SEISMIC STRENGTHENING OF RECTANGULAR RC COLUMNS WITH CFRPS

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1 INTRODUCTION

Known vulnerabilities of typical building columns (low concrete strength, use of plain bars and insufficient transverse reinforcement etc.) in Turkey were found to be responsible for total collapse or partial damage of buildings during recent earthquakes. The use of fiber reinforced polymers (FRPs) for ductility enhancement of deficient rectangular columns has gained increasing popularity in Turkey. Mainly, for ductility enhancement of RC columns using FRPs, the adverse effect of column rectangularity on seismic behavior was observed in the previous experimental studies. In addition, the effectiveness of internal FRP ties in seismic performance of RC columns was investigated [1, 2]. Nevertheless, the lack of experimental data for FRP wrapped rectangular columns with aforementioned deficiencies motivated this research. The experimental study reported herein focuses on the confinement and ductility enhancement of flexure dominated rectangular RC columns upon CFRP wrapping and providing simple design guidelines.

2 EXPERIMENTAL STUDY

2.1 Test Specimens and CFRP Application

In the experimental program, a total number of five specimens were tested and the measured parameters are shown in Table 1. The rectangular RC column specimens with an aspect ratio of 2 and dimensions of 200×400×2000 mm (width×depth×length) were vertically cast together with a column stub of 400×500×1350 mm as shown in Figure 1a. Two levels of confinement ratio and three different details of carbon fiber reinforced polymer (CFRP) dowel configuration for confinement effectiveness were selected as the test parameters.

Table 1 Specimen properties

Spec.	Specimen Properties				Longitudinal Steel Ratio	Axial Load N/N_0 *	CFRP	
	f_c'	f_y	Reinforcement					
	(MPa)	*(MPa)*	**Longitudinal**	**Transverse**	*(%)*	*(%)*	**Ply**	**Anchor Type**
S1	12.0	287	8 x 18 mm (plain bars)	10 mm diameter bars at 200 mm	2.55	35	0	Ref.
S2	10.0						1	16-Pin
S3	10.5						1	8-Pin
S4	9.0						1	No-Pin
S5	15.5						1	16-Pin

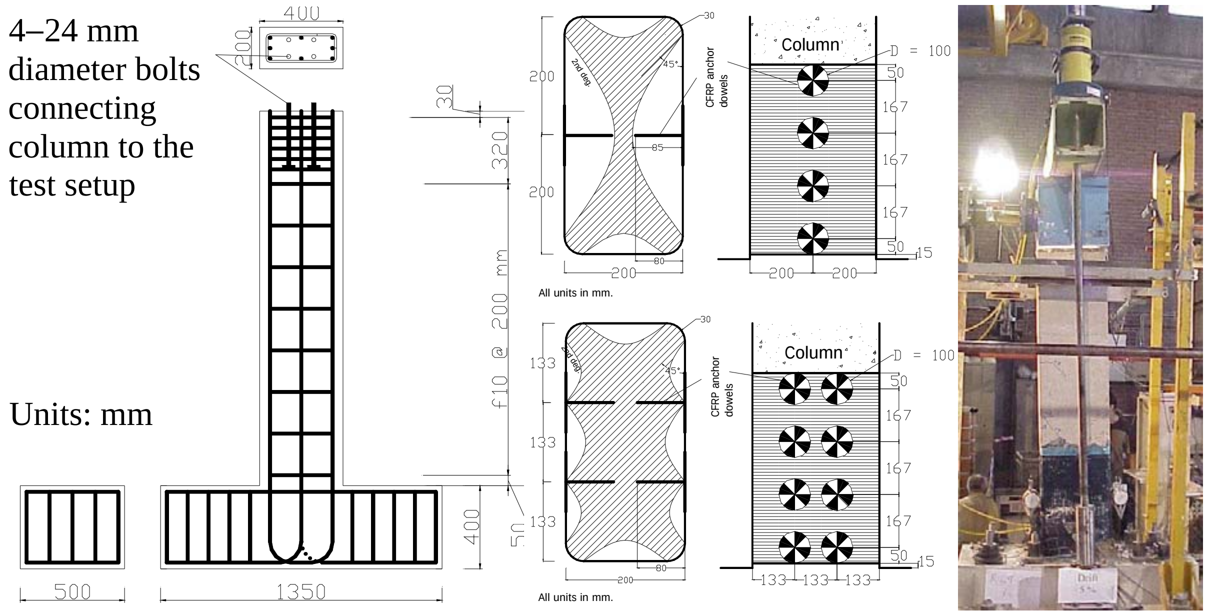
*: $N_o = 0.85 f_c' A_g + A_s f_y$

Strengthening process was implemented by 1 layer of CFRP sheet that was wrapped around the column over a height of 600mm. Subsequently, hand-rolled 120×130 mm^2 CFRP anchor dowels were inserted 80mm into the previously drilled and cleaned holes that were available at both faces of the column (8 and 16 holes for 8 and 16-pinned configurations, respectively) as shown in Figure 1b. The CFRP anchor dowel locations were arranged symmetrically in order to ensure a homogeneous distribution over the CFRP wrapped region. All the specimens tested in the experimental program were wrapped with one layer of CFRP except the reference specimen, S1, with no strengthening. The strengthened specimens S2 and S5 were identical having 16-pinned CFRP anchor dowels however with different concrete compressive strength values hence resulting in two different confinement ratios.

For the remaining other two specimens, S3 had 8-pinned CFRP dowel configuration whereas there were no anchor dowels used in specimen S4. The confinement ratio of specimens S2, S3 and S4 were similar to each other (i.e. moderate level confinement) as compared to specimen S5 with higher confinement ratio (Figure 1b). The carbon fiber sheets used for strengthening had a thickness of 0.165 mm with a rupture strain of 0.015 and elasticity modulus of 230000 MPa as obtained from the manufacturer's data.

2.2 Instrumentation and Testing

In order to monitor the column deflections and hinging region rotations LVDTs and electronic dial gages were used in all stages of axial and lateral loading. Two couples of LVDTs were placed at 2000 mm recording tip deflections and the remaining ones were used to monitor deflections of the specimen at various drift levels in pull and push directions. Axial and lateral loading were applied by hydraulic actuators that were controlled by three load cells. The specimens were guided with four rollers to assure bending in plane of lateral loading during the lateral displacement cycles (Figure 1c).



a. b. c.

Figure 1 a. Specimen properties, b. CFRP confinement scheme and c. Test setup

Table 2 Test Results

Specimen	ϕ	M_u^+	M_u^-	P_{ya}	Interface Cracking	CFRP Debond	CFRP Rupture	DR_u* +	DR_u* -
		(kNm)	*(kNm)*	*(kN)*	*Drift (%)*				
S1	0	99.0	111.2	49.5		1.5 (crushing)		1.85	1.66
S2	0.322	75.2	92.0	34.5		2.0	6.0	6.11	6.11
S3	0.178	82.4	101.0	39.0	0.5	2.0	2.5	3.77	3.68
S4	0.207	82.0	100.0	36.5		2.0	4.0	3.92	3.84
S5	0.215	120.0	131.2	59.5		2.0	4.0	4.02	4.00

* *Ultimate Drift where lateral capacity dropped 20% of the peak in positive and negative cycles.*

2.3 Test Results

The seismic performance of each specimen was evaluated over the cyclic lateral load (P) – tip deflection (Δ) responses of the columns. In order to compare the seismic behavior of the specimens regarding the concrete compressive strengths, the envelope of each specimen response was normalized by the yield forces that were found analytically from standard sectional analysis (Table 2). In the normalization process, each lateral load value was divided by its yield force for all specimens. Normalized column envelope responses are compared in Figure 2. Considering the flexural failure mechanism, observed behavior of all the specimens was similar to each other by the formation of plastic hinging at the column base. Specimen S2 demonstrated better seismic behavior (i.e. larger deformation capacity and better maintenance of lateral load) than that observed in S5 owing to its lower concrete strength and resultant higher confinement ratio. The specimens S3 and S4 exhibited a similar response concerning the ultimate drift levels of about 4%.

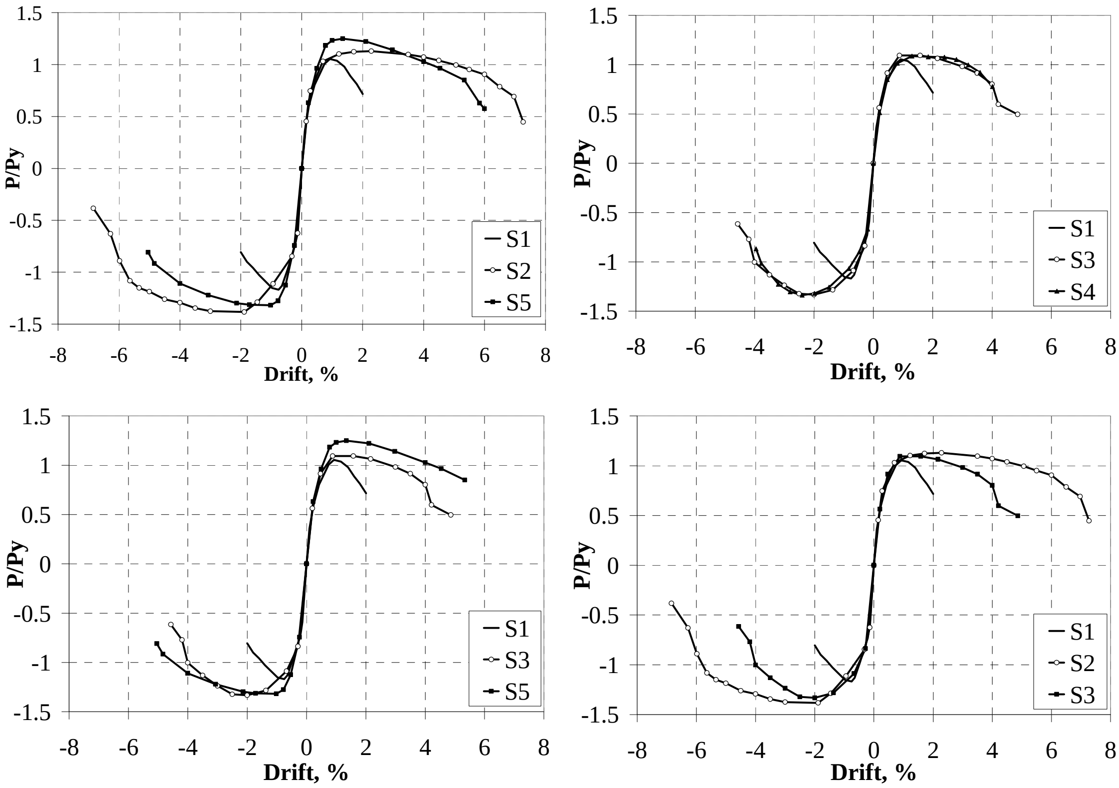


Figure 2 Normalized Responses of Specimens according to Yield Forces

2.4 Discussion of Test Results

The effect of confinement ratio on ultimate drift ratio was observed upon comparing the specimens S1, S2 and S5. According to the conducted tests, increasing the confinement ratio led to an improvement in the ultimate drift levels. Since the concrete strength of the specimen S2 was lower than S5, wrapping the column by one layer of CFRP eventuated in a higher value of confinement level. 8-pinned or no-pinned CFRP anchor configurations (S3 and S4, respectively) made the columns sustain about 4% drift. The same ultimate drift level was attained for the specimen S5 due to the increase in the confined area concerning the 16-pinned configuration. In addition, for the specimen S2, confinement ratio was enhanced since the column had relatively lower concrete compressive strength than S5. Furthermore, the CFRP anchor dowels changed the shape of the effectively confined region for both specimens S2 and S5. For 8-pinned detailing, due to the placement of the anchors at the middle of the column face, the CFRP anchors were not clamped to the parabolic borderline of the CFRP confined region. Nevertheless, this phenomenon was not factual for 16-pinned detailing while the CFRP anchor clamping was observed by changing the shape of the confined region (Figure 1b).

3 DRIFT BASED DESIGN METHODOLOGY

Concerning the inadequacies in predicting ultimate drift levels of flexural columns, a column database containing a total of 47 specimens (with square and rectangular columns with various cross-section dimensions, corner rounding radii and transverse reinforcement ratios) was acquired. 19 columns were wrapped with CFRP out of 26 FRP strengthened columns and the remaining ones were strengthened with GFRP. Considering the design parameters that influence the seismic behavior of the columns (confinement ratio, axial load ratio, and longitudinal reinforcement ratio), nonlinear regression analysis was conducted to develop a predictive design equation. The parameters of longitudinal steel ratio (ρ_l), axial load ratio (n) and confinement ratio (ϕ) are used to obtain ultimate drift levels (DR_u) for the columns at which the lateral resistance dropped to 80% of the peak. The confinement ratio parameter (ϕ) encapsulates also the effect of the CFRP anchor dowels for 16-pinned configuration regarding the enhancement in confined region as observed throughout the experimental program. According to the regression analysis, the design equation is obtained as shown in Eq. 1.

$$DR_u = 2.47 + 50\frac{\phi^{0.64}}{\rho_l^{0.35} n^{1.29}} \quad (1)$$

where ϕ, ρ_l and n are in percents (%).

In Figure 4, the drift estimations of the proposed equation at column 'failure' are compared with those obtained from test results. It should be noted that the minimum longitudinal reinforcement ratio of 0.5 % should be used and the axial load level that a column can sustain should be in limits of 10 % (compression) to 70 % (compression) of the axial capacity. In addition, the section aspect ratio should be smaller than two as stated by Ozcan et al. [3].

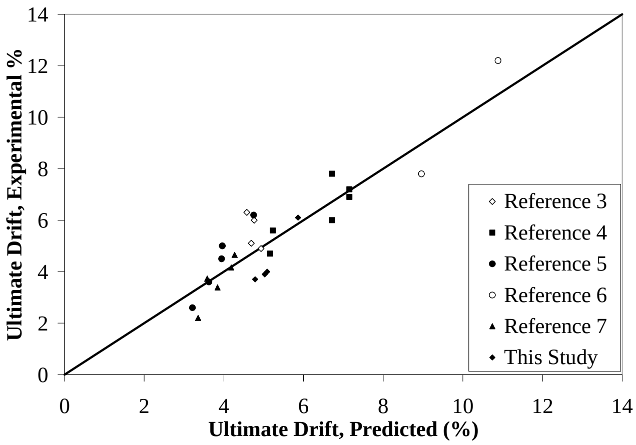


Figure 4 Predicted results by nonlinear regression analysis for proposed design equation

4 CONCLUSIONS

The obtained conclusions from this study can be summarized as follows:

- The improvement in the confinement ratio enabled the columns to sustain greater levels of ultimate drift ratios. Since the enhancement in confinement ratio was higher for the columns having low concrete compressive strengths, the drift capacity was improved concerning the increase in the area of confined region.
- Using 16-pinned CFRP anchor dowel configuration induced higher confinement ratios than the 8-pinned type while the confined region of the columns extended by closely spaced CFRP dowels.
- A drift-based design method was proposed including the parameters of longitudinal reinforcement ratio, axial load level and confinement ratio. The drift capacities of the columns in the experimental database were predicted with a good approximation.

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