CIAMTIS

U.S. DOT Region 3 University Transportation Center

Experimental Investigation of Residual Compressive Strength of Partially Confined Concrete Column Retrofitted Using CFRP Wrap

April 30, 2020

Prepared by:
M. Shokouhian, M. Adegoke, G. Upton, K. Aslan
Morgan State University

r3utc.psu.edu

PennState
College of Engineering

LARSON
TRANSPORTATION
INSTITUTE

Technical Report Documentation Page

1. Report No.
CIAM-COR-R17

2. Government Accession No.

3. Recipient’s Catalog No.

4. Title and Subtitle
Experimental Investigation of Residual Compressive Strength of Partially Confined Concrete Column Retrofitted Using CFRP Wrap

5. Report Date
April 30, 2020

6. Performing Organization Code

7. Author(s)
K. Aslan, https://orcid.org/0000-0002-7617-0175,
M. Shokouhian, https://orcid.org/0000-0001-9823-0661,
M. Adegoke, and G. Upton

8. Performing Organization Report No.

9. Performing Organization Name and Address
Morgan State University
Department of Civil Engineering
1700 E. Cold Spring Lane
Baltimore, MD 21251

10. Work Unit No. (TRAIS)

11. Contract or Grant No.
69A3551847103

12. Sponsoring Agency Name and Address
U.S. Department of Transportation
Research and Innovative Technology Administration
3rd Fl, East Bldg E33-461
1200 New Jersey Ave, SE
Washington, DC 20590

13. Type of Report and Period Covered
Final Report 03/01/2019 – 03/01/2020

14. Sponsoring Agency Code

15. Supplementary Notes
Work funded through The Pennsylvania State University through the University Transportation Center Grant Agreement, Grant No. 69A3551847103.

16. Abstract

External confinement of concrete columns by means of carbon fiber reinforced polymer (CFRP) wraps has proven to be an efficient technique for structural retrofitting and strengthening. This report presents an experimental investigation that was conducted to assess the residual compressive strength of CFRP wrapped 1/6-scale concrete columns using strips to enhance confinement while still enabling visual column inspection. The experimental work was carried out to evaluate the remaining strength and stress-strain behavior of partially damaged concrete columns externally retrofitted with CFRP strips. Fourteen cylinder specimens were constructed, instrumented, and tested in seven groups, including fully double-layer vertically and horizontally wrapped, partially wrapped with 2-strip, partially wrapped with 3-strip, fully single-layer vertically and horizontally wrapped, and unwrapped concrete column specimens with 4-inch diameter and 16-inch height. The same concrete mix and curing conditions were used throughout the study to achieve 4,000 psi compressive strength in 28 days. All of the test specimens were subjected to monotonic uniaxial compression loads in two steps: (1) before retrofitting and loading up to 70% of failure point and (2) after retrofitting and loading up to failure. Several parameters that influence confinement effectiveness of CFRP and increase the residual compressive strength of retrofitted column were evaluated, including the number of CFRP composite layers and fiber orientations with respect to the circumferential direction. A finite element model was developed using Ansys 19.2 to compare with the test results, and a close agreement was achieved.

17. Key Words
Engineering education, bridge design

18. Distribution Statement
No restrictions. This document is available
from the National Technical Information Service,
Springfield, VA 22161

19. Security Classif. (of this report)
Unclassified

20. Security Classif. (of this page)
Unclassified

21. No. of Pages
23

22. Price

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

Chapter 1

Introduction

Structural use of fiber reinforced polymer (FRP) wrap is very applicable to the current state of infrastructure civil engineering. Every four years, the American Society of Civil Engineers (ASCE) releases a structural report card evaluating and grading America's infrastructure in what is called the Infrastructure Report Card. In 2017, the ASCE's Infrastructure Report Card deemed that 56,007 (9.1%) of all bridges within the United States are structurally deficient. Structural deficiency is defined as a bridge that requires significant maintenance, rehabilitation, or replacement as critical load-carrying elements were found to be in subpar condition. In regard to repairing and increasing the serviceable lifespan of structures and bridges, FRP materials can provide a lightweight and cost-effective means to improve the current state of bridges and structures. Although FRP has an extensive list of applications, it can be used to strengthen reinforced concrete structures and has been a material of interest in this regard for many decades.

BACKGROUND

Many research studies have been carried out on the repair and strengthening structures using FRP sheets and wraps in the last decade. Pan et al. (2017) undertook a study of the stress-strain relation of concrete confined by CFRP under preload. The study report presents the results of an experiment using 32 circular-section and 16 square-section concrete columns confined by CFRP sheets under axial compression (Pan et al., 2017). It focused on how the FRP sheets are applied when retrofitting concrete columns under different extents of preloading. It analyzed different failure modes and mechanical behaviors of the confined concrete columns under the preload. To acquire the outcomes, the examination arranged model was utilized to catch how the FRP is confining, and concrete center cooperated. It was discovered that the preload has an adverse effect on the FRP sheet constraint. Therefore, increasing the preload ratio, the tensile strain lag of FRP enlarged. The study also obtained that when the amplitude of peak stress and strain is reduced, the preload ratio and number of CFRP pipes increased. The study recommends that another experiment can be carried out to acts as a verification of the theoretical models used for this particular experiment. It should target the test data from testing small diameter columns, as well as the validity of large-scale specimens.

Gao et al. (2018) investigated the effects of pre-damage on the compression performance of CFRP-confined rectangular steel-reinforced concrete columns. The study mainly aimed to analyze the axial compression behavior of pre-damaged steel-reinforced concrete (SRC) rectangular short columns confined by carbon fiber-reinforced polymer (CFRP) laminates. The experiment used 13 steel-reinforced concrete rectangular short columns. It is essential to note that during the testing procedures, the loading conditions needed to be considered, and also the columns had to be subjected to a constant maintained load. After experimenting, the study aims to come up with a suitable finite element model, and also analyze the confinement mechanisms in-depth. For the unconfined SRC 0-0 column, the concrete first cracked at the column top (692.0 KN). All confined SRC columns failed with the rupture of CFRP after the peak load. The results also showed that the capacity degradation rate increased with the pre-damage level. Both the measured and simulated results show that the pre-damage and the number of CFRP layers are informative about the effectiveness of confinement provided by CFRP laminates (Gao et al. 2018).

Al-Kamaki et al. (2015) performed an experimental and numerical study of the behavior of heat-damaged RC circular columns confined with CFRP fabric. The research aimed to investigate how RC columns behave when damaged by heating and wrapped using CFRP. It targeted 20 reinforced concrete (RC) columns. The comprehensive strength of the concrete was 32 MPa at 28 days, with a maximum aggregate size of 14 mm. The columns were heated in a vertical two-half electric furnace. It reached a maximum furnace temperature of 600 ºC (Al-Kamaki et al. 2015). Typical failure modes of the control and CFRP-wrapped columns were used, and since a duplicate column was tested for each case, only the failure mode for one column of each pair is presented. The failure mode for unwrapped columns exhibited, prior to failure, vertical cracking starting from the top of the column and propagating downward along the length in the direction of loading. These columns failed by splitting as the result of shear stresses. The RC columns were able to maintain 30% of the maximum load of the unwrapped undamaged columns. The residual compressive strength and modulus of elasticity of the RC columns were noted to reduce after heating to 600 ºC, 800 ºC, and 1,000 ºC. The Vic-3D camera system documented that the strains varied along the height of the specimens. Khairallah (2013) investigated the mechanical behavior of confined concrete column, which depends on several parameters, including concrete strength, types of fibers, volume and shape of cross section, and length-to-diameter (slenderness) ratio of the column. The influence of column slenderness ratio on their axial load capacity, axial strains, and radial strains was also investigated. The experimental program was classified into three different groups with slenderness ratios from 9 to 18. Utilizing plastic tubing for confinement significantly influences the failure mechanisms of concrete columns. Results also show that the stiffness of the tested long confined concrete column specimens increases as slenderness ratio decreases. It is necessary to strengthen the deteriorated and damaged concrete columns to increase their carrying capacity (axial load and bending moment), and ductility to improved seismic performance (Khairallah 2013).

Eid and Paultre (2017) investigated the compressive behavior of RC column with fiber-reinforced concrete confined by CFRP strips. A total of seven columns were fabricated with FRC and the concrete mixtures were prepared with the inclusion of polypropylene (PP) fiber in the rate of 0.50% in volume of concrete. Of the seven columns, six were confined by 50 mm CFRP strips having the spacing of 20 mm and 30 mm with one, two, and three layers and the remaining one was a reference column (Eid and Paultre 2017).

Hadi and Le (2013) investigated the behavior of hollow core square reinforced concrete columns wrapped with CFRP with different fiber orientations. The study aimed to analyze how the fiber orientation affects the behavior of hollow core columns. The experiment used 12 specimens, which measured 200 mm by 200 mm in cross-section. FRP was used to strengthen the solid core columns by wrapping it transversely concerning the column's axial axis. The columns that were not confined had the highest load-carrying capacity when tested under concentric loading (Hadi and Le 2013).

In this regard, the purpose of the present study was to analyze the residual strength of a concrete column by using CFRP as a confinement reinforcement. Fifteen concrete columns with dimensions of 406.4 x 101.6 mm were created along with five compression test cylinders with dimensions of 203.2 x 101.6 mm. Seven-, 14-, 21-, and 28-day ASTM C39-12 compression tests were performed using an Instron Industrial Series HDX 1000 Universal Testing Machine on five 203.2 x 101.6 mm compression test specimens. The uniqueness of this research is that different orientations and positioning of the unidirectional CFRP were considered to understand which scenario achieved the highest residual compressive strength. This report presents the experimental study, numerical analysis, verification and discussion, and conclusions. The experimental study section discusses the materials used, how the specimens were created, the instrumentation setup for the testing, and an overview of the captured results. The numerical analysis explains the model and its purpose, all assumptions used for the modeling, and a breakdown of the theoretical results. The verification and discussion section aims to correlate the experimental study and the numerical analysis as a way to validate results from both sections and shed insight on any potential irregularities. The final section, the conclusion, briefly reiterates the project as a whole and touches on major trends found within the testing.

Chapter 2

Experimental Study

SPECIMENS

For this experiment a total of 15 cylindrical column specimens with dimensions of 406.4 x 101.6 mm and 5 compression cylinders specimen with dimensions of 203.2 x 101.6 mm were created using a dry ready-mix with an achieved slump of 38.1 mm as shown in Fig. 1 and Fig. 2. Table 1 also provides material properties of the CFRP wrap, epoxy, and concrete that were used in this study. All 20 cylindrical specimens were poured with a single batch. The 15 column specimens were tapped with a rubber hammer and tamped 25 times in 6 layers each. The 5 compression cylinder specimens were prepared according to ASTM C192, where three layers were tamped 25 times and the sides of the cylinders were tapped with a rubber hammer. Once all the specimens were poured, they were allowed to sit for 2 days and then placed into an indoor water bath.

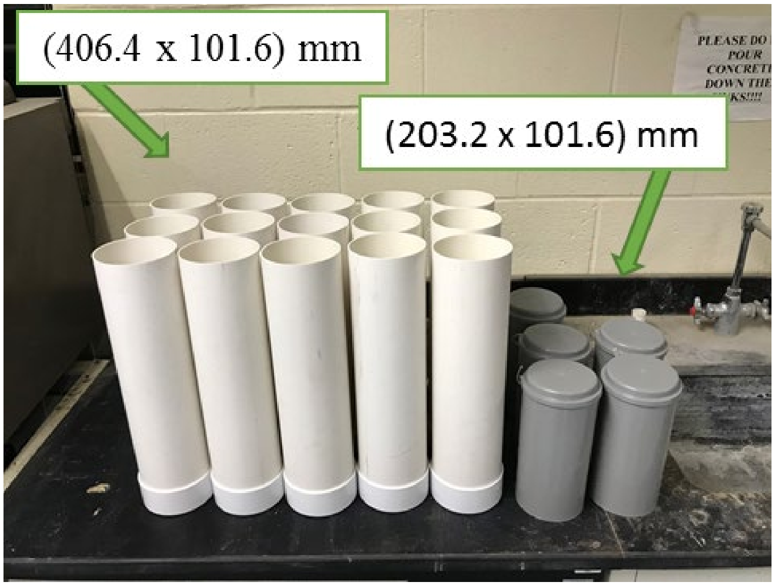


Fig. 1. PVC formworks for each specimen

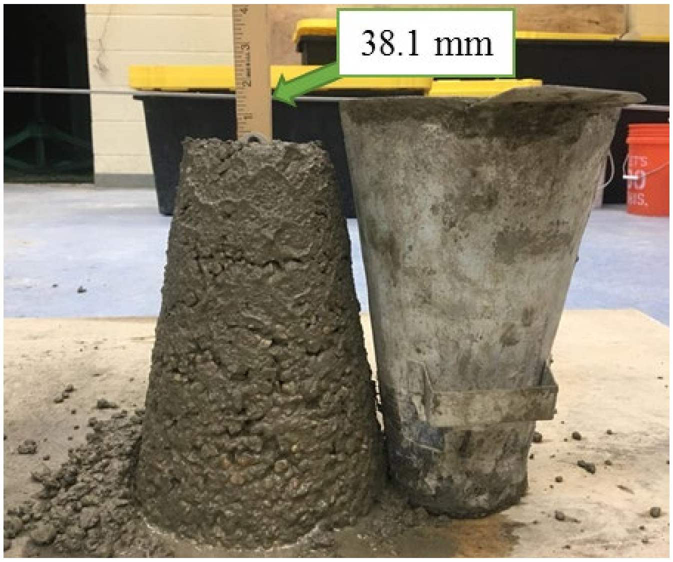


Fig. 2. Slump test results

Table 1. Material properties

Materials	Tensile Strength (MPa)	Compressive Strength (MPa)	Nominal Thickness (mm)
Undirectional CFRP	4,900	--	0.4445
EPOXY	19.3	34.5	--
Ready Mix Concrete	--	27.6	--

Among the compression cylinder specimens, C1 and C2 were tested on day 7. Specimens C3, C4, and C5 were broken on day 14, day 21, and day 28, respectively, as shown in Table 2. Fourteen column specimens were grouped into 7 column groups, CG1, CG2, CG3, CG4, CG5, CG6, and CG7. These groups consisted of all CFRP wrap scenarios that were investigated in this study. Column groups 1, 2, 3, 4,5, 6, and 7 looked at scenarios in which the column specimens were wrapped with 2 strips, 3 strips, 2 full vertical layers, 1 single vertical layer, 1 single horizontal layer, 2 full horizontal layers, and no CFRP. CGX* was the column specimen that was loaded until failure. From the position versus load plot generated from CGX*, the initial crack was seen to occur at 70% of fc'. This was the stress that was regarded as step 1 of the initial axial loading to which all additional 14 column specimens were subjected before being reinforced with CFRP. After the pre-loading, the 14 column specimens were placed back into their groups on a clean workbench and wrapped in an orientation according to Table 2. All specimens with CFRP were wrapped with a 1-inch overlap.

Table 2. Total specimen count and their ID

Specimen #	Specimen ID	Scenario	# CFRP
1	CG1-1	2 Strip I	1
2	CG1-2	2 Strip II	1
3	CG2-1	3 Strip I	1
4	CG2-2	3 Strip II	1
5	CG3-1	Double Vertical I	2
6	CG3-2	Double Vertical II	2
7	CG4-1	Single Vertical I	1`
8	CG4-2	Single Vertical II	1
9	CG5-1	Single Horizontal I	1
10	CG5-2	Single Horizontal II	1
11	CG6-1	Double Horizontal I	2
12	CG6-2	Double Horizontal II	2
13	CG7-1	No CFRP I	0
14	CG7-2	No CFRP II	0
15	C1	7-Day Compression Test	0
16	C2	7-Day Compression Test	0
17	C3	14-Day Compression Test	0
18	C4	21-Day Compression Test	0
19	CGX*	21-Day Compression Test	0
20	C5	28-Day Compression Test	0

TEST SETUP

Axial loading for all 406.4 x 101.6 mm and 203.2 x 101.6 mm specimens were conducted using an Instron Industrial Series HDX 1000 Universal Testing Machine at the Materials Laboratory at Morgan State University. Data were acquired through the accompanying data acquisition software. All column specimens were plated within the axial loading UTM, which was set to a rate of 0.241 MPa/s. See Figures 3 and 4.

Fig. 3. Preparing specimens for retrofitting: (a) specimen and materials for testing and (b) CFRP wrap for column specimen

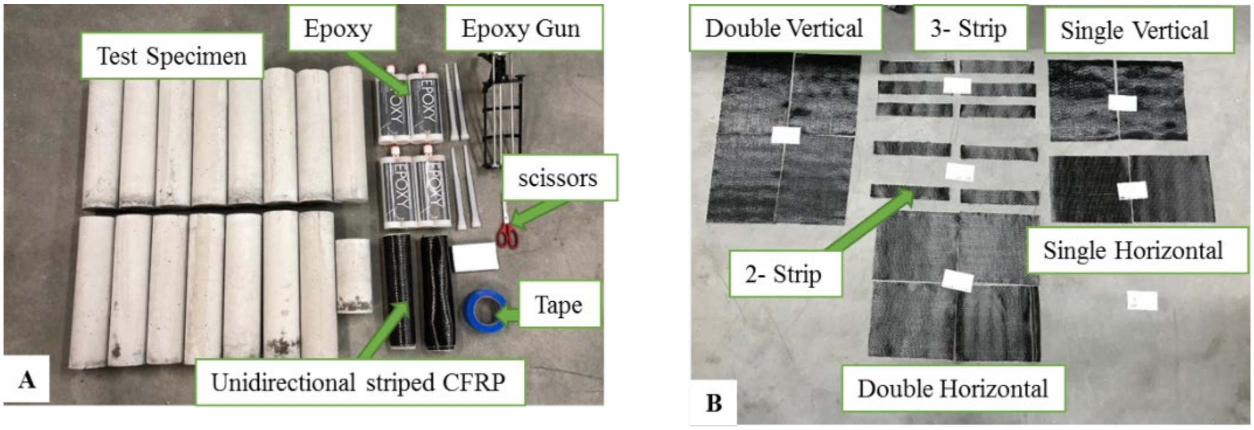
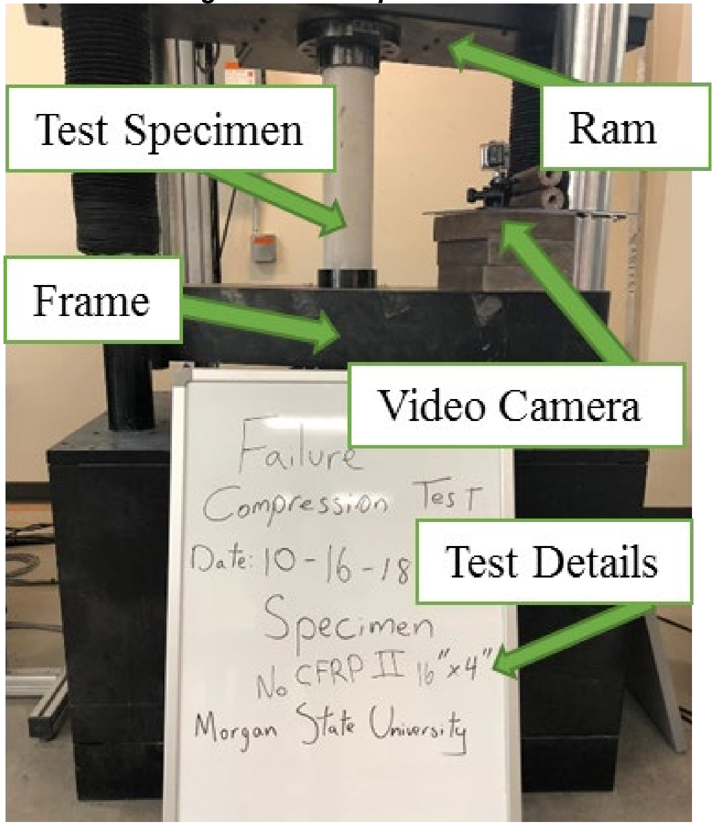


Fig. 4. Test setup conditions



EXPERIMENTAL RESULTS

As stated previously, the aim of this project was to investigate how the different CFRP scenarios affect the column residual compressive strength and which CFRP scenario yields the highest residual strength. Average compressive cylinder results, as shown in Table 3, represent the compressive strength of the concrete batch as it ages. Figure 5 shows the column specimens after axial loading.

Table 3. Compressive test data for 7-, 14-, 21-, and 28-day ASTM C39-12 tests

Test #	Maximum Stress (MPa)
7-Day	20.50
14-Day	24.35
21-Day	26.83
28-Day	30.85

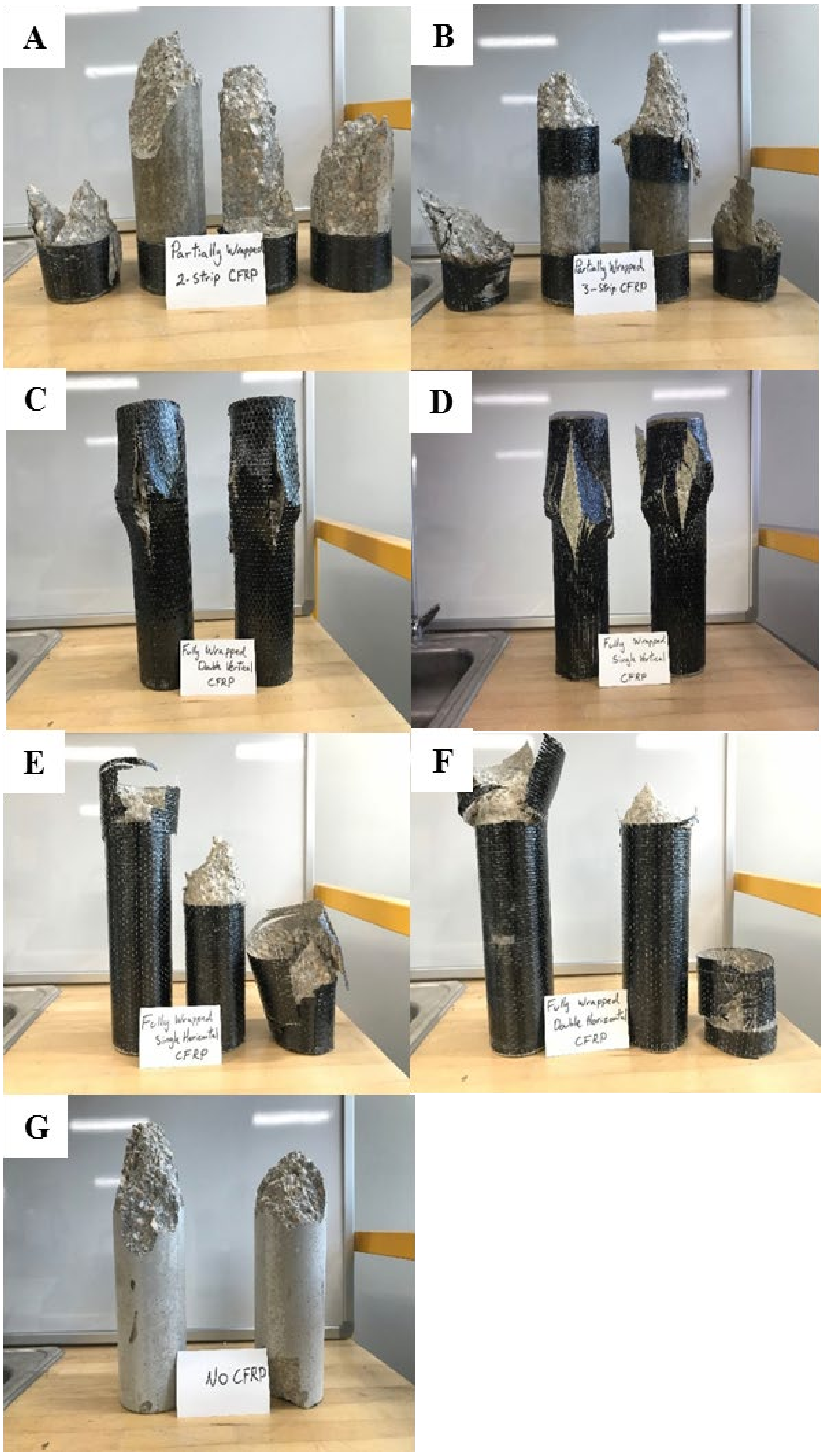


Fig. 5. Column specimens after axial loading. The specimen IDs are as follows: (a) CG1-1&2, (b) CG2-1&2, (c) CG3-1&2, (d) CG4-1&2, (e) CG5-1&2, (f) CG6-1&2, (g) CG7-1&2

The CFRP wrap scenarios that had the highest residual compressive strength were CG5 and CG6, where the specimens were wrapped in the horizontal direction. In the horizontal direction, the tensile strength of the CFRP (4,900 MPa) greatly aided in laterally reinforcing the column specimen. The CFRP wrap scenarios that performed the poorest were the single vertical and double vertical orientations as shown in Fig. 8. Due to the vertical weave of the CFRP running along the length of the column specimen, there lacked lateral strength to resist the axial loading.

Chapter 3

Numerical Analysis

A three-dimensional realistic model was developed based on the test specimens using a commercial software package (ANSYS 19.2, 2018). The seven models were carefully developed in ANSYS Workbench to mimic the behavior of concrete column test specimens using nonlinear static analysis.

MODEL DESCRIPTION

The models were developed in the Static Structural environment of ANSYS. The specimens had dimension height of 406.4 mm and diameter of 101.6 mm. The thickness of the CFRP layers was considered to be 0.4445 mm. The material properties available in the engineering data source had default data, which were replaced by the data obtained from the experiment. Equations 1 and 2 were used to determine the modulus of elasticity of concrete and ultimate tensile strength as required in the model development. ANSYS Workbench creates contact pairs when bodies are contact pairs, therefore the mechanical bond between the concrete and CFRP is automatically detected by the program-controlled contact region. The bonded contact region was defined similar to the CFRP epoxy adhesive used in the experiment. The discretization of element (mesh) is program-controlled and automatically integrated; ANSYS mesh detects the type of analysis, the geometry, and the solution definition and the program implements the most suitable mesh based on the program standard (ANSYS 2018). In the experiment, the columns were tested to failure under the UTM; similar boundary condition and loading were considered in the model. A fixed support was assigned at the bottom while force was applied at the top of the column.

ASSUMPTIONS

From the experiment data, the compressive strength f_c' at the stress where the first crack occurred was considered to be the residual stress in the concrete; subsequently, the elasticity modulus and modulus of rupture of concrete (f_r) were calculated using Equations 1 and 2 (ACI 318-14). The CFRP material used has a unidirectional carbon fabric; fiber strands exhibit orthogonal properties in the directional planes (xy, xz, and yz planes) as xyz are coordinates (see Figure 6).

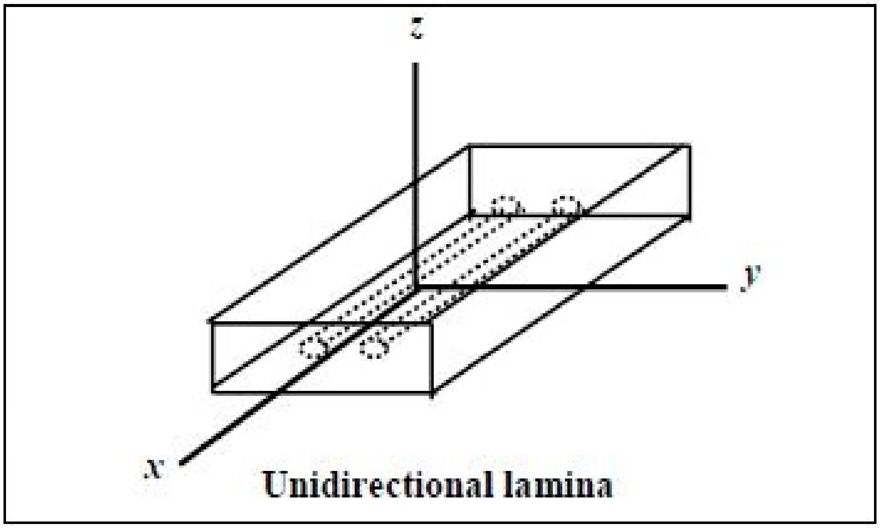


Fig. 6. Schematic of FRP composites (Gibson 1994)

The unidirectional lamina (CFRP) has maximum value (x axis) of mechanical properties (i.e., strength and elasticity modulus) along the fibers direction with minimum values of the same properties in the normal direction (y, z) axes of the fibers (Bejan et al. 2007). The different orientations for wrapping the column with CFRP were considered in the modeling; as a result, the principal coordinate is the x-direction, which is the horizontal direction specified by the manufacturer, y & z axes are perpendicular to the x direction.

$$E_c\ (psi) = 57000\sqrt{f_c'} \qquad \text{Equation 1}$$

$$f_r\ (psi) = 7.5\sqrt{f_c'} \qquad \text{Equation 2}$$

Table 4. ANSYS input data for concrete and CFRP

Concrete	CFRP
Density = 2300 kg/m^3	Young's modulus x direction = 2.5 x 10^5 MPa
Modulus of elasticity (E_c) = 2.45 x 1010 Pa	Young's modulus y direction = 23000 MPa
Compressive ultimate strength (f_c') = 2.68 x 107 Pa	Young's modulus z direction = 23000 MPa
Tensile ultimate strength (f_r) = 2.0 x 106 Pa	Poisson's ratio xy = 0.2
Poisson's ratio (υ) = 0.2	Poisson's ratio yz = 0.4
	Poisson's ratio xz = 0.2
	Shear modulus xy = 9000 MPa
	Shear modulus xy = 8214.3 MPa
	Shear modulus xz = 9000 MPa
	Thickness = 0.4445 mm

The damage level of the CFRP-wrapped column differs significantly, based on the type and orientation of CFRP wrap. The stress-strain relationship of the concrete model is set to determine the failure point. In 1989, Bangash stated that the stress-strain curve of concrete in compression is linear-elastic from 0-30% of ultimate compressive strength f_c', the stress slowly increases to reach the ultimate compressive strength f_c', reaching the softening and then failure occurred (see Figure 7). The FE analysis assumed strain ε_{cu} = 0.003 to be the point of concrete rupture. The corresponding ultimate stress (σ_{cu}) at ultimate strain (ε_{cu}) is compared with the experiment data.

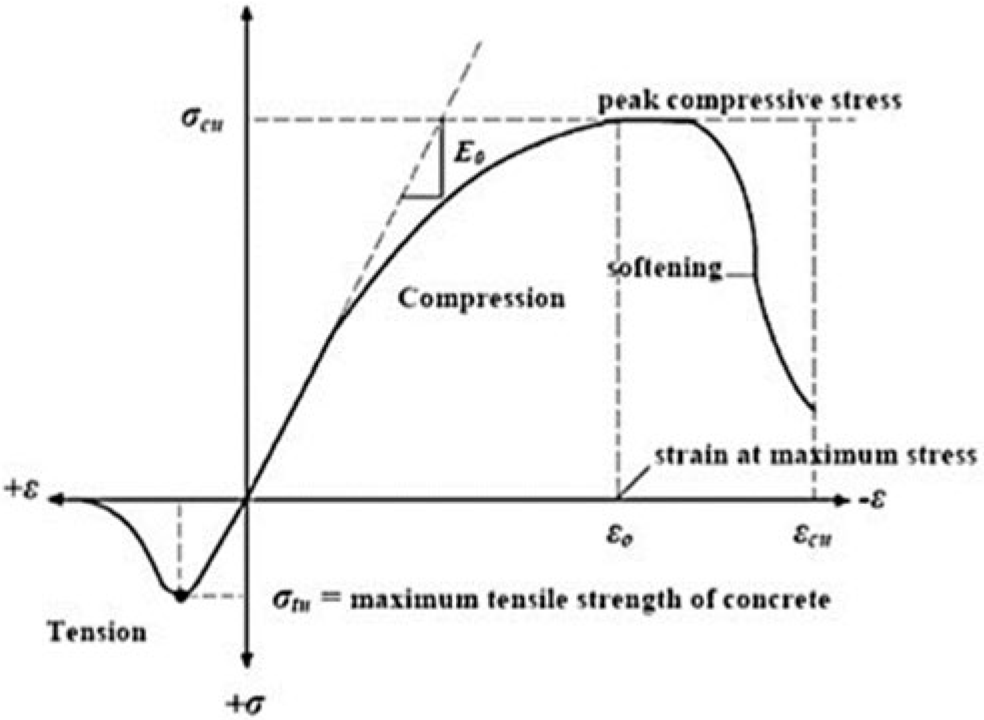


Fig. 7. Typical uniaxial compressive and tensile stress-strain curve for concrete (Bangash 1989)

ANALYSIS AND RESULTS

The results obtained from the seven columns of the FE models showed the strains at maximum stresses; the strain ε_{cu} = 0.003 is considered to have reached the failure point and the damages on each model are different based on the compressive stresses to reach crushing and softening of the concrete.

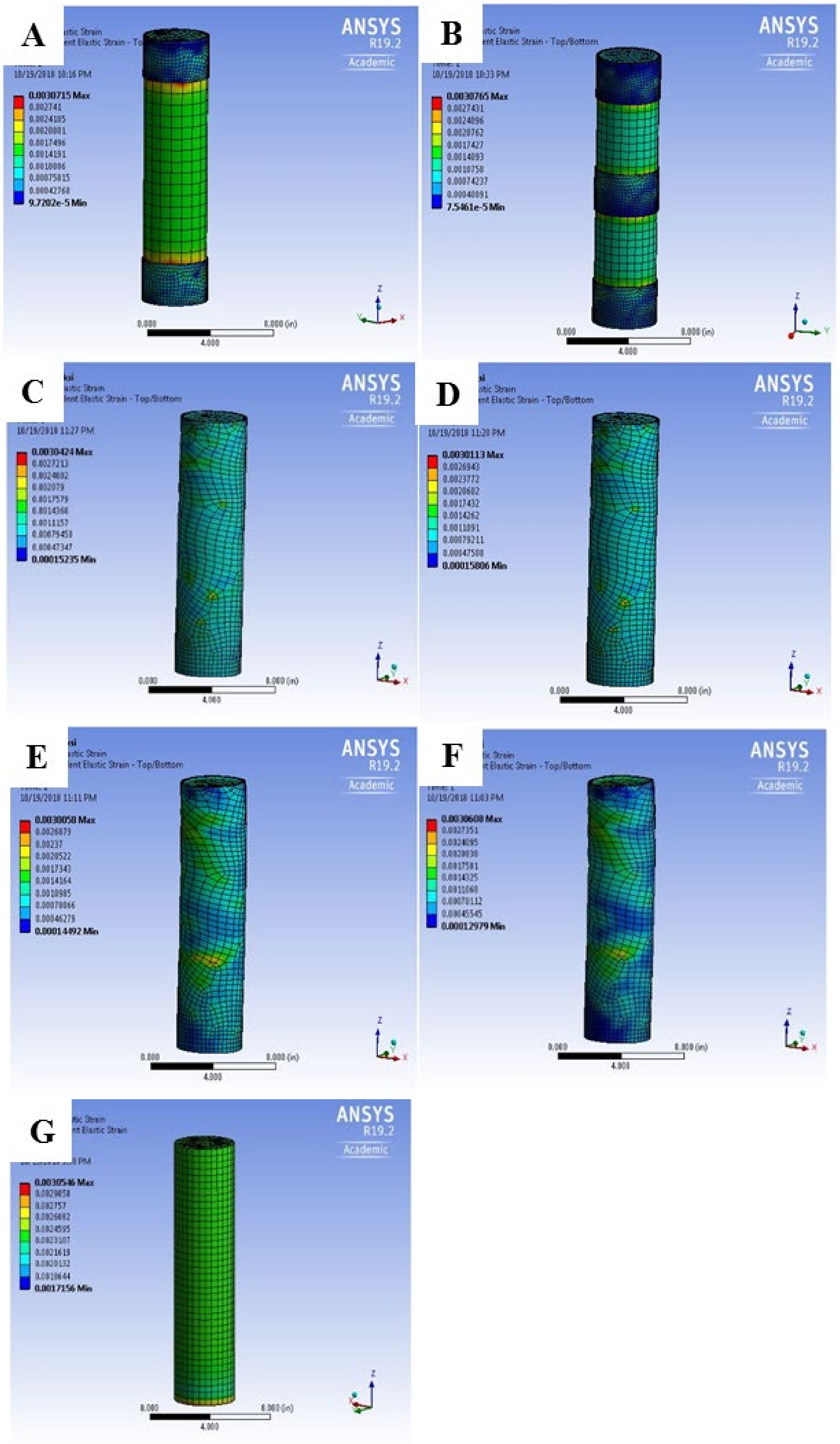


Fig. 8. Finite element analysis of modeled CFRP wrap scenarios. Column specimens after axial loading. The specimen IDs are as follows: (a) CG1-1&2, (b) CG2-1&2, (c) CG3-1&2, (d) CG4-1&2, (e) CG5-1&2, (f) CG6-1&2, (g) CG7-1&2

Chapter 4

Verification and Discussion

The numerical models of the CFRP-wrapped column were validated with experimental tests. The behavior of the columns that were partially damaged were presented with different types of scenarios. The approach shows a range of repair methods with different outcomes in terms of column strengthening and different wrapping orientations. Comparison between the compressive stress of the experiments and numerical studies differs between 5% - 10%; the no-CFRP specimen results vary by 10%. Two-strip CFRP results between the experiment and numerical studies have a 7% margin, and the strength increases by 26% between no-CFRP and 2-strip. The result of the 3-strip specimen shows a 32% increase from no-CFRP and increases by 8% between 2-strip and 3-strip CFRP wrap. Single horizontal wrap gained 37% strength increase compared to no-CFRP while the double horizontal wrap gained more than twice (262%) the strength compared to no-CFRP and 40% gain over the single horizontal wrap. Due to the unidirectional lamina properties of this particular CFRP material, the modulus of elasticity is higher in the x-direction (see Table 5 and Figure 9) compared to the y- and z-direction. Strength gained in both single and double vertical wraps are lesser compared to horizontal wraps. As a result, the orientation of CFRP fibers significantly changed the residual strength of repaired and strengthened structural members. The damage propagation of 2-strip and 3-strip wraps are similar, the fracture of concrete occurred at the exposure. The double horizontal wrap showed significant crushing and softening of the concrete compared to single horizontal wrap, and minimal crushing and softening of concrete occurred on both single and double vertically wrapped columns after failure.

Table 5. Experimental versus modeled specimen

Sample ID	Description	Experiment MPa	Modeled MPa
CG1	Partially wrapped with 2 Strip	29.62	31.72
CG2	Partially wrapped with 3 Strip	32.43	33.78
CG3	Fully wrapped/ double vertical	30.95	29.65
CG4	Fully wrapped/single vertical	29.32	28.27
CG5	Fully wrapped/ Single Horizontal	34.77	44.13
CG6	Fully wrapped/ Double Horizontal	57.21	51.71
CG7	No CFRP	21.81	24.13

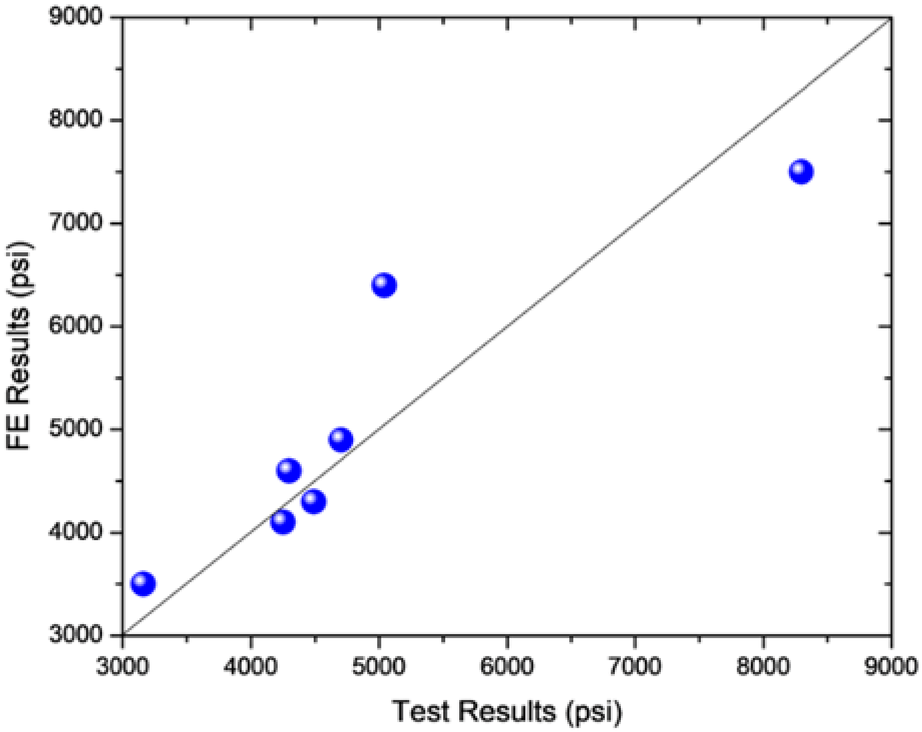


Fig. 9. Plot of the correlation between averaged and modeled test results

CONCLUSIONS

The experimental and numerical results illustrate that using CFRP wrapping is an effective method in repairing and retrofitting concrete structural members, particularly for members subjected to compression forces. The numerical model was developed and experimentally validated with 3.1% error. The experimental results show retrofitting concrete column with double CFRP horizontal wrapping can increase the residual compressive strength by 162.3%. The orientation of CFRP fibers can significantly change the residual strength of repaired and strengthened columns up to 85%, which was observed in fully wrapped columns with double horizontal layers. Thickness and number of CFRP layers have also considerable effect on the residual compressive strength; 65% increase in residual compressive strength was seen in double layers as compared to the single-layer CFRP wrap. However, only 5.6% gain in residual strength was achieved with double-layer CFRP wrapped column compared to the single layer, when the fiber orientations are changed from horizontal to vertical.

References

ANSYS 19.2 (2018). Retrieved from https://www.ansys.com.

American Concrete Institute 318-14 (2014). *Building Code Requirements for Structural Concrete*. Farmington Hills, MI: American Concrete Institute.

Bangash, M. Y. (1989). *Concrete and concrete structures: Numerical modeling and applications*. London: Elsevier Science Publishers Ltd.

Bejan, L., & Taranu, N. (2007). Eigentensors and eigenelastic constants for woven composites. *Journal of Optoelectronics and Advanced Materials*, 9(9):2902-2909.

Eid, R., & Paultre, P. (2017). Compressive behavior of FRP-confined reinforced concrete columns. *Engineering Structures*, 132:518-530.

Gao, P., Wang, J., Li, Z., Hong, L., & Wang, Z. (2018). Effects of predamage on the compression performance of CFRP-confined rectangular steel reinforced concrete columns. *Engineering Structures*, 162:109-120.

Gibson, R. F. (1994). *Principles of Composite Material Mechanics*. New York: McGraw-Hill, Inc.

Hadi, M. S., & Le, T. D. (2014). Behaviour of hollow core square reinforced concrete columns wrapped with CFRP with different fibre orientations. *Construction and Building Materials*, 50:62-73.

Khairallah, F. (2013). Mechanical behavior of confined self-compacting reinforced concrete circular columns under concentric axial loading. *Ain Shams Engineering Journal*, 4(4):641-649.

Pan, Y., Rui, G., Li, H., Tang, H., & Xu, L. (2017). Study on stress-strain relation of concrete confined by CFRP under preload. *Engineering Stuctures*, 143:52-63.

Al-Kamaki, Y. S., Al-Mahaidi, R., & Bennetts, l. (2015). Experimental and numerical study of the behaviour of heat-damaged RC circular columns confined with CFRP fabric. *Composite Structures*, 133:679-690.

Vasumathi, A. M., Rajkumar, K., & Ganesh Prabhu, G. (2014). Compressive Behaviour of RC Column with Fibre Reinforced Concrete Confined by CFRP Strips. *Advances in Materials Science and Engineering*, 2014:10.