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Retrofit using CFRP Composites of RC Bridge Columns under Combined Loads

Abdeldjelil (DJ) Belarbi*, Pedro F. Silva**, Sang-Wook Bae*
**Missouri University of Science and Technology, Rolla, Missouri, USA*
***George Washington University, Washington DC, USA*

ABSTRACT: Bridge columns subjected to combined axial, shear, flexural, and torsional loads and retrofitted with carbon fiber reinforced polymers (CFRP) have not been extensively studied. Although many retrofit techniques have been implemented in the past on circular columns, these techniques have been predominantly investigated under unidirectional loading profiles and only a few bidirectional loading patterns have been investigated. Essentially no data exists for columns under torsional loading or combined with the usual shear and flexural loading conditions. This paper presents test results of four columns tested under different combined loading effects. Amongst these columns one column was subjected to significant damage level and subsequently retrofitted with CFRP composites.

1 INTRODUCTION

During an earthquake, bridge columns may be subjected to torsional loads combined with other loading actions, such as bending moments, shear forces, and axial loads. Combined actions are especially more significant in superstructures supported on outrigger beams, curved bridges, and skewed bridges. In regular bridges with outriggers, rotation of the superstructure could be significant due to deformation restraints from the abutment keys. In curved bridges, the responses of the transverse and longitudinal directions are coupled causing the columns to experience multi-directional deformations combined with significant torsion. In skewed bridges, torsion may be a result of deck and abutment pounding. When bridge abutments exhibit significant stiffness, lateral seismic loads will cause single-column bents to translate laterally and rotate slightly (Silva & Belarbi, 2005). Spread footings and pile cap footings have adequate torsional restraint to be considered fixed against rotation. As such, the superstructure rotation will cause compatibility torsion in the columns. Since many bridge columns and beams were not designed to carry these additional load effects and maybe deficient to resist the additional torsion it may be necessary to retrofit these columns using FRP composites (Panchacharam & Belarbi, 2002, Ghobarah et al., 2002). This is a retrofit technique that has been extensively studied to enhance confinement and shear resistance capacity of bridge columns (Seible et al., 1997, Silva et al., 2007, Okano et al., 1997).The objective of this paper is to present one of the first tests ever performed on the use of FRP to strengthen RC columns subjected to combined axial, shear, flexural, and torsional loads. Experimental and analytical results from this research program are presented in this paper.

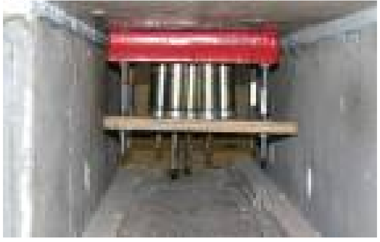
2 RESEARCH PROGRAM

2.1 *Test Setup and Test Columns*

This paper presents a series of three test specimens that were constructed in the structures laboratory at the Missouri University of Science and Technology, Rolla. Amongst these, one column was subjected to significant damage level and subsequently retrofitted with CFRP composites. As such, a total of four columns were tested using the test setup shown in Figure 1. The column height/diameter aspect ratio of approximately 6.00, which indicates that the response of the columns was dominated by flexural behavior. In Table 1, one column was subjected only to combined bending and shear and was designated as Unit 1. The second column was tested under pure torsion and was designated as Unit 2. The third and forth units were tested under a combined torsion (T) and flexural (M) loading along with shear with a ratio of T/M = 0.20 and were designated as Units 3 and 4. Unit 4 consisted of retrofitting Unit 3 column using CFRP composites. The gravity load was simulated via seven high strength steel strands running through the center of the column and anchored to a plate underneath the test specimen, see Figure 2.

Figure 1: Test Setup

(a) Axial load fixture (b) Column base



(c) Base of footing

Figure 2: Axial Load Fixtures

Table 1. Test Columns

Unit ID	Column designation	Torsion/Moment ratio (T/M)	Transv. Reinf. Ratio	Longitudinal Reinf. ratio
1	Flexure/Shear (no Torsion)	0.00	0.73 %	2.1 %
2	Pure Torsion	Infinity	0.73 %	
3	Flexure/Shear/Torsion (Control)	0.20	0.73 %	
4	Unit 3, Retrofitted	0.20	0.73 %	

2.2 *Test Units Reinforcement Layout and Material Properties*

The cross section of the test units is depicted in Figure 3. The column diameter was 610 mm, and the clear cover to the column longitudinal reinforcement was 25.4 mm. Longitudinal reinforcement consisted of 12-D25 for a ratio of approximately 2.1%. The transverse reinforcement consisted of D-9.5 hoops spaced at 70 mm for a volumetric ratio of approximately 0.73%. Figure 1 depicts Unit 1 fully instrumented during testing. Material properties are listed in Table 2.

2.3 *Unit 4 - Retrofit Strategy*

The objectives of the retrofit scheme were to restore the original strength. In order to archive this goal, the retrofit was conducted in five major steps consisting of: *i)* removal of damaged concrete, *ii)* restoration of the cross-section of the column using a low viscosity grout as shown in Figure 4(b), *iii)* application of CFRP sheet in the longitudinal direction to restore some of its original flexural strength *iv)* application of CFRP sheet in the circumferential direction to restore the axial compression strength and *v)* application of mechanical anchorage to ensure the CFRP sheet in the longitudinal direction as shown in Figure 4(c) and (d). The mechanical properties of the CFRP sheets used for the retrofit are presented in Table 3. Three layers of CFRP sheets were applied in both longitudinal and circumferential directions using the wet lay-up technique. The design process of the CFRP strengthening is discussed in detail in the next section.

Table 2. Material and Cross-Sectional Properties

Height	3.66 m
Diameter	610 mm
Clear cover	25.4 mm
P/f'cAg	7%
Longitudinal	12 – D15
Long. Steel Ratio	2.1%
Spiral	D9.5
Spiral Pitch	70 mm
Transv. Steel Ratio	0.73%
Longitudinal reinforcement	f_y=455 MPa, f_u=663 MPa
Transverse reinforcement	f_y=450 MPa, f_u=648 MPa
Concrete Strength	f'_c=42 MPa*

* f'_c for Unit 1 was 29MPa, and 38 and 42MPa for Units 2 and 3(4), respectively.

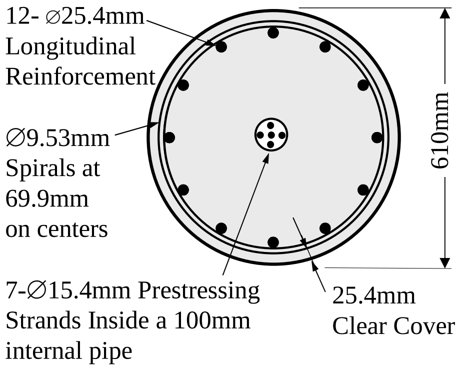
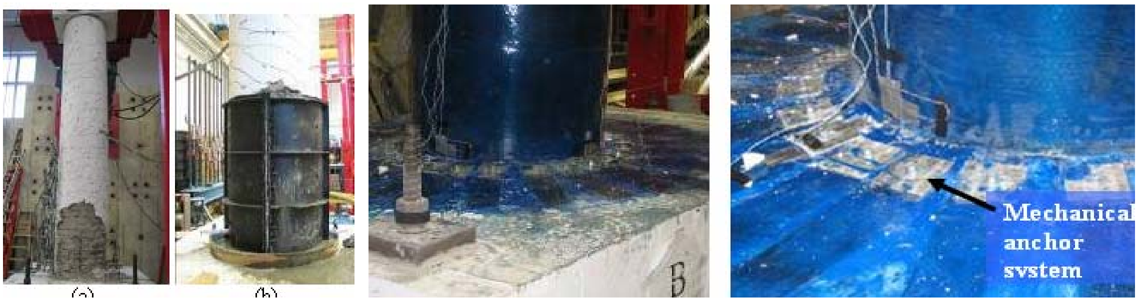


Figure 3: Column Cross-Section

Table 3. Mechanical Properties of CFRP Sheets

Product Name (Manufacturer)	*Design Thickness*	*Design Strength*	*Design Strain*	*Tensile Modulus*
CF 130 High Tensile Carbon (MBrace Composite Strengthening Systems)	0.165 mm	3,790 MPa	0.017	227 GPa



(a) Damaged Column (b) Filling Cracks (c) Base Detail (d) Base Detail Mechanical Anchors

Figure 4: Retrofit Strategy

3 DESIGN OF CFRP STRENGTHENING SYSTEM

Design of the CFRP strengthening system was mainly accomplished to restore Unit 3 original axial compression and flexural strength. This design objective was accomplished by applying the CFRP sheets in both the circumferential and the longitudinal direction. The following major assumptions were made during the design process; *1)* the buckled reinforcing bars cannot resist neither compressive nor tensile stresses, *2)* the strength of the grout used to restore the cross-section of the damaged column was 42 MPa, and *3)* the reinforcing bars in the column-foundation joint were not damaged and; thus, can resist both compressive and tensile stresses.

3.1 *Restoration of Axial Compression Strength*

The original axial compression strength of column, Unit 4 can be calculated as

$$P_0 = 0.85 f'_c \left(A_g - A_{st}\right) + f_y A_{st} = 12{,}940 \text{ kN} \tag{1}$$

where: A_g is the gross cross-sectional area of the column or 2,870 cm^2, A_{st} is the area of column longitudinal reinforcement or 61.16 cm^2, f'_c is the concrete compression strength at the time of testing or 42 MPa, and f_y is yield strength of the steel reinforcement or 455 MPa. For the CFRP strengthened column, the restored axial compression strength was:

$$P_{0,repaired} = 0.85 f'_{cc} \left(A_g - A_{st,damaged}\right) + f_y A_{st,damaged} = 16{,}725 \text{ kN} = 1.3\, P_0 \text{ kN} \tag{2}$$

where: $A_{st,damaged}$ is the area of longitudinal steel reinforcement of the damaged column which excluded the buckled reinforcing bars or 25.48 cm^2 (5 bars total), and f'_{cc} is the concrete strength confined with 3 layers of CFRP sheets. The confined concrete compression strength was 63 MPa as determined based on a procedure proposed by Bae (2004). Figure 5 shows the stress-strain curves of the concrete confined by different layers of CFRP sheets.

3.2 *Restoration of Flexural Strength*

Post-test inspection of Unit 3 revealed that seven reinforcing bars out of the twelve bars were buckled in the damaged column. In order to compensate for the loss of flexural strength due to the buckled bars, CFRP sheets were also applied in the longitudinal direction. The amount of CFRP sheets used was calculated first by considering the confinement effect due to the spiral reinforcement. The stress vs. strain relationship of both cover and core concrete was developed based on the confinement model by Mander *et al.* (1986) and the ultimate strain of the cover concrete was assumed to be 0.003 and that of the core concrete was 0.02. The resulting entire moment vs. curvature relationship of the undamaged column is shown in Figure 6.

The flexural strength of CFRP strengthened column was determined similar to the calculation of the undamaged column; however, the stress-strain relationship of concrete confined by three layers of CFRP jackets, shown in Figure 5, was used. The ultimate strain of both cover and core concrete was 0.02. With these assumptions, the flexural strength of the CFRP strengthened column was determined as 757 kN-m and the failure mode was the rupture of CFRP sheets as shown in Figure 6. However, it should be noted that the objective of this strengthening project was not to increase its flexural strength but to restore it up to its original strength.

The longitudinal CFRP sheets were extended ~304 mm beyond the column-foundation interface, see Figure 4. This extended portion was anchored with an anchorage system consisting of steel expansion bolts and CFRP procured plates. Design indicated that three anchors were necessary to reach the maximum stress in the CFRP sheets; however, only one mechanical anchor was used at each CFRP sheet. This was because the purpose of the anchorage was mainly to investigate the behavior of the anchorage system for future development.

4 EXPERIMENTAL RESULTS

4.1 *Loading Protocol*

The first step in the testing procedure consisted of applying the vertical load for *gravity load simulation*. The applied axial load was 600 kN, correspondingly approximately to 7% of the axial capacity. Next, for Unit 1, the column was first subjected to single cycles under force control at 25%, 50%, 75% and 100% of the theoretical first yield. Section yielding was obtained from a moment curvature analysis of the column and matched the yielding of the column longitudinal reinforcement. After yielding, Unit 1 was loaded under displacement control with 3-cycles at each of displacement ductility level. In order to obtain a direct correlation to Unit 1 performance, Units 3 and 4 were subjected to the same force and displacement controlled cycles. Unit 2 was tested under pure torsion and was tested under force controlled up to torsional yielding and loaded in rotation control at 5 degrees increments.

4.2 *Test Results and Discussion*

Figure 7 shows the results for Units 1, 3, and 4. Figure 8 shows the results for Units 2, 3, and 4. Overall, in Units 1, 3, and 4 onset of flexural cracking occurred at the interface of the column-footing in the first cycles. Figure 9(a) shows the strain-deformation response for the longitudinal gages at the interface with the footing. These curves show a strong agreement between the experimental results and the analytical predictions for Unit 1. In Units 3 and 4, the strain values are almost 50 % lower, showing a strong influence from the applied torsional moment. Also, the strain values for the Units 3 and 4 are nearly the same. Figure 7 shows that the load deformation response for Units 3 and 4 are nearly identical and the two units reached nearly the same load and displacement ductility levels. On the other hand, Figure 8 shows that Unit 4 reached significantly higher torsional capacity than values computed for Unit 3. This clearly shows that the retrofit scheme was adequate in enhancing the flexural capacity of Unit 4. Since anchorage for the longitudinal CFRP sheets pulled out from the footing base as shown in Figure 10, regain in the flexural capacity of this unit could be attributed to the confining action of the horizontal CFRP sheets in increasing the concrete compression strength and buckling restraining effects for the internal longitudinal reinforcement. Confinement action of the CFRP sheets is clearly depicted in Figure 11(a), which shows that the strain values recorded in the horizontal CFRP sheets and transverse reinforcement for Unit 4 are consistently higher than those recorded in Units 1 and 3. Strain values recorded in Figure 11(b) also shows that the CFRP sheets were able to enhance the shear capacity.

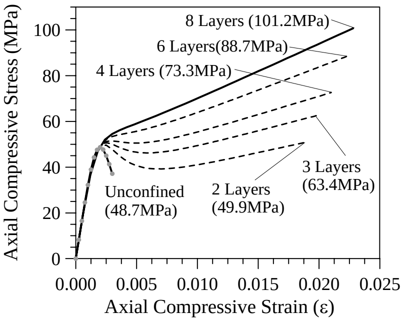


Figure 5: Axial Stress vs. Axial Strain Curves of CFRP Confined Concrete

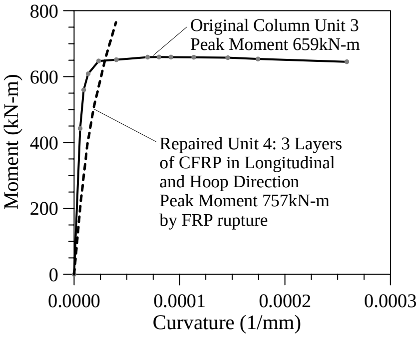


Figure 6: Moment vs. Curvature Curves of the Undamaged, and CFRP Strengthened Columns

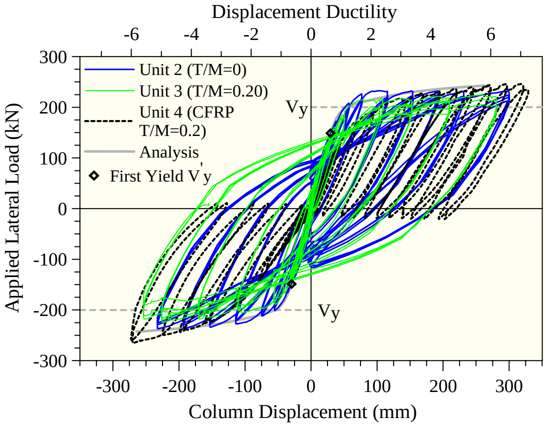


Figure 7: Load-Deformation Curves

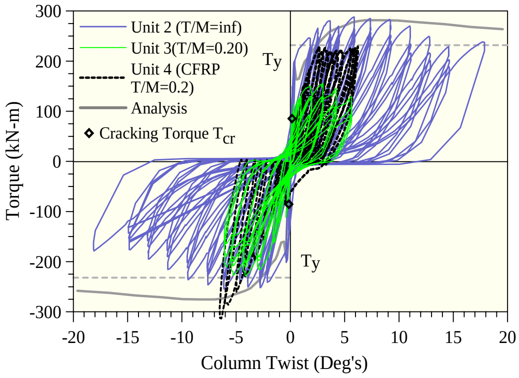
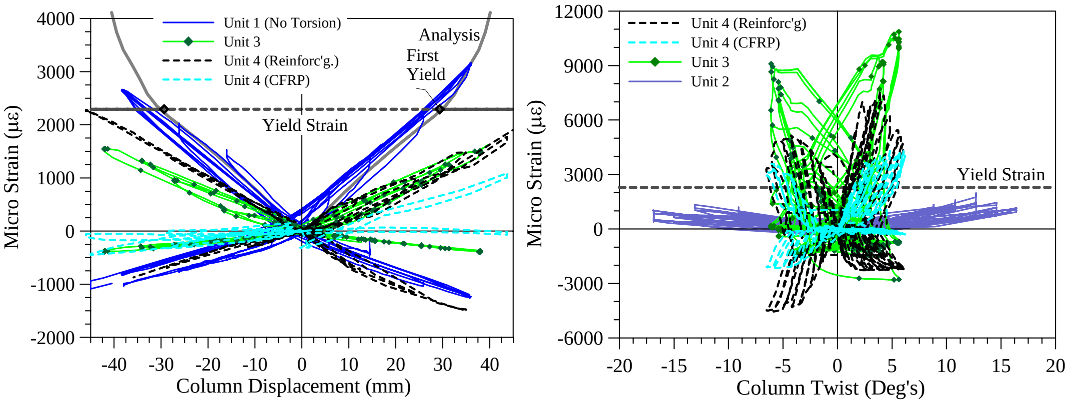


Figure 8: Torque-Twist Curves



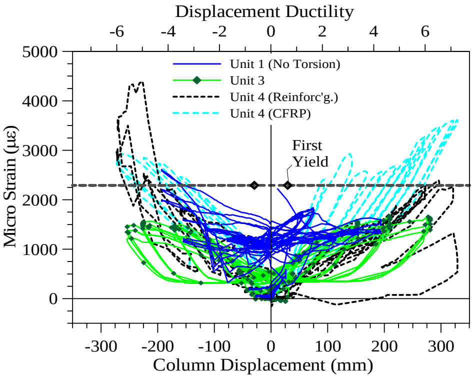
(a) Longitudinal Strain – Deformation

(b) Longitudinal Strain – Twist

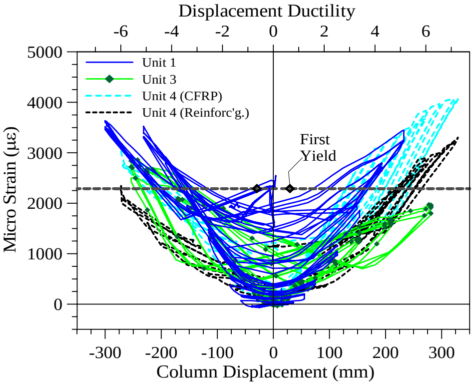
Figure 9: Longitudinal Reinforcement Strain History

Unit 2 was tested under pure torsion. During the first stages of testing, onset of diagonal cracking developed within the central region of the columns. This performance level was also associated with a sharp decrease in stiffness and was registered at a computed torque of 85 kN-

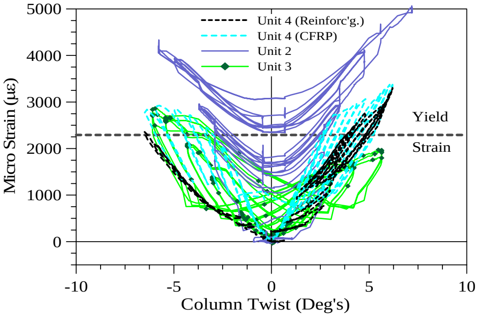
m. As shown in Figure 9(b), although yielding in the longitudinal reinforcement was not observed for Unit 2, the recorded strain levels clearly show that the reinforcement was mobilized in resisting the applied torsional load. Strain values depicted in Figure 11(c) clearly show that yielding and torsional resistance of Unit 2 was dominated by the transverse reinforcement.



(a) Confinement-Deformation



(b) Shear-Deformation



(c) Shear-Twist

Figure 11: Transverse Strain History

Figure 10: Failure Unit 4

5 CONCLUSIONS

The following conclusions can be summarized:

- Retrofit using CFRP sheets enhanced the flexural and torsional resistance capacity of the damaged column.
- Horizontally placed CFRP sheets were effective in providing confining action as means to increase the concrete compression strength.
- Experimental results also show that the horizontally place CFRP sheets were effective in providing buckling restraining effects for the internal longitudinal reinforcement.
- The longitudinally placed CFRP sheets pulled out from the footing base at low load levels. However, the longitudinal CFRP sheets may not be required in these types of retrofit, provided that fracture of the column reinforcement did not occur. Otherwise longitudinal CFRP sheets may be required.

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