracking is started. After then, the tensile stresses are transferred to the CFRP composite and the failure is accompanished with the rupture of the CFRP sheet. It is noted that there is no debonding between the concrete and the CFRP sheet. The plastic hinge is also formed at the midheight of the column. The cracking pattern, the crushed section, and the rupture of CFRP composite at the failure are shown in Figure 2.

Figure 2: Failure and cracking pattern of unstrengthened and strengthened specimens

3.2. Load-displacement Relationship

The load-displacement curves of the specimens are shown in Figure 3. In Figure 3, the horizontal axis is the longitudinal displacement (U_{Lon}) which is obtained from the actuator displacement gauge, and the vertical axis shows load capacity of the columns in KN. The unconfined column has a nearly linear behavior up to the yield point (i.e., Y) of 156.24 KN, the corresponding longitudinal displacement of 8.35 mm, and the secant stiffness of 24.72 KN/mm. After then, load carrying

capacity increases till a load level of 215.04 KN and the longitudinal displacement of 11.82 mm. The postpeak behavior of the specimen includes a softening branch where the plastic hinge is formed and the compressive bars are buckled. All strengthened columns show the similar behavior to the unstrengthened specimens up to the yield point. Strengthening with CFRP composite improves the secant stiffness, the yield point, and the total load carrying capacity of the columns. For example, for S-225-75-LT, the load level of the yield point of the tensile steel bars increases by more than 78%. The secant stiffness, the yield point of tensile bars, and the failure point of all specimens are summarized in Table 3. This shows that CFRP-confined rectangular RC columns have the better behavior to the unstrengthened columns where the longitudinal layers increases the maximum load carrying and flexural capacity of columns (i.e., F), but the transverse layers increases ductility significantly.

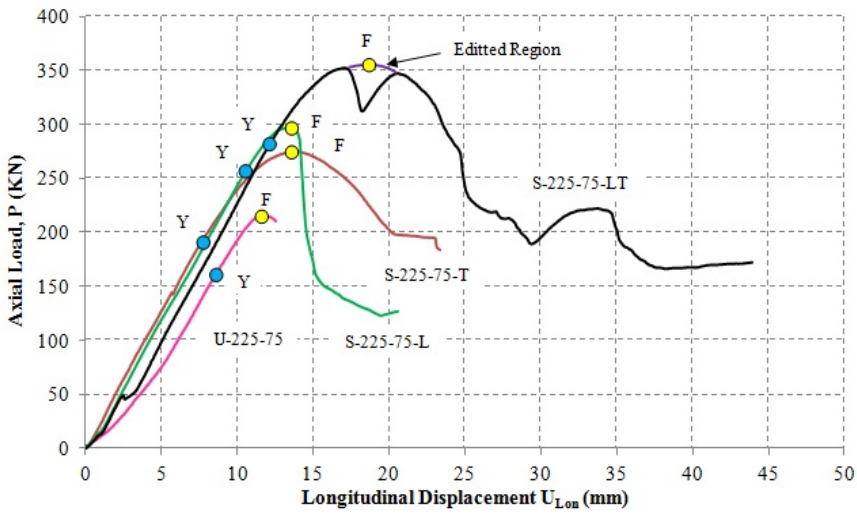

Figure 3: Load-displacement curves of the specimens

Table 3: Specimens design details

Specimen	*Secant Stiffness (KN/mm)*	Yield Point		CFRP Failure Point	
		Load (KN)	*U_{Lon} (mm)*	*Load (KN)*	*U_{Lon} (mm)*
U-225-75	24.72	156.24	8.35	215.04	11.82
S-225-75-L	26.34	250.34	10.31	296.69	13.28
S-225-75-T	25.03	194	7.75	274.62	13.72
S-225-75-LT	25.73	277.46	11.92	352.78	17.06

3.3. Moment-curvature Relationship

The moment-curvature relationships of the columns are studied about two main and weak axes of the cross-section. Figures 4 and 5 show the moment-curvature curves of the specimens around the weak and the main axes of the cross-section, respectively. The moments around the weak and main axes, M_y and M_x, are calculated by multiplying the axial load (P) by the actual eccentricities. The

actual eccentricities are predefined eccentricities, e_y and e_x, plus midheight lateral deflections ($U_{Lat\text{-}y}$ and $U_{Lat\text{-}x}$). The bending moment is given as equation (1). By substituting x with y in the equation (1), M_y will be calculated.

$$Mx = P\,(ex + U_{Lat\text{-}x}) \tag{1}$$

The columns have two curvatures in both directions of the main and weak axes (i.e. φ_x and φ_y respectively). The curvatures are calculated using equation (2) based on the plane section assumption. By substituting x with y in equation (2), φ_y will be determined.

$$\varphi x = \frac{(\varepsilon_{L-top})_x - (\varepsilon_{L-bottom})_x}{h} \tag{2}$$

Where ε_{L-top} = longitudinal strain of the tension face; $\varepsilon_{L-bottom}$ = longitudinal strain of the compression face; and h= height of the cross-section corresponding to each axis (i.e., 450 mm and 150 mm for the main and weak axes, respectively).

The results show that strengthening improves the moment capacity of the columns and it is clear that the longitudinal layers in comparison to the transverse layers have a greater effect on the moment capacity of the specimens. As the number of longitudinal layers increases, the CFRP stiffness also increases. In this regard, the curvatures are not enhanced significantly. The moment-curvature behavior of the specimens is dependent on the fibers orientation. It is noted that the rectangularity of the cross-section decreases the effect of the CFRP composite.

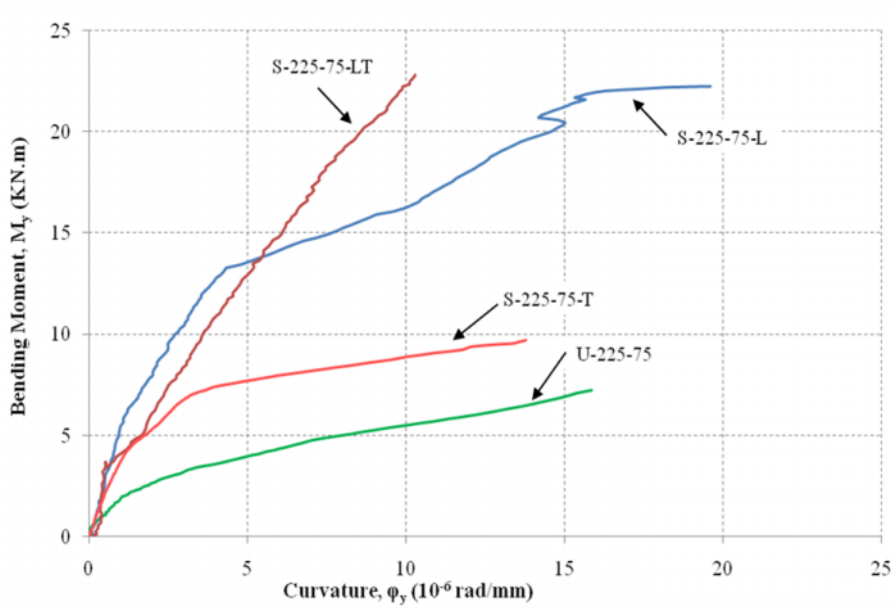

Figure 4: Moment-curvature behavior of the columns around the weak axis

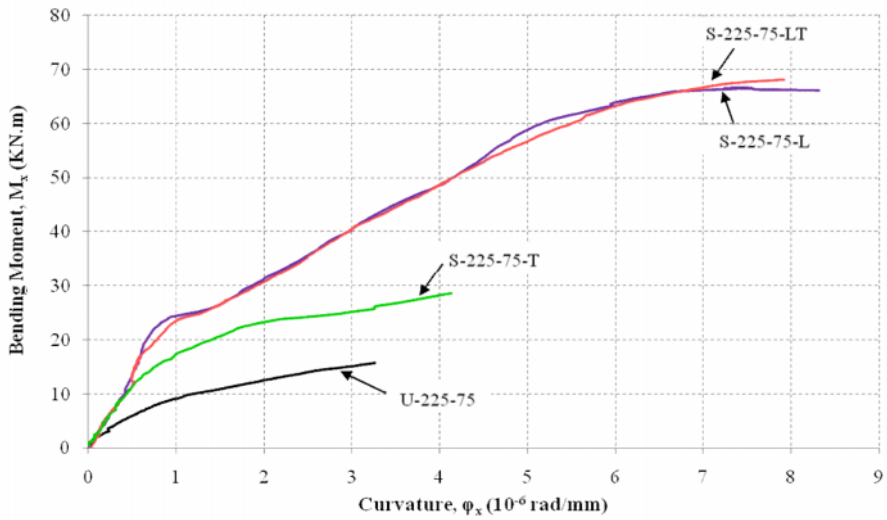

Figure 5: Moment-curvature behavior of the columns around the main axis

4. CONCLUSIONS

This paper expresses the behavior of rectangular RC columns strengthened with CFRP composites under axial load and biaxial bending. Four large-scale RC columns are built and tested under biaxial bending up to failure. The effect of the fiber orientation on the moment-curvature and load-displacement relationships of wall-like CFRP-confined RC columns is studied. The results indicate the following conculsions:

1) The overall behavior of the strengthened and unstrengthened RC columns is similar up to the yield point and then the load carrying capacity increases till the CFRP rupture. At the failure, tensile cracks propogate along the weak axis and a region at the bottom of the load point is crushed. The load-displacement curves of the columns have a descending branch which is soft for the strengthened columns with the transverse layers. It is clear that strengthening improves the compressive and flexural capacity of the specimens. The ductiliy also increases as the CFRP thickness increases which is resulted in improving the energy dissipation.

2) Strengthening with CFRP composites increases the bending stiffness and moment capacity of the specimens. The moment-curvature curves about the main and weak axes of the cross-section show tri-linear relationships that CFRP confining improves the moment capacity of the columns. The longitudinal layers have a greater effect on the moment capacity rather than the transverse layers. It is clear that the curvature around the weak axis is about 2.5 times of the main axis. In fact, the weak axis governs the failure mode of the specimens. In addition, all columns fail in the tension-controlled failure zone.

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