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Behaviour of eccentric loading of FRP confined fibre steel reinforced concrete columns

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Eccentric Loading of FRP Confined Fibre Steel Reinforced Concrete Columns

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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 specimens were wrapped with Carbon Fibre Reinforced Polymers (CFRP). The next four specimens had steel fibres added to the concrete. The final four specimens were reinforced with steel fibres 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, axial force-bending moment interaction diagrams were drawn based on the experimental results and compared with theoretical estimation. The experimental programme proved that the introduction of fibres as well as wrapping the specimens with FRP improve the properties of concrete, especially its ductility.

Keywords: FRP, reinforced concrete columns, steel fibres, force-moment interaction diagrams.

1. Introduction

High Strength Concrete (HSC) has been used in the construction industry for the last few decades. Compared to normal strength concrete (NSC), HSC has higher strength but lower ductility. One of the techniques used to increase the ductility of concrete is the addition of fibres to the concrete. This technique of adding fibres to concrete has been used for the last several decades and has been proven a viable technique. Another technique that has been used more recently is wrapping concrete elements with layers of fibre reinforced polymers (FRP). Again this technique has been proven a viable one for increasing the strength and ductility of reinforced concrete members. In addition, this technique protects the concrete and its reinforcement from the elements, thus reducing the environmental effects on the concrete, such as carbonation of concrete and erosion of the reinforcing steel.

With a few exceptions, for example Parvin and Wang (1), Fam et al. (2), Li and Hadi (3), Hadi (4), Hadi and Li (5), Hadi (6). Hadi (7), Hadi (8), most of the research conducted so far on wrapping reinforced concrete columns is based on the application of concentric loads. It is obvious that most columns will be subject (with varying magnitudes) to a combination of axial load, lateral load and a combination of bending moment in one or two directions. The bending moment will be of higher magnitude especially in the higher level columns at the sides and corners of buildings. Construction errors can also lead to eccentric loads. Lateral loads can occur in columns due to earthquake loads and vehicular loads (due to acceleration, deceleration and braking) in bridge type structures. Besides the above-mentioned studies, there have been several other studies on wrapping columns with FRP. All these studies are based on testing columns under concentric loads. Hence there is a gap in knowledge of the behaviour of

FRP wrapped concrete columns when tested under eccentric loads. This paper is a step in this direction.

This paper presents results of testing fibre reinforced specimens that are wrapped with FRP. 16 circular specimens were cast and tested. The dimensions of the specimens were 925 mm in height and 205 mm in diameter. All specimens had the same amount of steel reinforcement. The 16 specimens were subdivided into four groups with four specimens each. The first group had specimens that were reinforced only and acted as reference specimens. The specimens of the second group were wrapped with three layers of Carbon FRP (CFRP). The specimens of the third group had 1% by volume steel fibres added to their concrete. The specimens of the last group had 1% of steel fibres added as well as being wrapped with three layers of CFRP. From each group, three specimens were tested as columns under 0 mm (concentric), 25 mm and 50 mm eccentricities. The last specimen was tested as a beam under pure flexure using four point loading regime. All these specimens were tested and comparisons were done to investigate the effectiveness of each of the techniques. Based on the results of the tests, interaction diagrams for axial load – bending moment were plotted for each of the four types of specimens. In addition, interaction diagrams were plotted based on mathematical calculations. In this case proposed stress-strain relationships for the different types of reinforcement were used in order to plot these diagrams. It is clear that considerable gains in strength and ductility are achieved when the concrete is wrapped with CFRP. In addition the ductility of concrete is enhanced when fibres are added.

2. Experimental Programme

In order to test the behaviour of fibre reinforced concrete FRP wrapped specimens, an experimental programme was designed and conducted. 16 specimens were cast and tested at the civil engineering laboratories at the University of Wollongong. All specimens were made of reinforced concrete. The specimens were divided into groups of four. The specimens of the first group, C were made of reinforced concrete. The specimens of the second group, CF were made of reinforced concrete and then wrapped with three layers of Carbon Fibre Reinforced Polymers (CFRP). The specimens of the third group, CS were made of reinforced concrete with added steel fibres. The specimens of the last group, CFS were made of reinforced concrete, steel fibres were added and then they were wrapped with three layers of CFRP. From each group of specimens, one specimen was tested under an axial concentric load; specimens tested under this testing regime are denoted 0. The second specimen was tested by applying an axial load with 25 mm eccentricity. These specimens are denoted 25. The third specimen was tested under a 50 mm axial eccentric load. These specimens are denoted 50. The last specimen is denoted B and was tested as a beam under four point loading. Table 1 shows a summary of the tested specimens.

The design of the concrete columns was done according to AS3600 (9). The internal reinforcement used 6N12 (12 mm deformed bars with 500 MPa nominal tensile strength) longitudinal bars and 165 mm diameter helix with 60 mm pitch by using R10 bars (10 mm plain bars of 250 MPa nominal tensile strength). A clear cover of 20 mm was maintained. Steel fibres were used at a volumetric ratio of 1%. The type of fibres used was FIBERSTEEL 184EE of 18 mm lengths. The external confinement that was used on the concrete columns was Carbon Fibre Reinforced Polymer (CFRP), which was wrapped to provide a passive confinement on the reinforced concrete columns.

2.1 Preliminary testing – material testing

Preliminary testing included testing concrete cylinders, reinforcing bars and CFRP. The concrete was ordered from a local supplier with 120 mm slump. The average compressive strength of the concrete without fibres at 7 days was 37.0 MPa and with 1% fibres at 7 days was 38.7 MPa. The average compressive strength at 28 days was 50.0 MPa for concrete without fibres and 53.3 MPa for concrete with fibres. Specimens of steel bars R10 and N12 were tested in tension using the Instron testing machine. The average tensile strength of the N12 bars was 640 MPa and the average tensile strength of the R10 bars was 437 MPa. Coupons of FRP were tested in the Instron testing machine. Table 2 shows a summary of testing the FRP coupons. All tests were conducted at the civil engineering laboratories at the University of Wollongong.

2.2 Preparation of Specimens

PVC formwork was used to form the test specimens. The 16 forms were cleaned and placed into a supporting frame. The supporting frame was made out of plywood and consisted of circular holes 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 hoop straps.

The concrete was supplied by a local supplier. The concrete was moved from the concrete truck agitator using a wheelbarrow. For the fibre reinforced concrete, a specified amount of concrete was put into a small mixer and then steel fibres at 1% by volume were added to the concrete and thoroughly mixed. The concrete was then placed into the formwork using shovels. Vibration of the specimens was carried out as the concrete was being placed.

The 16 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 specimens were removed from their forms. 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.

Carbon fibre tape was obtained from Advanced Composites and was used for the external confinement of the 16 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 columns 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 column, 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.

3. Testing the Specimens

3.1 Procedure for Testing Columns

The caps shown in Figure 1 were used in testing the specimens. High strength plaster was cast in the heads and the specimen was placed in the head. The plaster was left to set for 10 min, the specimen was then turned around and the same procedure was repeated for the other end.

After which the column was lifted by two people by wooden clamps and was placed against the rig where it was strapped tightly against it. When the plaster was hardened the belt of the column was removed, whereby the forklift was used to lift the specimen and placed it in the Denison 500 tonne testing machine.

A laser LVDT was placed at the back of the protector box shooting through the hole provided on to the concrete column. This LVDT was used to measure the lateral displacement of the column. After these procedures were set in place the testing of the specimen began. The testing was done as a displacement controlled test with a rate of 0.3 mm/min to 0.6 mm/min. Data acquisition software was used to capture the applied load and the deflections of the tested specimens.

3.2 Testing Procedure for Pure Bending

The pure bending was tested by the help of two rigs top and bottom, see Figure 2, two square plates and two round plates were used. For lifting these specimens a manual crane was used.

The following procedure was conducted to test the beam specimens: The bottom rig was placed on the bottom plate of the Denison machine diagonally across the centreline, then the laser LVDT was placed under the rig shooting through the hole provided on to the concrete beam as shown in Figure 3 where it measured the deflection of the specimen. After the placement of the laser LVDT, the specimen was lifted and placed on the bottom rig by two people. When it was in place it was adjusted on the ends by 40 mm from the rigs by holding a clamp to the end of the specimen. The top rig comprising a second two steel plates and a steel cylinder was then placed. The top plate of the compression machine was lowered about 2 mm to the steel cylinder and the clamp test piece set was selected while a person was levelling the top of the rig. The beam was tested by displacement control, the position end point was set at 60 mm depending on the beam and the ramp rate was set at 0.3 mm/min to 0.6 mm/min.

4. Experimental Results and Analysis

4.1 Reinforced Concrete Column under Concentric Load

Four specimens were tested to failure under a uniformly distributed concentric load. A LVDT was used to measure the axial deflection of the specimens. Figure 4 shows a summary of the four concentrically tested specimens. Specimen C-0 shows a small load and a small axial deflection. The failure of the concrete specimen C-0 was observed by the exterior layer of concrete first failing then the snapping of reinforcement and helix. Specimen CF-0 had a high load and a sudden drop of failure, where a loud noise occurred. The failure of CF-0 was not obvious but failure occurred at about 200 mm from the top of the column. The concrete column remained in an up right position. Steel reinforcement was nearly imbedded in steel cap and bending of the steel occurred when the cover of concrete failed and snapped off.

Specimen CS-0 shows the influence of the use of steel fibre. The ductility can be clearly seen by the long extension of the curve until the specimen failed. It exhibited the highest axial deflection and hence high ductility. The specimen CFS-0 did not fail as the applied load came close to the capacity of the machine which was 5000 kN, and the column’s highest load was 4791kN. The testing was brought to a halt in case of a machine malfunction.

In this analysis the ductility of the concrete was also calculated. The ductility was calculated by two methods. In the first method, the equation $\lambda=\delta u/\delta y$, was used to calculate the ductility where λ = ductility, δu = ultimate deflection and δy = yield deflection. In the second method the area under the load-axial deflection curve was used. Two areas were calculated, A_1 which represents the area up to the yield load and A_2 which represents the area to the ultimate deflection. The ductility was calculated as A_2/A_1. The behaviour of the tested specimens is shown in Table 3.

Table 3 summarises results of testing the four column specimens concentrically. It shows the specimens different theoretical results versus the tested results of the axial deflection of the columns and their ductility. The method proposed incorporating Lam and Teng (10), Warner et al. (11) and Razvi and Saatcioglu (12) was by replacing f_{cc}' with f_{co}', the values were closer to the tested values.

4.2 Reinforced concrete columns under eccentric loading

Eight specimens were tested eccentrically, four of them with a load eccentricity of 25 mm and the second four with a load eccentricity of 50 mm. The eccentricity was produced by two knife edges which were set on top and bottom of the column.

Figure 5 shows the axial and lateral deflection versus the applied load of the specimens tested under 25 mm eccentric load. All the 25 mm eccentrically loaded columns failed in compression. It can be seen that by using steel fibres the deflection has increased but the load has decreased and by using CFRP the load was higher but the deflection was lower.

Four specimens were tested under 50 mm eccentric load. The eccentricity was determined by two knife edges, where one was placed on top of the column, and the other on the bottom of the column. Figure 6 shows the load-deflection curves of the tested specimens. It is to be noted that due to experimental error, the lateral deflection of Specimen C-50 was lost. The highest load was produced by specimen CFS-50. Figure 6 also shows that the axial deflection was smaller than the lateral in all the specimens.

It was observed that by the use of CFRP a column can withstand higher load than an unconfined reinforced concrete column, and the use of steel fibres results in higher deflection.

From testing the eight eccentrically loaded columns, it can be clearly seen that by introducing CFRP the load has increased, and by introducing steel fibre the ductility of the specimen has also increased. This analysis has been outlined in Table 4. The ductility of the specimens was calculated by two methods in the same way as the concentrically loaded columns were calculated as explained above. By analysing these specimens it can also be concluded that by increasing the eccentricity the ultimate load decreases.

4.3 Beam Specimens Testing

A pure bending test was conducted in order to determine the maximum bending moment capacity of the four tested specimens. All specimens were tested under four point loading regime.

Figure 7 shows the load-mid span deflection of the different types of specimens with no fibre and no CFRP (B), no steel fibre and wrapped with 3-layers of CFRP (BF), 1% steel fibre no

CFRP (BS) and 1% steel fibre and wrapped with 3-layers of CFRP (BFS). It can be seen that the introduction of CFRP produces the highest load.

Table 5 summarises the analysis of the beam specimens. Table 5 shows BFS having the lowest yield deflection and the highest ultimate load of the fours beams. The ductility of the concrete can also be seen to have improved. The calculations were conducted using the same equations and methods explained for the concentrically and eccentrically loaded columns. The highest ductility was produced by specimen BFS as shown in Table 5.

4.4 Interaction Diagrams

Figure 8 shows the interaction curves for a circular section determined by theoretical calculations based on the work of Lam and Teng (10) and Warner et al. (11). Figure 9 shows the interaction diagrams for the 16 tested specimens.

5. Conclusions

From the experimental work conducted in this study, the following conclusions can be drawn:

- By increasing the load eccentricity the ultimate load decreases whereas the lateral deflection has no relation with the eccentricity.
- By providing external confinement with FRP-composite the strength of a concrete column can increase considerably.
- Providing steel fibres to a concrete column increases the ductility.

- The four point load test indicates that adding FRP-composite to a column increases its maximum bending moment, the lateral deflection is smaller and the load is higher indicating the importance of the external confinement. Adding steel fibre to the reinforced concrete column does not increase the strength as much as the FRP-composite, but the ductility is increased. The lateral deflection was very close to the specimen with 3-layers of CFRP and steel fibre. These observations can be seen in the deflection diagrams of the zero, 25 mm and 50 mm eccentricities where confinement minimises axial and lateral deflection.
- Introducing FRP-composite external confinement to a reinforced concrete column provides the concrete specimen capacity to carry higher loads. Providing steel fibre to the concrete specimen, will increase the ductility. It should be noted that specimen CFS-0 when loaded concentrically did not fail.

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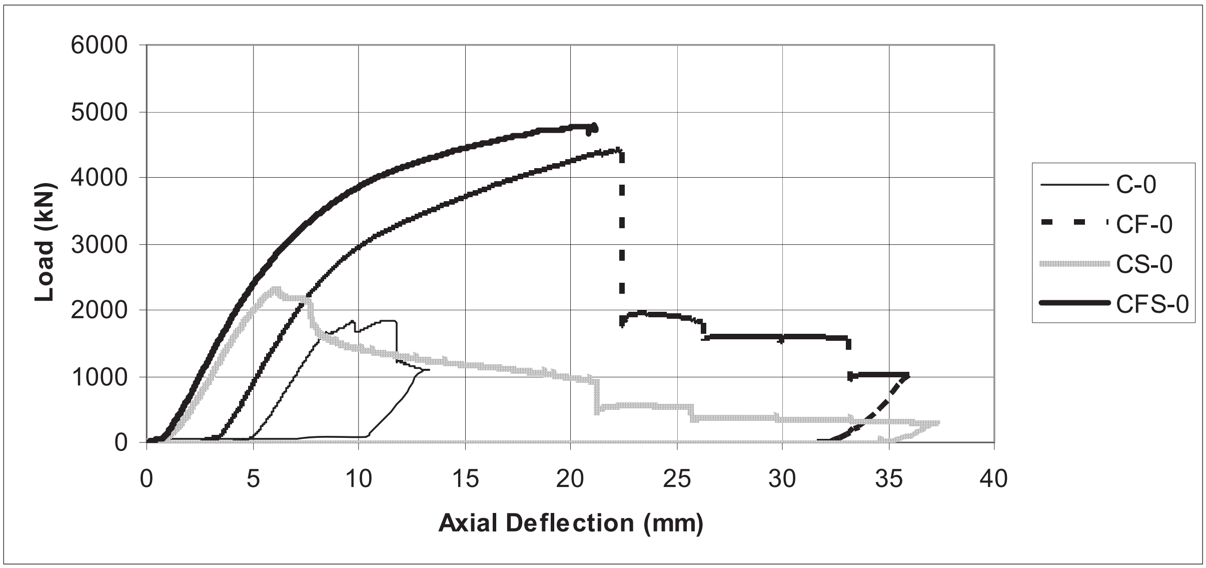

Figure 4 Load-Deflection Diagrams of Concentrically Tested Column Specimens

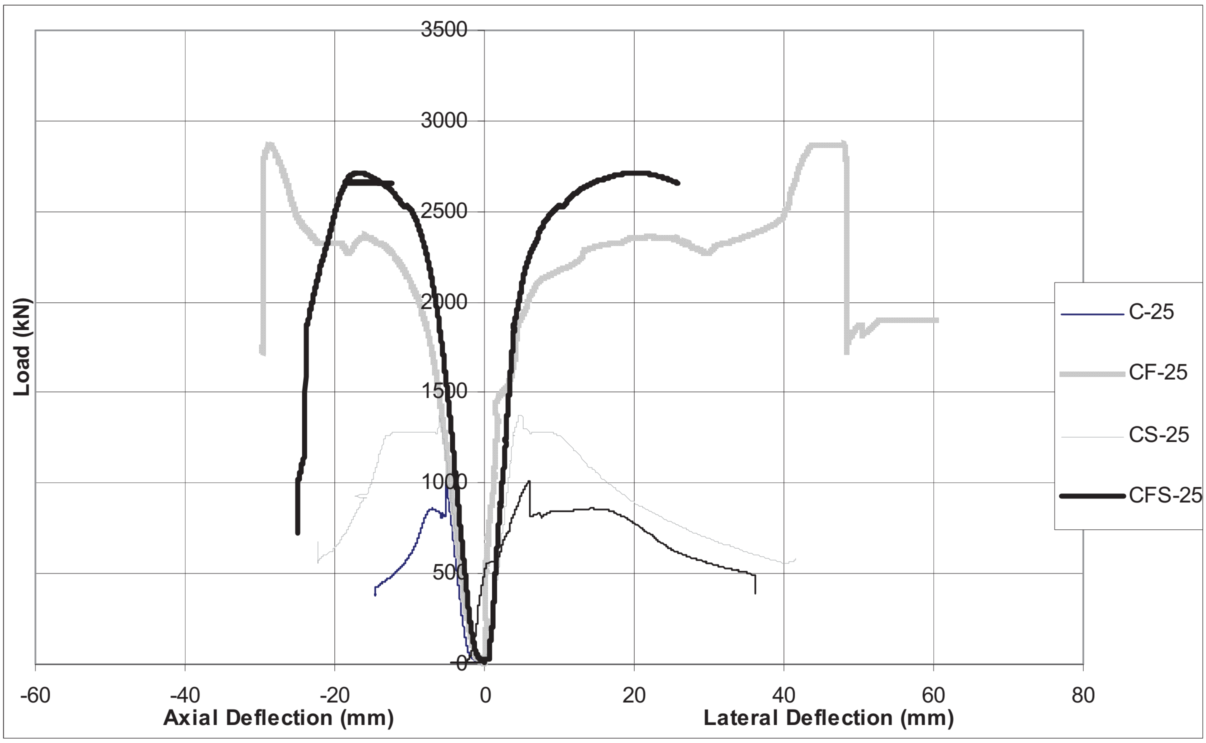

Figure 5 Load-Deflection Diagrams for Column Specimens Tested under 25 mm Eccentricity

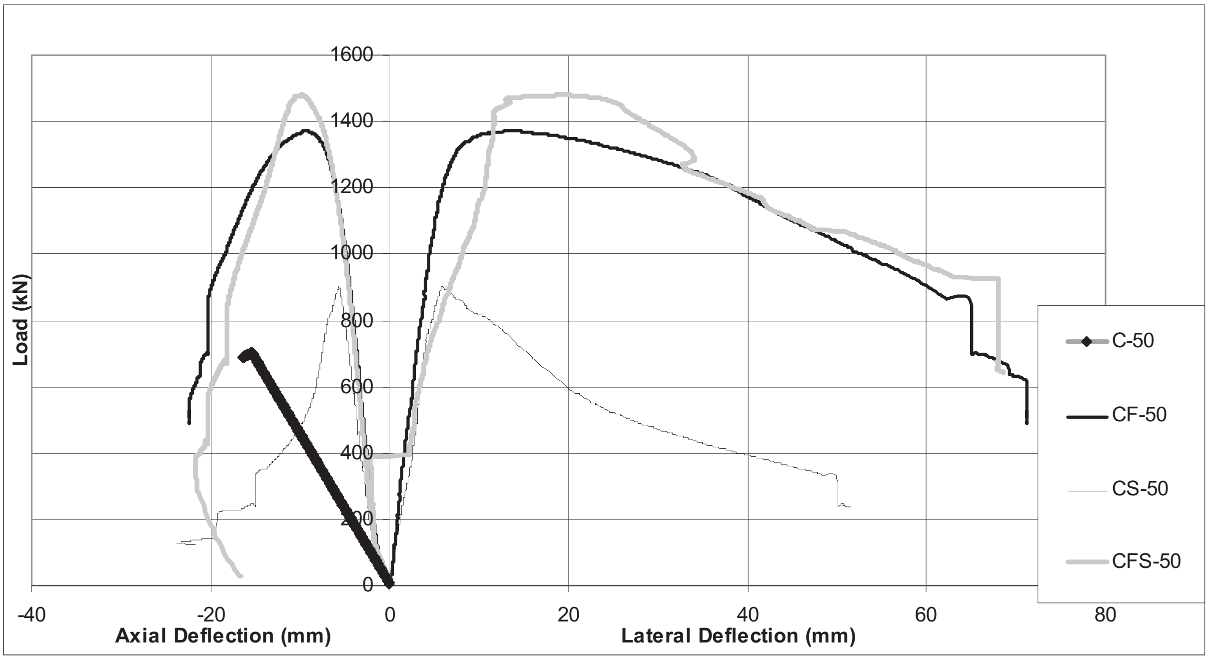

Figure 6 Load-Deflection Diagrams for Column Specimens Tested under 50 mm Eccentricity

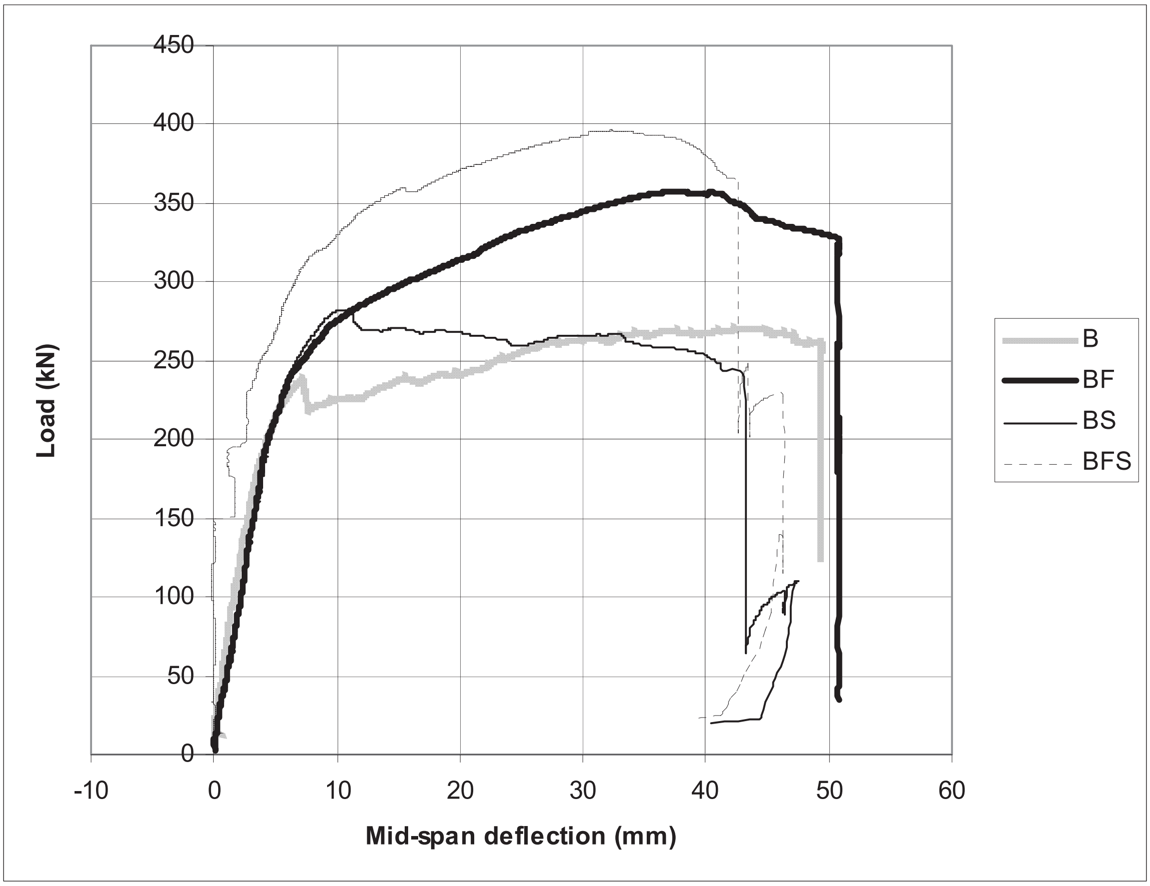

Figure 7 Pure Bending Deflection Diagrams

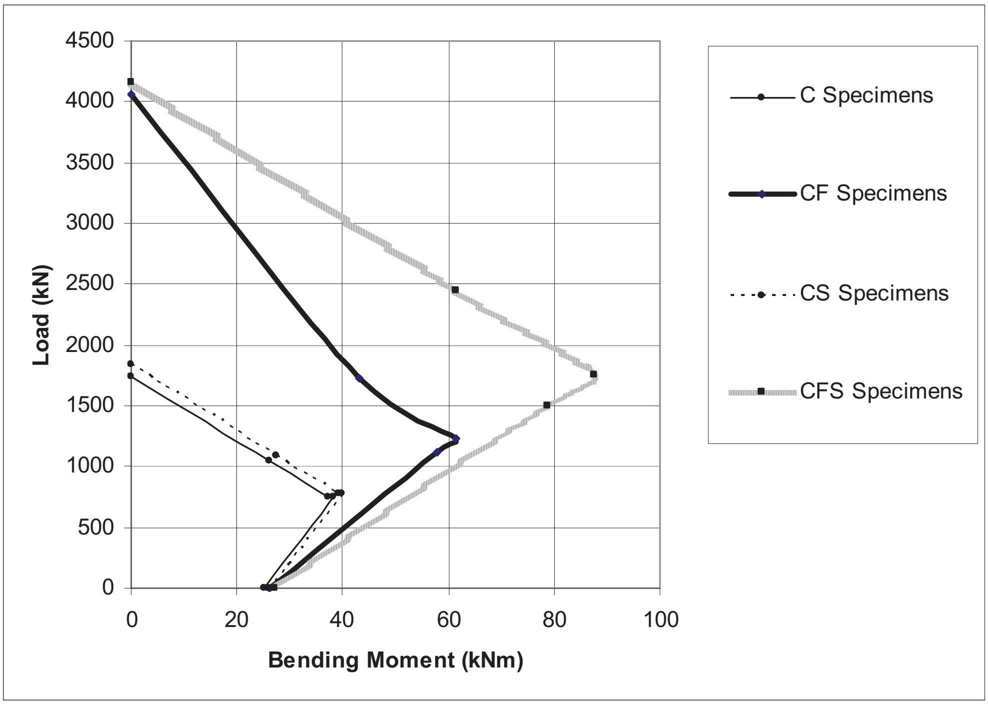

Figure 8 Theoretical Interaction Diagrams Determined by Theoretical Calculation [Lam and Teng (11) and Warner et al. (12)].

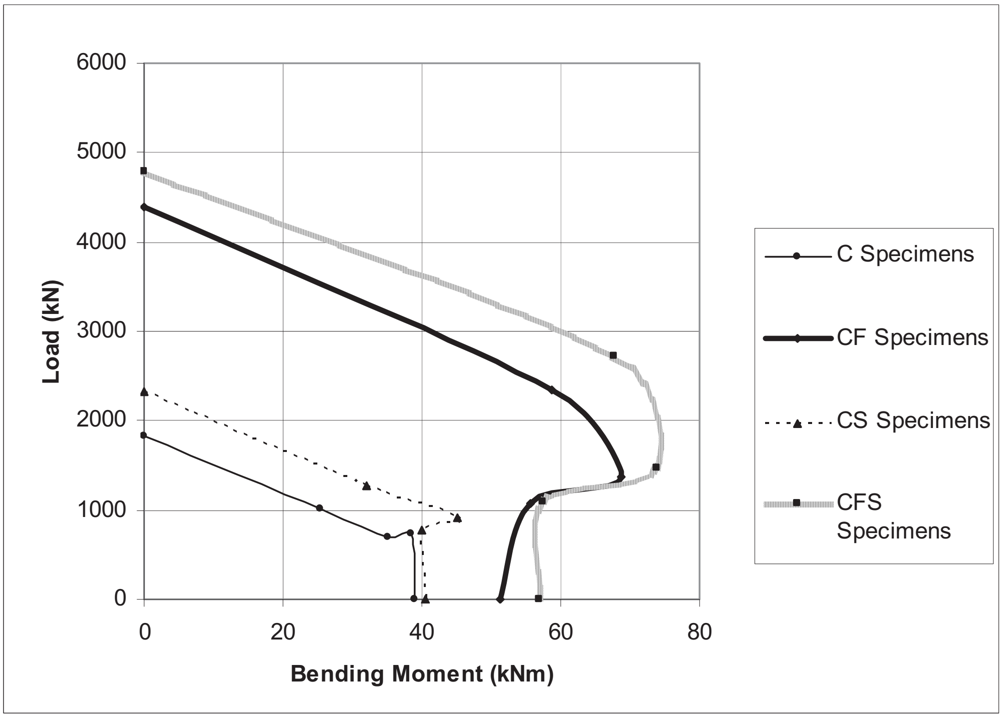

Figure 9 Interaction Diagrams Determined by Experimental Values

Table 1 Configuration of Specimens

Specimen No	Diameter (mm)	Height (mm)	Steel Fibre	Wrapping FRP	Type of test	Test load Eccentricity (mm)
C-0	205	925	No	No	Column	0
CF-0			No	3-layers CFRP		
CS-0			1%	No		
CFS-0			1%	3-layers CFRP		
C-25			No	No	Column	25
CF-25			No	3-layers CFRP		
CS-25			1%	No		
CFS-25			1%	3-layers CFRP		
C-50			No	No	Column	50
CF-50			No	3-layers CFRP		
CS-50			1%	No		
CFS-50			1%	3-layers CFRP		
B			No	No	Beam	4-point loading
BF			No	3-layers CFRP		
BS			1%	No		
BFS			1%	3-layers CFRP		

Table 2 Results of Testing Carbon fibre Coupons

Number of Layers	1			3		
Specimen number	1	2	3	1	2	3
Maximum load (kN)	15.82	14.88	15.79	54.25	53.08	48.91
Maximum Deflection (mm)	5.09	4.59	4.8	5.46	5.78	5.2
Thickness (mm)	0.454	0.456	0.453	1.588	1.587	1.59
Width (mm)	38	38	37	38	37	38
Length (mm)	280	280	280	280	280	280
Maximum Stress (MPa)	917	858.73	942.07	899.01	903.97	814.64
Maximum Strain	0.01818	0.01639	0.01714	0.0195	0.02064	0.01856

Table 3 Results of Testing the Four Concentrically Loaded Column Specimens

Specimen	C-0	CF-0	CS-0	*CFS-0
Maximum measured load (kN)	1825.3	4393.4	2325.8	*4791
Maximum predicted load (kN) Lam and Tang (10) , Warner et al., (11)	1742.1	2768.15	1833.5	*2867.4
Maximum predicted load (kN) Warner et al., (11), Razvi and Saatcioglu (12)	1742.1	4067.6	1833.5	*4167.4
Deflection at axial yield (mm)	4.46	19.03	6.22	*
Load at axial yield (kN)	1669.8	4350.8	2282.9	*
Ultimate axial deflection (mm)	9.29	33.40	37.30	*
Ductility method 1	2.08	1.76	6.00	*
Ductility method 2	2.63	0.46	3.89	*
Failure mode	Yield	Yield	Yield	did not fail

* Specimen CFS-0 did not fail

Table 4 Results of Testing the Eccentrically Loaded Column Specimens

Specimen	C-25	CF-25	CS-25	CFS-25	C-50	CF-50	CS-50	CFS-50
Maximum experimental load (kN)	1012.3	2344.8	1278.6	2712.4	701.0	1371.9	904.1	1479.4
Maximum predicted load (kN) Lam and Tang (11) , Warner et al., (12)	1041.9	1649.5	1096.1	1708.3	744.2	1176.2	782.7	1218.1
Maximum predicted load (kN) Warner et al., (12), Razvi and Saatcioglu (13)	1041.9	1726.7	1096.1	2454.0	744.2	1231.1	782.7	1748.4
Deflection at axial yield (mm)	5.209	18.046	6.108	10.555	13.757	9.218	5.917	10.105
Load at axial yield (kN)	1012.3	2271.1	1370.6	2522.8	700.0	1370.6	887.0	1478.0
Ultimate axial deflection (mm)	14.622	29.934	22.336	25.039	14.901	22.478	23.278	21.720
Ductility method 1	2.81	1.66	3.66	2.37	1.08	2.44	3.93	2.15
Ductility method 2	3.63	2.90	5.58	4.64	2.46	1.95	2.73	3.87
Failure mode	Yield	Yield	Yield	Yield	*	Yield	Yield	Yield

Table 5 Results of Testing Beam Specimens

Specimen	B	BF	BS	BFS
Maximum load (kN)	270.96	356.95	282.33	396.25
Yield deflection (mm)	9.27	11.038	10.98	8.49
Load at yield deflection (kN)	237.59	242.73	281.61	251.49
Ultimate deflection (mm)	43.70	49.153	36.31	43.04
Ductility method 1	4.71	4.45	3.31	5.07
Ductility method 2	9.41	11.67	3.52	11.93
Failure mode	Yield	Yield	Yield	Yield