2008

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Muhammad N. S Hadi
University of Wollongong, mhadi@uow.edu.au

Publication Details

This conference paper was originally published as Hadi, MNS, Behaviour of Fibre RC Columns Wrapped with FRP under Eccentric Loads, Australasian Structural Engineering Conference (ASEC), Melbourne, Australia, 26 – 27 June 2008. Original conference information available here

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M.N.S. Hadi

University of Wollongong, Wollongong, NSW, Australia

Abstract

This paper presents results of testing 16 specimens, 12 of which as columns under different eccentricities and four as beams under four point loading regime. All 16 specimens were circular in cross section and were made of reinforced concrete. Four specimens served as reference specimens and were just made of reinforced concrete. The next four had steel fibers added to the concrete. The next four specimens were wrapped with Carbon Fibre Reinforced Polymers. The final four specimens were reinforced with steel fibbers and wrapped with CFRP. From each group of specimens, one specimen was tested as a column under a concentric load, the second specimen was tested as a column under 25 mm eccentricity, the third specimen was tested as a column under 50 mm eccentricity, and the final specimen was tested as a beam under four point loading regime. For each group of specimens, interaction diagrams (see Figure 1) were drawn based on the experimental results and compared with theoretical estimation. The experimental programme proved that the introduction of fibbers as well as wrapping the specimens with FRP improve the properties of concrete, especially its ductility.

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M.N.S. Hadi[1]
[1] University of Wollongong, Wollongong, NSW, Australia

1. Introduction

FRP has been used in recent years to strengthen concrete members. For FRP wrapped reinforced concrete columns, most of the research reported concerns testing specimens under concentric axial load. In reality the loads on columns can be eccentric due to column's location (corner and edge columns) or due to construction errors. This paper presents the influence of FRP on concrete columns' carrying capacity of concentric and eccentric loads. Twelve high strength reinforced concrete columns were cast and tested. They were divided into three groups: one group consisted of reinforced concrete columns; the second group consisted of reinforced concrete columns and wrapped with three layers of horizontal CFRP; the third group consisted of reinforced concrete specimens and wrapped with three layers of horizontal and three layers of vertical CFRP. From each group, three specimens were tested as columns and axial loads were applied at eccentricities of 0 mm (concentric), 25 mm and 50 mm. The fourth specimen was tested as a beam under a four point loading. Load-deflection curves were plotted from the tested specimens. Results of this study showed that FRP is an effective material for strengthening columns under eccentric loads.

The effectiveness of wrapping concrete elements, for example beams and columns have been proven by several researchers. Several studies have reported on testing reinforced concrete columns wrapped with different types of FRP. With the exception of few studies, for example (Parvin and Wang, 2001, Li and Hadi, 2003, Hadi, 2003, Hadi and Li, 2004, and Hadi, 2006), most of the studies are based on testing columns under concentric loads. It is clear that there is a need to investigate the behaviour of columns under eccentric loads as most of the columns in buildings, especially at the edge and corner of buildings are subject to eccentric uniaxial or biaxial loading. The aim of this paper is to investigate the behaviour of concrete columns reinforced with vertical FRP straps and wrapped with FRP under the application of an eccentric axial load.

2. Experimental study

Twelve cylindrical specimens of 205 mm diameter and 925 mm height were cast and tested. All specimens were made of concrete and reinforced with the same amount of steel reinforcement, 6N12 (deformed bars of 12 mm diameter and 500 MPa nominal tensile strength) longitudinal reinforcement and R10 (plain bars of 10 mm diameter and 250 MPa nominal tensile strength) at 60 mm pitch helical reinforcement. All specimens were designed to the requirements of AS3600 (2001). The 12 specimens were subdivided into three groups with four specimens each. The specimens of the first Group RC were made of reinforced concrete, the specimens of the second group CF were made of reinforced concrete and were wrapped with three layers of carbon FRP (CFRP), and the specimens of the third group VCF were made of reinforced concrete and alternately wrapped with vertical CFRP straps then wrapped with CFRP. This alternate wrapping was repeated three times. Three specimens from each group were tested as columns at eccentricities of 0 mm, 25 mm and 50 mm. These specimens have the notation 0, 25 and 50, respectively. The fourth specimen, denoted B, was tested as a beam under four point loading. The test plan was to allow for a direct comparison of ultimate strength, deflections and internal stresses for the four different types of loading. Table 1 shows a summary of the tested specimens.

Table 1 Tested specimens' configurations

Specimen	Dia. (mm)	Length (mm)	Internal Reinf.	Confining Material	Test Pattern	Eccentricity (mm)
RC-0	205	925	Yes	None	Column	0
RC-25			Yes	None	Column	25
RC-50			Yes	None	Column	50
RC-B			Yes	None	Beam	Bending
CF-0			Yes	3 lateral layers of CFRP	Column	0
CF-25			Yes	3 lateral layers of CFRP	Column	25
CF-50			Yes	3 lateral layers of CFRP	Column	50
CF-B			Yes	3 lateral layers of CFRP	Beam	Bending
VCF-0			Yes	3 lateral and 3 vertical layers of CFRP	Column	0
VCF-25			Yes	3 lateral and 3 vertical layers of CFRP	Column	25
VCF-50			Yes	3 lateral and 3 vertical layers of CFRP	Column	50
VCF-B			Yes	3 lateral and 3 vertical layers of CFRP	Beam	Bending

2.1 Preliminary testing and results

In order to determine the properties of reinforcing steel and FRP, the following specimens were tested: three R10 steel bars, three N12 ribbed steel bars, three 1 layer carbon fibre coupons and three 3 layer carbon fibre coupons. All tests were carried our in the civil engineering laboratories at the University of Wollongong

The two different types of steel reinforcement tested were the N12 (500 MPa grade steel) bars used for the longitudinal reinforcement and R10 (250 MPa grade steel) bars used in the helical bars. All steel specimens were cut to a specified length of 550 mm. The specimens were clamped in the Instron testing machine with a clear distance of 400 mm. All specimens were tested until complete failure was observed. The tests revealed that the average tensile strengths of R10 and N12 bars were 435 MPa and 645 MPa, respectively.

Tensile testing was carried out on one layer and three layer specimens of carbon fibre. The original width of the carbon fibre was 100 mm and was manufactured in 100 m rolls. The one layer specimens were tested to indicate the strength and strains for the vertically orientated carbon fibre. The three layer specimens were tested to determine the stress and strains of the lateral layers of confinement used in this study. The test revealed that the average ultimate stress fir the single layer CFRP was 829.9 MPa with a corresponding strain of 0.017. The respective values for the three layered CFRP specimens were 884.6 MPa and 0.0197.

2.2 Casting the specimens

Twelve PVC forms were cleaned and placed into a supporting frame. The supporting frame was made out of plywood and consisted of circular holds for each of the forms. The reinforcement cages were then placed into the forms on top of plastic chairs to ensure correct concrete cover at the bottom of the columns. The formwork was secured to the supporting frame using a series of vertical and hooping straps.

The concrete was supplied by a local supplier. The concrete mix was specified to have 120 mm slump to ensure that the concrete was workable enough to fit around the reinforcement cage. The concrete was moved from the concrete truck agitator using a wheelbarrow. The concrete was then placed into the formwork using shovels. Vibration of the specimens was carried out as the concrete was being placed. Electric vibrators were used to remove any air voids in the concrete.

The twelve specimens were cured in their forms for seven days. A plastic sheet was placed and tied down over the top of the specimens to keep the moisture in. After seven days the columns were removed from their forms. After an inspecting the columns it was clear that only a few surfaces showed small imperfections, which were patched up immediately with a concrete slurry. The concrete specimens were cured in moist conditions for the following 21 days. The specimens were placed under wet Hessian rugs with plastic sheets on top to maintain moisture.

2.3 FRP wrapping

Carbon fibre tape was obtained from a local supplier and was used for the external confinement of the specimens. The rolls of carbon fibre were 100 m in length and 100 mm in width.

The surface of the specimens was cleaned of all rough surfaces and Hessian that remained attached to the specimens after curing. A wet lay-up system was used to apply the carbon fibre. An epoxy resin, one part hardener to five parts resin was used to cure the carbon fibre. The epoxy resin was generously brushed onto the specimens, then the carbon fibre was applied, making sure the carbon fibre was pulled into tension. Once the relevant layer was wrapped, another coat of the epoxy resin was applied. FRP in the laterally wrapped specimens (CF) was applied horizontally with a 15 mm overlap.

For the vertically orientated carbon fibre specimens (VCF), the carbon fibre was restrained at the bottom of the specimen by placing a flap under the base of the specimen. The carbon fibre was pulled up the specimens and placed under a weight on top of the specimen to ensure that the carbon fibre was in tension. The carbon fibre was then applied with another coat of epoxy resin. A lateral layer was then applied to the specimen and the lateral layers overlapped 15 mm until the entire specimen was covered, the layers were alternated between vertical and lateral layers. The process was repeated until the required number of layers was achieved.

2.4 Concrete strength testing

Seven and 28 day compressive strength tests were carried out to find the compressive strength of the concrete. The concrete specimens were 100 mm in diameter and 200 mm long. The compressive strength specimens were cured in the same moist conditions as the concrete specimens. The seven day compressive test specimens were tested using a rubber cap and the 28 day compressive test specimens were tested using a plaster cap. The caps were used to ensure that the concrete cylinder is tested under concentric loading. The 28 day compressive strength test showed typical behaviour of HSC. There was no warning to failure and explosive behaviour was observed. The average compressive strength of the concrete was found to be 75 MPa.

Loading caps

Accurate eccentric loading using a wedge plate has proven to be difficult in previous studies. To avoid using a wedge plate, Li and Hadi (2003) simulated eccentric loading by developing a nonprismatic circular column. However, it was concluded from their results that the positioning of the load was not accurate and the columns had a tendency to break at the tapered connection.

A new loading cap was designed based on a loading cap designed by Hadi (2006). The loading cap consisted of four adjustable clamps, to allow for the eccentric load to be accurately positioned prior to testing. The eccentric load was exerted on the loading cap via a wedge plate that was positioned into the 25 mm or 50 mm grooves, respectively. The loading caps were manufactured in the Engineering Laboratory at the University of Wollongong and were made of high strength steel.

2.5 4-Point bending frame

A four point loading bending frame was designed for the circular specimens. The four point loading frame was designed considering similar four point frames produced for rectangular beams in the Engineering Laboratory, University of Wollongong. The specimens are supported and the load is exerted on the specimens via circular arcs to simulate a line load across the column.

3. Testing the specimens

A uniformly distributed concentric load was applied on the specimens up to failure. The load was displacement controlled. The displacement rate was initially set at 0.3 mm/minute and when the trend remained stable or had only a slight change the rate was increased to 0.5 mm/min or up to 0.7 mm/min.

A laser LVDT was set on the back of the column specimens to measure the lateral deflection for eccentrically loaded column specimens. The readings from the LVDT to measure the lateral deflection and the axial load and the axial deflection were taken from the testing machine and were captured in a Strain-Smart system connected to a PC computer.

Figure 1 shows the load-axial deflection curves for Columns RC-0, CF-0 and VCF-0. Figure 2 shows the load-deflection curves for Columns RC-0, RC-25 and RC-50. Figure 3 shows the load-deflection curves for Columns CF-0, CF-25 and CF-50. Figure 4 shows the load-deflection curves for Columns VCF-0, VCF-25 and VCF-50.

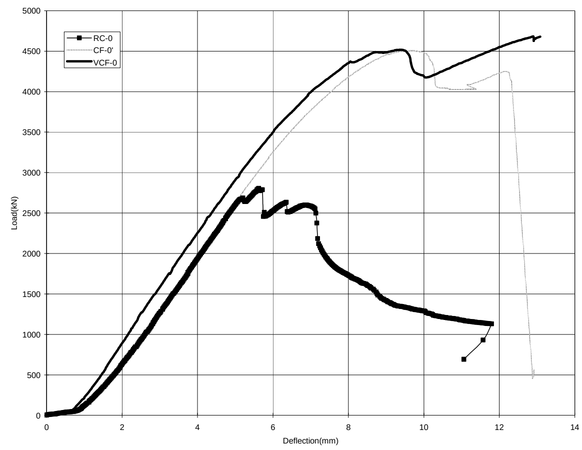

Figure 1 Load-deflection for Specimens RC-0, CF-0 and VCF-0

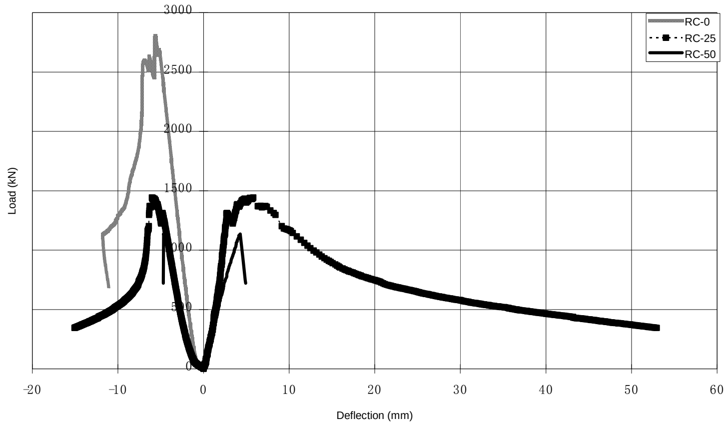

Figure 2 Load-deflection for Specimens RC-0, RC-25 and RC-50

The test results of the nine concentrically and eccentrically load columns are summarised in Table 2. Among the six eccentrically loaded specimens, Specimen (VCF-25) which was confined with three vertical layers and three horizontal layers of CFRP and tested under 25 mm eccentricity (VCF-25) resisted the highest load which was more than 3060 kN, while the reinforced concrete column with 50 mm eccentricity (RC-50) resisted the lowest load, 1135 kN.

A combined load-deflection curves for the eccentrically loaded columns under 25 mm and 50 mm eccentricities are shown in Figures 5 and 6, respectively. Some remarks can be obtained from this diagram:

- The load carrying capacity of the columns significantly depends on the eccentricity. As the eccentricity increases the load carrying capacity decreases.
- Comparing Columns CF-25 and CF-50 to VCF-25 and VCF-50, the extra three layers of vertical FRP improved the load capacity of the concrete; in addition, this improvement became more obvious as the eccentricity increased.

Beams RC-B, CF-B and VCF-B were tested under four-point loading regime. The objective of the bending test was to investigate the effect of FRP on mid-span deflection and tensile stress and to investigate the effect of the direction of FRP confinement on the bending moment. Load-midspan deflection curves for all three beam specimens are presented in Figure 7. A summary of the experimental results for the bending test is shown in Table 3.

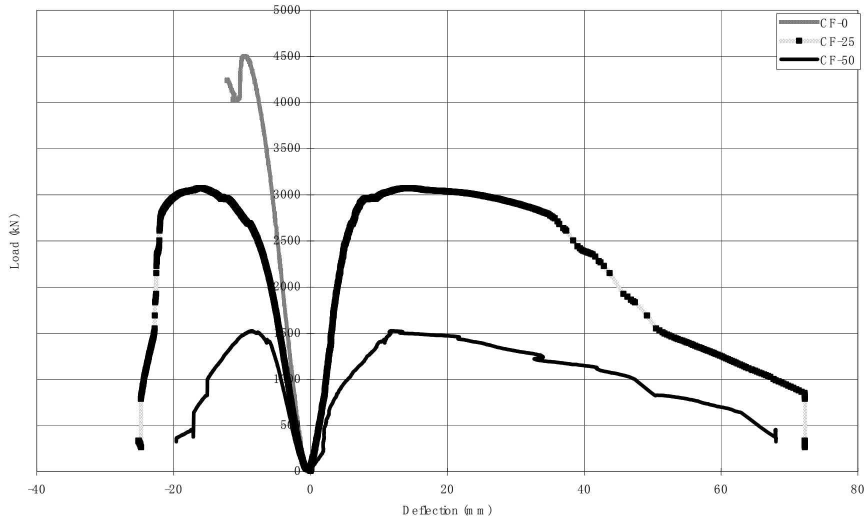

Figure 3 Load-deflection for Specimens CF-0, CF-25 and CF-50

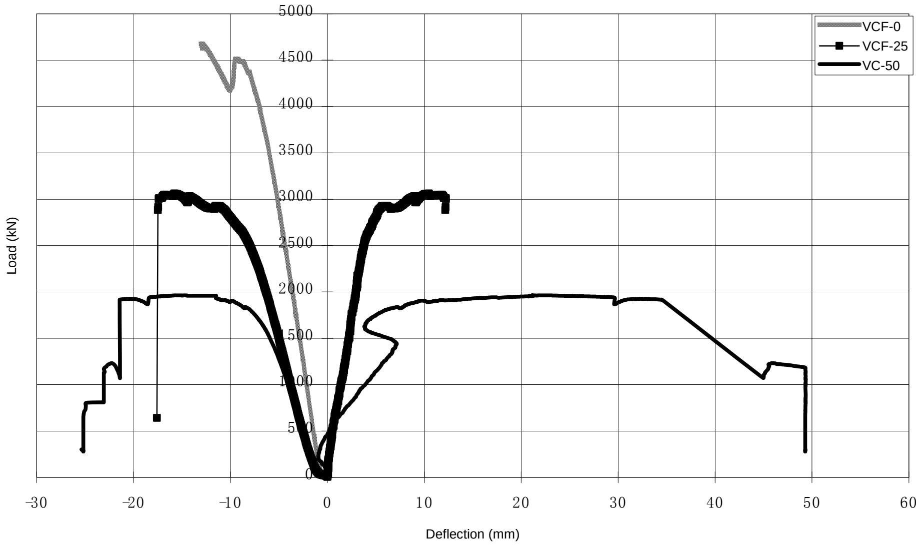

Figure 4 Load-deflection for Specimens VCF-0, VCF-25 and VCF-50

Table 2 Results of testing the column specimens

Specimen	RC-0	RC-25	RC-50	CF-0	CF-25	CF-50	VCF-0	VCF-25	VCF-50
Yield load (kN)	2498	1308	1135	4487	2969	1442	4507	>2904	1958.9
Corresponding axial deflection (mm)	5.1	4.84	*	9.972	13.2	6.865	9.432	<10.89	11.48
Corresponding lateral deflection (mm)		2.79	*		9.606	11.06		>5.44	21.135
Maximum load (kN)	2632	1442	1135	4503	3071	1521	>4800	>3060	1963
Maximum axial deflection (mm)	7.163	15.06	4.667	12.325	16.64	9.28	>13.08	15.79	15.647
Maximum lateral deflection (mm)		52.94	4.292		14.93	12.84		10.46	22.796

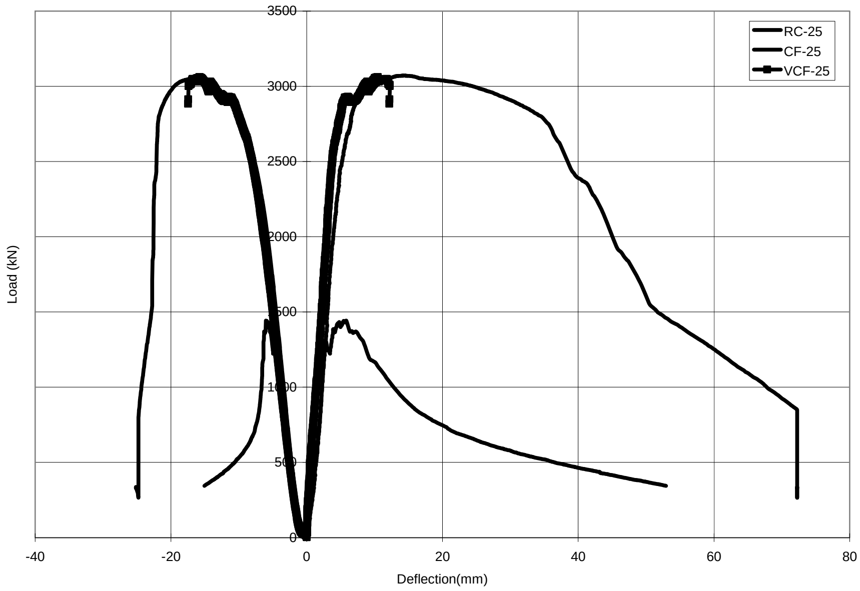

Figure 5 Load-deflection for Specimens RC-25, CF-25 and VCF-25

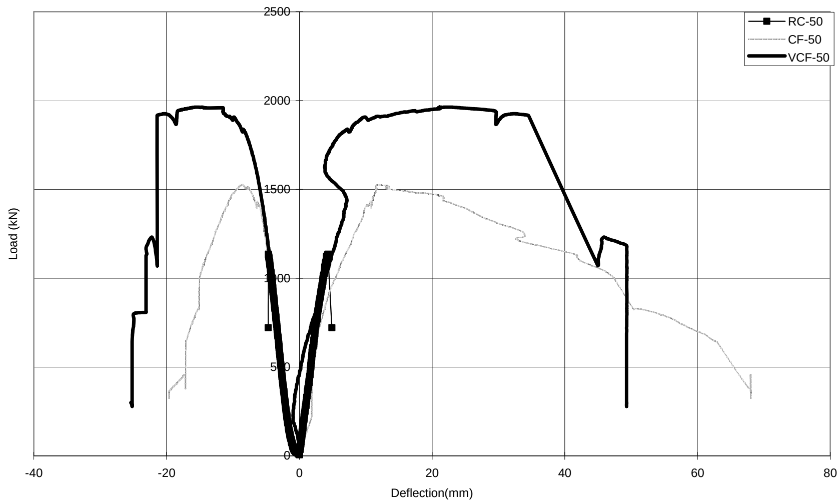

Figure 6 Load-deflection for Specimens RC-50, CF-50 and VCF-50

Table 3 Results of testing the beam specimens

Specimen	RC-B	CF-B	VCF-B
Yield load (kN)	294.75	344	496
Corresponding mid-span deflection (mm)	9.15	15.42	8
Maximum load (kN)	294.75	378.8	735.73
Corresponding mid-span deflection (mm)	9.15	28.94	31.06

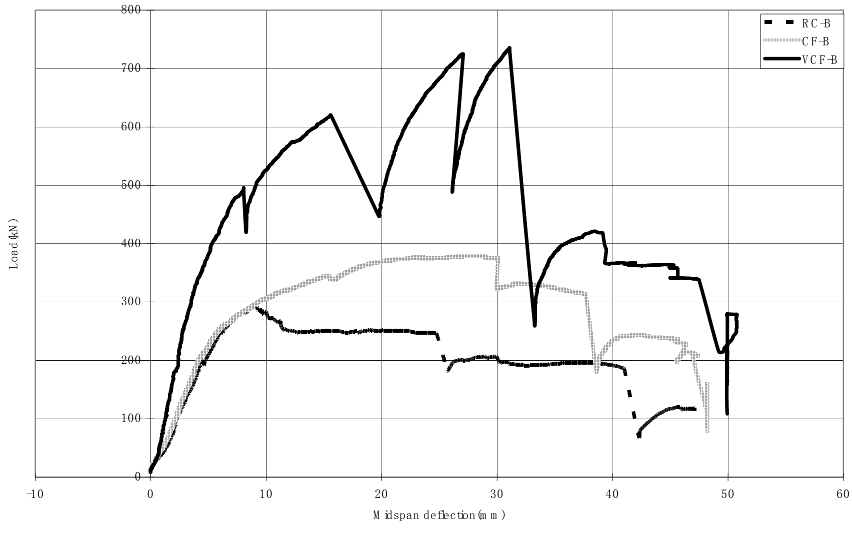

Figure 7 Load-deflection for Specimens RC-B, CF-B and VCF-B

The ductility of the tested specimens was calculated using two measures. In the first measure the ductility was calculated as the ultimate deflection divided by the yield deflection. In the second measure the ductility was calculated using the load-axial deflection curve for column specimens and the load-lateral deflection curve for the beam specimens. For all specimens the ductility was calculated as the ratio of area under the curve between the ultimate deflection and the yield deflection to the area under the curve at the yield deflection. Table 4 shows a summary of the ductilities using both methods.

Table 4 Ductility of tested specimens

Specimen	Ultimate to yield deflection ductility	Area under the curve ductility
RC-0	1.69	1.65
CF-0	6.94	1.59
VCF-0	1.26	1.62
RC-25	2.83	3.09
CF-25	4.65	3.19
VCF-25	2.32	2.00
RC-50	1.01	1.02
CF-50	4.99	3.53
VCF-50	5.99	3.7
RC-B	8.93	4.72
CF-B	14.79	8.08
VCF-B	24.66	11.91

4. Conclusions

Based on the experimental programme of this study, the following conclusions are drawn:

i. Columns made of plain concrete and vertically reinforced with CFRP as well as being wrapped by CFRP performed better than the reference column which was reinforced with steel. The better performance applies both for strength and ductility.
ii. Although being tested under eccentric loads, the CFRP columns outperformed the steel reinforced columns.
iii. The VCF specimens outperformed all corresponding specimens, especially columns under high eccentricity and in the beam specimens.

Finally, based on the results of this study, it can be concluded that FRP is an effective material for enhancing the strength and ductility of concrete. However, the concrete used in the current study had a compressive strength of 75 MPa. Further research is required to cover more strengths of concrete.

5. References

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