2007

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Publication Details
Hadi, M. N. (2007). Behaviour of FRP wrapped circular concrete columns under eccentric loading. In T. C. Triantafillou (Eds.), Fiber-Reinforced Polymer Reinforcement for Concrete Structures. Proceedings of the 8th International Symposium on Fiber-Reinforced Polymer Reinforcement for Concrete Structures, FRPRCS-8 Greece: University of Patras.

BEHAVIOUR OF FRP WRAPPED CIRCULAR CONCRETE COLUMNS UNDER ECCENTRIC LOADING

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Keywords: Columns, eccentric loading, FRP.

1 INTRODUCTION

The use of steel reinforcement in concrete construction has proven to be very effective due to the excellent properties that the reinforcing steel has that compliment the concrete properties, for example increase in tensile strength and ductility. However, one of the drawbacks of steel is its long-term behaviour especially in areas where the humidity is high. In such areas, the steel usually suffers from rust and oxidation which eventually lead to the deterioration of the concrete structure. One method to reduce this effect is to protect the reinforcing bars, for example wrapping or using cathodic protection. This paper investigates the behaviour of reinforced concrete columns reinforced with FRP both in the vertical and horizontal directions.

As most columns are subject to a combination of axial forces and bending moments, the experimental programme presented in this paper is for columns that are eccentrically loaded. A total of twelve specimens were cast and tested.

This paper experimentally investigates the performance of high strength concrete (HSC) columns confined with vertically and horizontally oriented carbon fibre reinforced polymer (FRP) wrapping, tested under eccentric loads. Previous studies have proven that HSC columns confined by FRPs have had positive effects under concentric and eccentric loading, however little is known about vertically oriented FRPs. 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 [1-5]) 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 REVIEW OF LITERATURE

A brief review of literature about FRP wrapping of concrete is presented below.

Mirmiran *et al.* [6] tested FRP tubes and enforced the theory of external confinement. Under concentric loading the FRP reinforced columns were stronger than the traditionally reinforced columns due to the full section being confined. The FRP tubed columns were found to be equivalent to having 6% conventional steel reinforcement. The failure observed in the test was ductile and gave plenty of warning of failure. This study verified the positive effects of external confinement.

Saadatmanesh *et al.* [7] investigated different properties of concentrically loaded columns with different spacing between the FRP straps. Two different types of FRP spacing were investigated; individual rings and continuous spiral. The study concluded that ductility increases linearly with the increase of strap thickness, however this factor decreases as the strapping spacing increases. Therefore, continually wrapped or overlapping the FRP wrapping will have a significant improvement on the behaviour of the column.

Results mentioned by Chaallal *et al.* [8] showed that the optimum angle for fibre orientation for axially loaded columns would range between 0 to 15 degrees.

Li and Hadi [2] found similar results, that is, FRPs can significantly increase the strength of HSC columns under concentric loading. Their studies also demonstrated that by increasing the number of layers of FRP, the performance of the column was enhanced.

Li and Hadi [2] experimentally proved that carbon fibre provides better lateral confinement than E-glass. The CFRP produced the largest lateral confinement pressure, resulting in high axial capacity of the specimens. Toutanji [9] found similar results, stating that the reason for the superior behaviour was directly related to the larger lateral stress carbon can produce compared to E-glass. Their results clearly demonstrated that HSC columns have improved properties under concentric loading, but under eccentric loading the effects of FRP confinement were less significant. This was related to the bending action produced by the eccentric load.

Parvin and Wang [1] found that FRP jackets can significantly enhance the strength and ductility of concrete columns under eccentric loading. However, Lee and Son [10] thought that FRP wrapping only enhanced the performance of concrete slightly. There is a huge variation in the results obtained for concentric and eccentric loading. This is a direct result of the bending action produced by the eccentric load. Furthermore, positive effects were seen with the increase of FRP layers, however the difference was only marginal.

It was noted in a number of studies (Lam and Teng [11], Parvin and Wang [1] and Toutanji [9]) that local failure of the FRP reinforcement was a major concern to eccentrically loaded FRP concrete columns. Local failure is where failure only occurs in a small defined region. Local failure of FRP requires only a small region of the FRP wrapping to fail for the entire column to fail, the failure occurs due to a build up of stresses in the failure region. Generally local failure of FRP wrapping occurs due to inconsistent wrapping methods of the FRP reinforcement.

3 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.

The 12 specimens were subdivided into three groups with four specimens each. The specimens of the first Group RC was made of reinforced concrete, the specimens of the second group CF was made of reinforced concrete and were wrapped with three layers of carbon FRP (CFRP), and the specimens of the third group VCF were reinforced with vertical straps made of CFRP then wrapped with CFRP. This alternate wrapping was repeated three times. In other words the vertical strap and the horizontal wrap were applied alternately.

Three specimens from each group were tested as columns with 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 Experimental column configurations.

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

3.1 Preliminary Testing and Results

In order to determine the properties of reinforcing steel 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. Three specimens of each type of reinforcement were tested to eliminate errors. This is especially important when considering the carbon fibre to ensure that discrepancies have not occurred due to preparation techniques.

The two different types of steel reinforcement tested were the N12 bars used for the longitudinal reinforcement and R10 bars used in the helical spiral. The steel bars consisted of two different steel grades; 500 MPa and 250 MPa. All steel specimens were cut to a specified length of 550 mm, however, once clamped in the Instron, the clear distance was 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 results of the carbon fibre testing can be seen in Table 2.

Table 2 Carbon fibre tensile test results.

	Single Layer			Three Layers		
	Specimen 1	Specimen 2	Specimen 3	Specimen 4	Specimen 5	Specimen 6
Maximum Load (kN)	15.82	14.88	16.09	54.25	53.08	48.91
Maximum Deflection (mm)	5.00	4.59	4.89	5.43	5.78	5.20
Thickness of Coupon (mm)	0.47	0.49	0.52	1.60	1.52	1.62
Width of Coupon (mm)	37.3	38.3	39.1	37.4	36.9	37.7
Length of Coupon (mm)	280	280	280	280	280	280
Maximum Stress (MPa)	902.40	792.88	791.36	906.58	946.37	800.83
Maximum Strain	0.018	0.016	0.017	0.019	0.021	0.019

3.2 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. Figure 1 shows the prepared forms.

Fig. 1 Prepared formwork.

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 as air pockets in a concrete section can jeopardise the structural integrity of the specimen.

The twelve specimens were cured in their forms for seven days. A plastic sheet was placed and tied down over the top of the columns to keep the moisture in. After seven days the columns were removed from their forms. After an inspection of the columns it was clear that only a few surfaces showed small imperfections, which were patched up immediately with a concrete slurry. The concrete columns were cured in moist conditions for the following 21 days. The columns were placed under wet Hessian rugs with plastic sheets on top to maintain moisture. Figure 2 shows the curing arrangement.

Fig. 2 Curing arrangement.

3.3 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.

For the vertically orientated carbon fibre, 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 over lapped 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. Figure 3 shows the external confine process.

3.4 Concrete strength testing

Three types of tests were undertaken on the concrete using the relevant Australian Standard, AS1012. Seven and 28 day compressive strength tests were carried out to find the actual 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; 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.

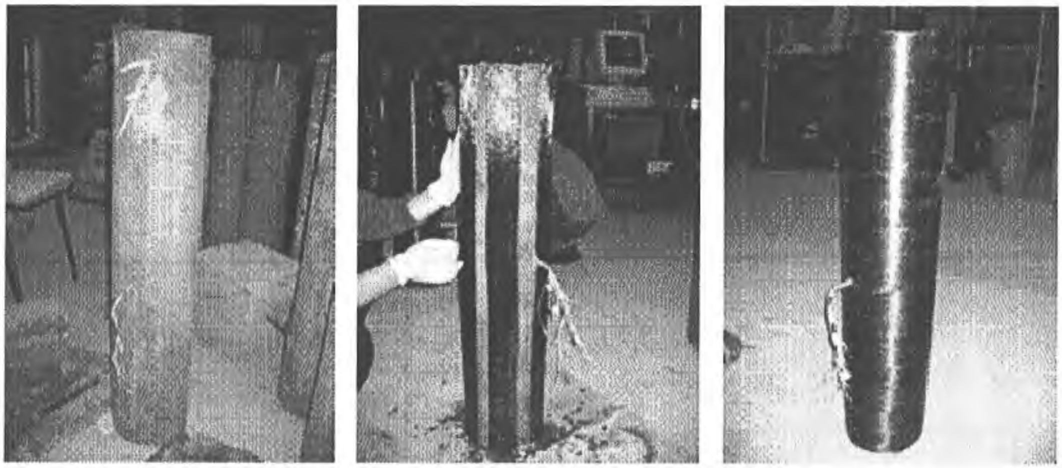

Fig. 3 External confinement application.

3.5 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 [2] simulated eccentric loading by developing a non-prismatic 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 [6]. 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. Figure 4 displays the loading caps. The loading caps were manufactured in the Engineering Laboratory at the University of Wollongong and were made of high strength steel.

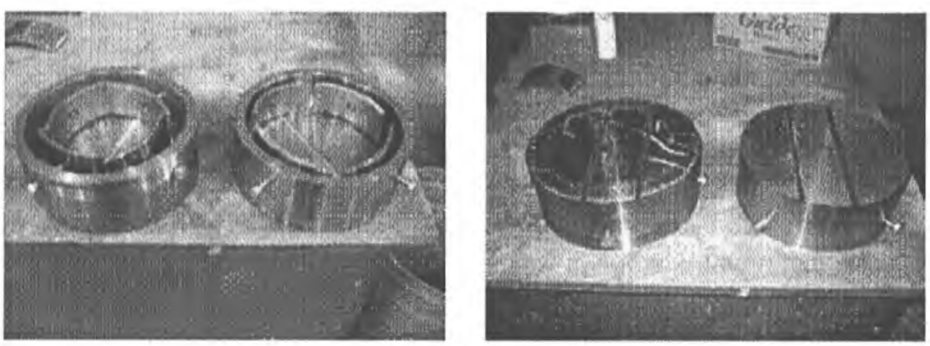

Fig. 4 Loading caps.

3.6 4-Point Bending Frame

A four point loading bending frame was designed for the circular beams. The four point load frame was designed considering similar four point frames produced for rectangular beams in the Engineering Laboratory. The specimens are supported and the load is exerted on the specimens via circular arcs to simulate a line load across the column. Figure 5 shows the four point loading frames which were manufactured in the Engineering Laboratory.

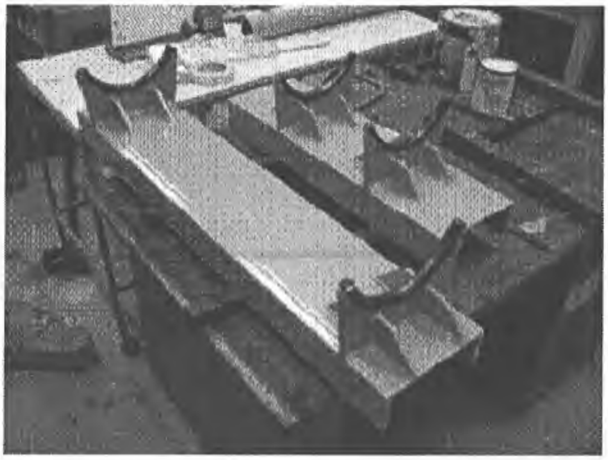

Fig. 5 Four point bending loading frame.

4 RESULTS

All specimens were tested using a 5000 kN compression testing machine in the civil engineering laboratories at the University of Wollongong. The displacement controlled load was applied gradually on the specimens. The column heads described above were used to apply the loads on the column specimens. These columns heads have the ability of applying concrete loads and loads with 25 and 50 mm eccentricities. All column specimens were aligned and a plaster was used for alignment. All the beam specimens were tested using the loading frame shown in Figure 5. Table 3 shows the load and deflections for all the column specimens and Table 4 shows the results of testing the beam specimens. Figures 6-12 show the load deflection curves for all tested specimens. Finally Figure 13 shows the axial load-moment interaction diagrams for the tested specimens and the corresponding theoretical diagrams.

Table 3 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)	2698	1308	1135	4487	2969	1442	4507	>2904	1958.9
Corresponding axial deflection (mm)	5.1	4.84	*	9.972	13.202	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	>5000	>3060	1963
Corresponding axial deflection (mm)	7.163	15.06	4.667	12.325	16.64	9.28	>13.08	15.79	15.647
Corresponding lateral deflection (mm)		52.94	4.292		14.93	12.84		10.46	22.796

Table 4 Results of testing the beam specimens.

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

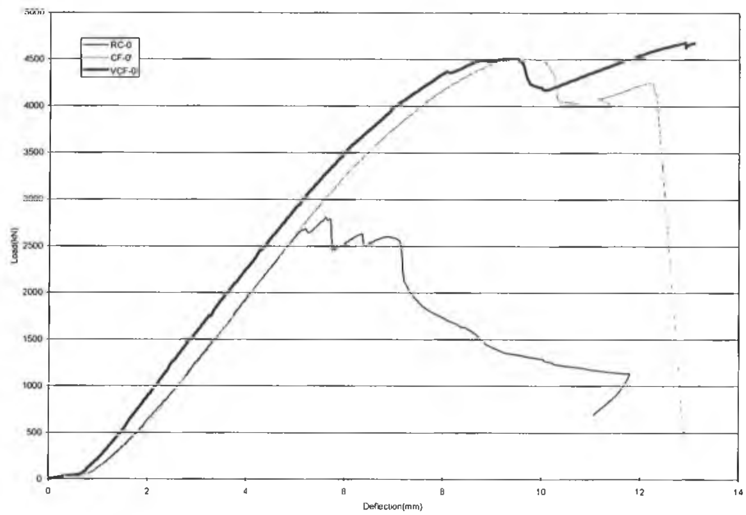

Fig. 6 Load-deflection for Specimens RC-0, CF-0 and VCF-0.

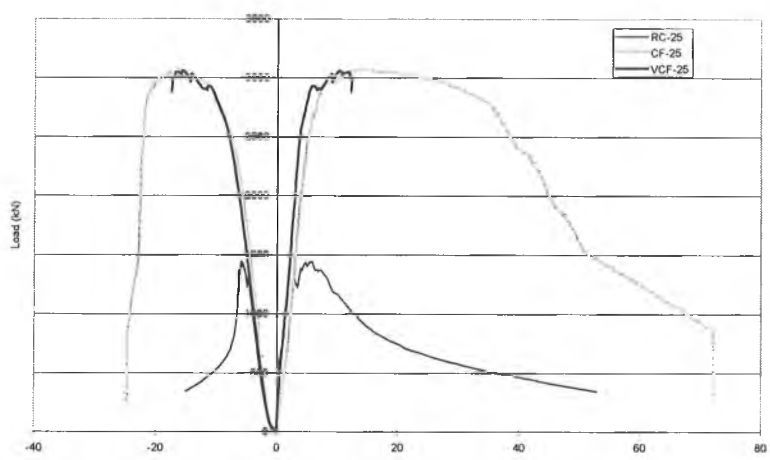

Fig. 7 Load-deflection for Specimens RC-25, CF-25 and VCF-25.

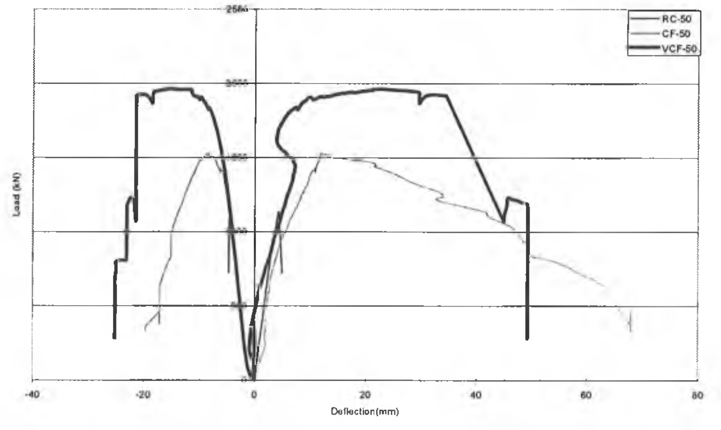

Fig. 8 Load-deflection for Specimens RC-50, CF-50 and VCF-50.

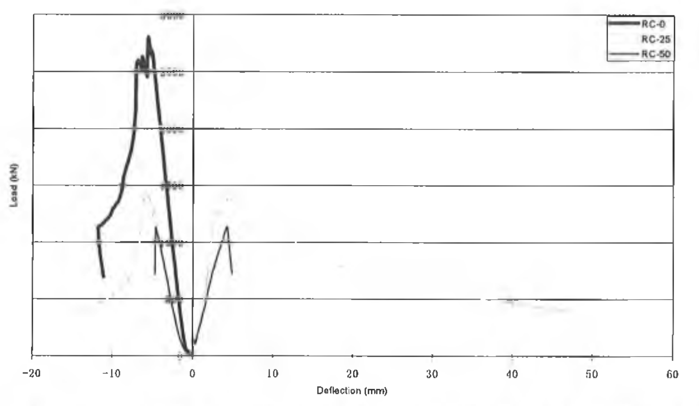

Fig. 9 Load-deflection for Specimens RC-0, RC-25 and RC-50.

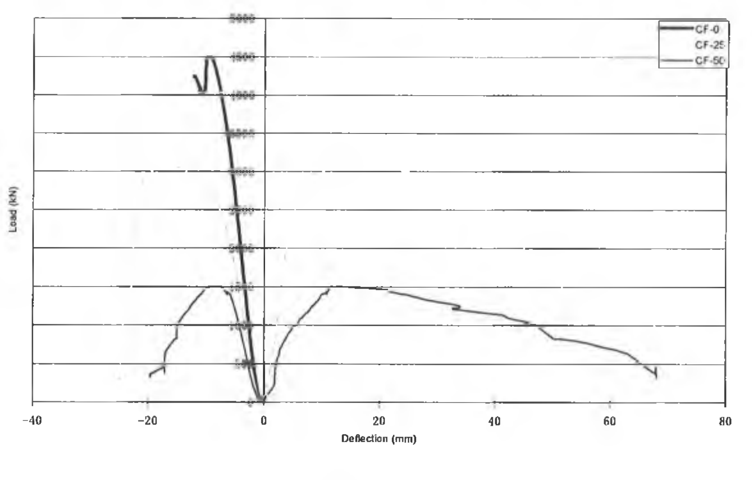

Fig. 10 Load-deflection for Specimens CF-0, CF-25 and CF-50.

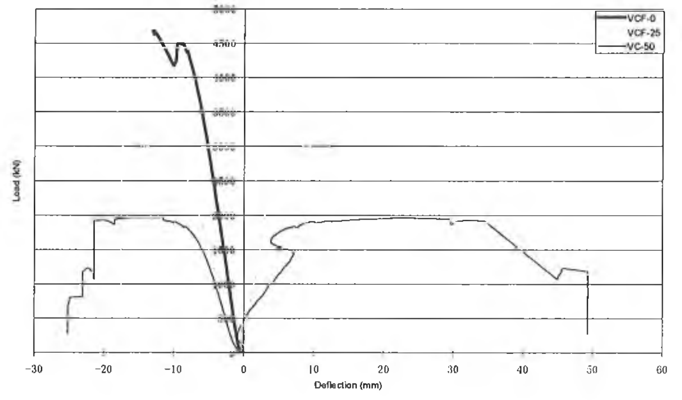

Fig. 11 Load-deflection for Specimens VCF-0, VCF-25 and VCF-50.

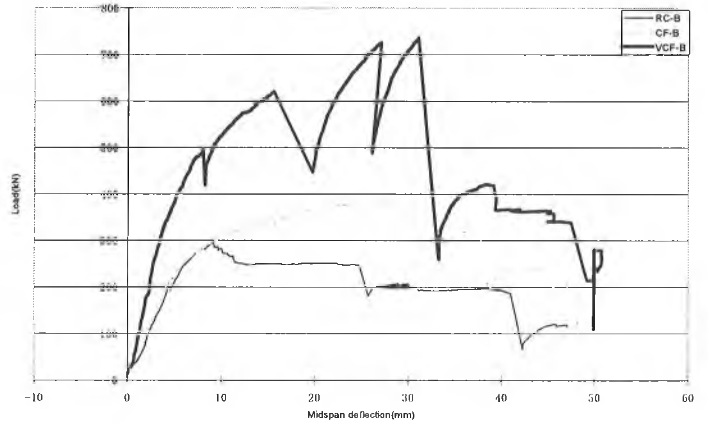

Fig. 12 Load-deflection for Specimens RC-B, CF-B and VCF-B.

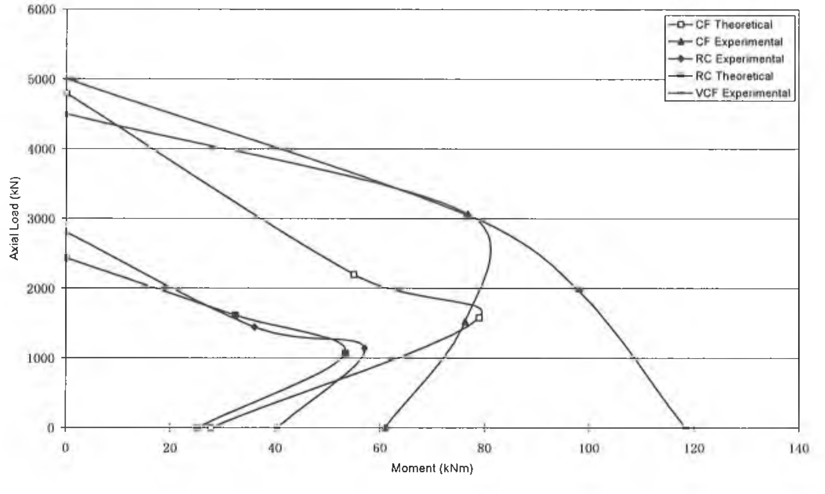

Fig. 13 Interaction diagrams for the tested specimens.

5 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.

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.

REFERENCES

[1] Parvin, A. and Wang, W., "Behavior of FRP Jacketed Concrete Columns under Eccentric Loading", *Journal of Composites for Construction,* 5,3, 2001, pp. 146-151.

[2] Li J. and Hadi M.N.S., "Behaviour of externally confined high strength concrete columns under eccentric loading", *J of Composite Structures,* 62,2, 2003, pp. 145-153.

[3] Hadi M.N.S., "Behaviour of wrapped HSC columns under eccentric loads", *Asian J Civil Engineering (Building and Housing),* 4, 2-3, 2003, pp. 91-100.

[4] Hadi M.N.S. and Li J., "External reinforcement of high strength concrete columns", *J. Composite Structures,* 65, 3-4, 2004, pp. 279-287.

[5] Hadi, M.N.S., "Behaviour of FRP Wrapped Normal Strength Concrete Columns under Eccentric Loading", *Journal of Composite Structures,* 72, 4, 2006, pp. 503-511.

[6] Mirmiran, A., Shahawy, M. and Samaan, M., "Strength and Ductility of Hybrid FRP-Concrete Beams-Columns", *Journal of Structural Engineering ASCE,* 125, 10, 1999, pp. 1085-1093.

[7] Saadaatmanesh, H., Ehsani, M.R. and Li, M.W., "Strength and Ductility of Concrete Columns Externally Reinforced with Fiber Composite Straps", *ACI Structrual Journal,* 91, 4, 1994, pp.434-447.

[8] Chaallal, O. and Shahawy, M., "Performance of Fibre-Reinforced Polymer-Wrapped Reinforced Concrete Column under Combined Axial-Flexure Loading". *ACI Structural Journal,* 97,4, 2000, pp. 659-665.

[9] Toutanji, H., "Durability characteristics of concrete columns confined with advanced composite materials", *Composite Structures,* 44, 2, 1999, pp. 155-161.

[10] Lee J.H. and Son, H.S., "Failure and Strength of High Strength Concrete Columns Subjected to Eccentric Loads", *ACI Structural Journal,* 97, 1, 2000, pp. 75-84.

[11] Lam, L. and Teng, J.G., "Strength Models for Fiber-Reinforced Plastic-Confined Concrete". *Journal of Structural Engineering ASCE,* 128, 5, 2002, pp.612-623.