# BEHAVIOUR OF FRP WRAPPED SQUARE RC COLUMNS UNDER DIFFERENT LOADING CONDITIONS

**Muhammad NS HADI**
Assoc Professor
University of Wollongong
School of Civil, Mining and Env Eng, Wollongong NSW 2522 Australia
*mhadi@uow.edu.au*

**Ida BR WIDIARSA**
Mr
University of Udayana, Bali 80361, Indonesia, currently a PhD Scholar at the School of Civil, Mining and Env Engineering, University of Wollongong, Wollongong, NSW 2522, Australia Affiliation
*ibrw943@uow.edu.au*

## Abstract

This paper presents results of testing square RC columns wrapped with FRP. The influence of the number of FRP layers and the magnitude of eccentricity were studied through experimental. A total of 16 short square reinforced concrete columns wrapped with CFRP were investigated. The columns had the dimensions 200 mm x 200 mm x 800 mm and a round corner with radius of 34 mm. 12 columns were tested under compressive loading and four columns were tested under flexural loading. Based on the number of CFRP layers, the columns were grouped into four: no-layer (unwrapped), wrapped with one layer, wrapped with three layers, and wrapped with two layers after the application of one vertical layer of CFRP straps. From each group, one column was tested under concentric loading, one column was tested under 25 mm eccentric loading, one column was tested under 50 mm eccentric loading and the last column was tested under flexure loading. The results have shown that wrapping column with CFRP composite increase the capacity and ductility of the column.

**Keywords**: CFRP, square reinforced concrete columns, eccentric loading, ductility.

## 1. Introduction

Retrofitting or strengthening reinforced concrete columns by using FRP composites is preferred than by using other materials like steel due to its high strength-to-weight ratio and high corrosion resistance. Several investigations on FRP retrofitted or strengthened concrete columns have been undertaken for many years. Most of these studies investigated the behaviour of columns under concentric loads [1-3] and only a few studies presented investigation of columns under eccentric loads. Consideration of applying eccentric loads was undertaken by researchers due to the reality that most columns in the field are loaded under a combination of axial compression load and bending moment.

Consideration of eccentric loads being applied on FRP strengthened concrete columns has been done by a few researchers. Other than the magnitude of eccentricities, the shape of column cross section is an important factor that influences the confining behaviour of the FRP strengthened concrete columns. Some investigations on FRP strengthened concrete columns under eccentric loads have been done by researchers and mostly concerned on columns having a circular cross section [4-9]. Only a few investigations have studied concrete columns with square or rectangular cross sections [10,11]. Moreover, most concrete columns in the field have square or rectangular cross sections rather than a circular one and may resist eccentric loads as well. Therefore, research on FRP strengthened square or rectangular concrete columns under eccentric loads is still required to be undertaken for the purpose of understanding their behaviour and performance.

This study investigates the behaviour and load carrying capacity of square reinforced concrete (RC) columns wrapped with carbon fibre reinforced polymer (CFRP) composites under eccentric compression loading.

## 2. Experimental Program

Sixteen short high strength reinforced concrete specimens were cast and tested in this study. All columns were tested at the laboratories of the School of Civil, Mining and Environmental Engineering at the University of Wollongong, Australia. Each specimen had a square cross section with a side dimension of 200 mm and having a height of 800 mm. Short columns were designed to avoid the formation of secondary moments due to the slenderness effect. Moreover, the dimensions were chosen to be adaptable with the condition and capacity of the available testing machine in the laboratory. For the purpose of avoiding premature failure and prepare sufficient effect of confinement of the columns, the four corners of the columns were rounded [3,12]. For providing a consistent concrete cover of 20 mm to the steel, a corner radius of 34 mm was then applied to the specimens. The longitudinal and transversal reinforcement of columns were designed in accordance with the Australian Standard for Concrete Structure AS3600-2009 [13]. All columns were designed inadequately as their internal steel reinforcement ratio was about the lowest ratio of that specified by the standard. The purpose of this design was to produce the condition of the column as an old column that has deteriorated and needs to be strengthened. In order to achieve this purpose, the longitudinal reinforcement was provided at the minimum required by the standard, i.e. one-percent of gross cross sectional area of column. In addition, the shear reinforcement provided was also at the minimum shear reinforcement required by the standard ($A_{sv.min}$). Therefore, the columns had four N12 (12 mm diameter deformed bars with nominal tensile strength of 500 MPa) as longitudinal steel reinforcement and R8 (8 mm diameter plain bars with nominal tensile strength of 250 MPa) spaced at 100 mm as transverse steel reinforcement (ties).

The specimens were divided into four groups: four specimens unwrapped, four specimens wrapped with one-layer of CFRP, four specimens wrapped with three-layers of CFRP and four specimens wrapped with two-layers of horizontal (circumferential) CFRP and one-layer vertical (along specimen axis) strap. For the fourth group, specimens were wrapped with two layers of CFRP after the application of one-layer vertical CFRP strap. The specimens were labelled as shown in the first column of Table 1.

Ready-mix high strength concrete supplied by a local supplier was used in this study to construct the test specimens. All specimens were cast from one batch of concrete. The compressive strength of the concrete was determined by conducting tests on 100 mm diameter cylinders. The average 28-day compressive strength of concrete was 79.5 MPa. Specimens were placed under wet hessian rugs and covered with plastic sheets to maintain their moisture conditions. Two types of steel reinforcements were used, deformed steel bars N12 for longitudinal reinforcement and plain steel bars R8 for transversal reinforcement (ties). Tests were conducted to determine the tensile strength of the reinforcing steel. The tensile strength of 564 MPa and 516 MPa were obtained for N12 and R8 reinforcing bars, respectively. Although R8 reinforcing bar was planned to be used, however when it was ordered and based on the test result the 8 mm reinforcing bars looked like L-grade reinforcing steel. The fibre composite used in this study for wrapping the specimens was carbon fibre reinforced polymer

(CFRP).  The fibre available was in the form of rolls which was 100 m in length and 75 mm in width.  Tensile test was also conducted to determine the tensile strength of CFRP according to ASTM D 3039/D 3039M – 08 [14].  Table 2 shows the average results of testing CFRP coupons.  Three coupons were tested for each number of layers.

**Table 1.  Configuration of test specimens**

| TEST SPECIMENS | INTERNAL REINF LONG | INTERNAL REINF TRANS | NUMBER OF CFRP LAYERS | TYPE OF LOADING |
|---|---|---|---|---|
| 0C0 | 4N12 | R8@100 mm | None | Axial, concentric |
| 0C25 | | | None | Axial, $e$ = 25 mm |
| 0C50 | | | None | Axial, $e$ = 50 mm |
| 0B | | | None | Flexure |
| 1HC0 | | | One-layer | Axial, concentric |
| 1HC25 | | | One-layer | Axial, $e$ = 25 mm |
| 1HC50 | | | One-layer | Axial, $e$ = 50 mm |
| 1HB | | | One-layer | Flexure |
| 3HC0 | | | Three-layers | Axial, concentric |
| 3HC25 | | | Three-layers | Axial, $e$ = 25 mm |
| 3HC50 | | | Three-layers | Axial, $e$ = 50 mm |
| 3HB | | | Three-layers | Flexure |
| 1V2HC0 | | | Two-layers with one-layer strap | Axial, concentric |
| 1V2HC25 | | | Two-layers with one-layer strap | Axial, $e$ = 25 mm |
| 1V2HC50 | | | Two-layers with one-layer strap | Axial, $e$ = 50 mm |
| 1V2HB | | | Two-layers with one-layer strap | Flexure |

Note: $e$ = eccentricity

**Table 2.  Properties of CFRP composites**

| | 1-LAYER | 3-LAYERS | 2-LONG. LAYERS AND 1-TRANSVERSAL LAYER | 1-LONG LAYER AND 2-TRANSVERSAL LAYERS |
|---|---|---|---|---|
| Average width (mm) | 18.6 | 19.5 | 18.2 | 17.7 |
| Average thickness (mm) | 0.79 | 1.67 | 1.45 | 1.42 |
| Average gauge length (mm) | 141.7 | 139.7 | 139.5 | 139.6 |
| Maximum stress (MPa) | 854 | 1148 | 793 | 449 |
| Strain at maximum stress | 0.0183 | 0.0203 | 0.0172 | 0.0192 |
| Modulus of elasticity (MPa) | 46507 | 56690 | 46002 | 23329 |

A total of sixteen specimens were tested; twelve columns marked as "C" in

Table **1** and four beams marked as "B".  The Denison 500 tonne compression testing machine was used to test all the specimens.  For compression testing, levelling the column ends was done first in order to obtain a uniform distributed load applied to the entire face.  High strength plaster was used for this purpose.  For applying the eccentric loading on the specimen, a loading mechanism was designed and a new set of loading heads made with high strength steel plate was manufactured.  The loading heads were attached at both ends of the specimen.  The loading head consists of two parts: a 25 mm thick steel plate, called bottom plate which has a ball joint, and a square 50 mm thick steel plate, called adaptor plate.  The bottom plate transfers the load generated by the machine to the adaptor plate through the ball joint which has a designed eccentricity with the specimen.  Then the adaptor plate exerts the load to the specimen.  For concentric loading, only adaptor plates were used for applying the load.

Two different monitoring systems were used for measuring the deflection of the column specimens.  For the concentrically loaded columns, one LVDT was connected directly to the testing machine to measure the axial displacement of the column during the test.  Data read from this LVDT was recorded at the same time with load data recorded by the testing machine.  A second LVDT which was a laser LVDT was also used in addition to the first one for eccentrically loaded columns to measure the lateral deflection of the column.  The second LVDT was placed horizontally near the mid-height of the specimen.  When the specimen and the instrumentation were placed in position and initial calibration was done, the compression testing of the specimen was then started.  The specimen was tested under displacement control with a rate of loading of 0.5 mm/min and the end point position was set at 50 mm.

As mentioned above, four specimens were tested as beams under flexural loading with a span of 700 mm. The loads were applied at 235 mm on each side of the supports. Pure bending was applied to the specimens by means of a four-point loading to determine the flexural capacity of the specimens without axial load. Two rigs top and bottom were used to exert the load that was generated by the Denison 500 tonne compression testing machine to the specimens. The applied load was recorded simultaneously during the test by the testing machine. A laser LVDT that was placed vertically underneath the bottom rig shot the specimen through the provided slot to measure the mid-span deflection of the specimen during the test. A forklift was used for lifting the test rigs and the specimens. The specimen was tested under displacement control, the end point position was set at 50 mm and the rate of loading was set at 0.3 mm/min.

## 3. Experimental Results and Analysis

All columns were tested to failure. For columns without CFRP wrapping, the failure was generally marked with sudden peeling of concrete cover, followed by rupture of the ties and buckling of the longitudinal reinforcement. The failure did not occur exactly at the mid height but still in the test region. Meanwhile, the failure of the columns wrapped with CFRP was initiated by the appearance of FRP ripple at some places on the column sides followed by a snapping sound when the load approached the maximum load. At the maximum load, the first rupture of CFRP resulted in decreasing of the load. The columns continued supporting the load until the rupture of the other CFRP while experiencing a large displacement. The rupture of CFRP and debonding between the CFRP layer and the concrete revealed the concrete expansion at the place where the CFRP failed. The FRP rupture occurred at the corner of the column. Buckling of longitudinal reinforcement and crushing of concrete in compression were also observed.

The ultimate load and the corresponding axial and lateral displacements were recorded during the compression testing and the results are summarised in Table 3. The ductility of the columns was analysed as well to describe the performance of the columns. Two methods were used in the analysis to determine the ductility of the specimens. The first method used the ratio of axial displacement at ultimate load to the axial displacement at yield load. The second method used the ratio of area under the load-axial displacement curve up to the ultimate displacement to the area under the curve up to the yield load. The ultimate displacement was assumed to be the displacement at 85% of the maximum load [15].

**Table 3. Testing results of columns tested under compression loading.**

| SPEC | ULT. LOAD (KN) | DISPL. ULTIMATE LOAD (MM) | | AXIAL DISPLACEMENT (MM) | | | DUCTILITY | |
|---|---|---|---|---|---|---|---|---|
| | | AXIAL | LATERAL | AT YIELD | AT 85% ULT. LOAD | MAXIMUM | METHOD 1* | METHOD 2* |
| 0C0 | 3248 | 5.093 | - | 3.747 | 5.218 | 5.711 | 1.39 | 2.14 |
| 1HC0 | 3279 | 5.073 | - | 3.749 | 5.294 | 14.428 | 1.41 | 2.17 |
| 1V2HC0 | 3522 | 5.415 | - | 3.992 | 8.983 | 21.510 | 2.25 | 4.38 |
| 3HC0 | 3585 | 6.004 | - | 4.340 | 14.179 | 19.219 | 3.27 | 7.13 |
| 0C25 | 1950 | 4.434 | 1.869 | 3.453 | 4.643 | 6.767 | 1.34 | 1.91 |
| 1HC25 | 2076 | 4.874 | 2.253 | 3.527 | 5.489 | 10.320 | 1.56 | 2.67 |
| 1V2HC25 | 2296 | 4.975 | 2.443 | 3.404 | 8.508 | 16.156 | 2.50 | 5.16 |
| 3HC25 | 2269 | 4.871 | 2.113 | 3.571 | 11.561 | 15.343 | 3.24 | 7.43 |
| 0C50 | 1336 | 4.381 | 2.645 | 3.449 | 4.524 | 5.181 | 1.31 | 1.89 |
| 1HC50 | 1433 | 4.633 | 2.315 | 3.602 | 5.567 | 13.781 | 1.55 | 2.83 |
| 1V2HC50 | 1533 | 4.506 | 2.520 | 3.401 | 9.736 | 15.066 | 2.86 | 7.01 |
| 3HC50 | 1534 | 4.454 | 3.193 | 3.350 | 7.106 | 13.554 | 2.12 | 4.58 |

*Refer to Section 3 for definition of the methods

Figure 1 shows the load-displacement curves for columns loaded concentrically. It is clear that the biggest maximum load and maximum axial displacement among the four columns was achieved by wrapping the column with three-layers of CFRP. The maximum load did not increase significantly with the CFRP wrapping. However, wrapping columns with CFRP enhanced the performance of the columns by increasing their displacement at failure, meaning more ductility. The increase of maximum load of 1%, 8.4% and 10.4% relative to the unwrapped column was achieved for Columns 1HC0, 1V2HC0 and 3HC0, respectively. The columns had a similar behaviour before reaching the maximum load.

Figure 2 shows the axial and lateral displacement versus the applied load curves for columns tested under 25 mm eccentric loading. All columns failed in compression. FRP rupture occurred in all wrapped columns before failure. 17.8% and 16.4% increase of maximum load was achieved for Columns 1V2HC25 and 3HC25, respectively. However, Column 3HC25 showed a better performance than Column 1V2HC25. Column 1HC25 also had a better performance than the unwrapped column although a small increase of maximum load was achieved. Columns 1HC25 had only 6.5% higher maximum load than the unwrapped column.

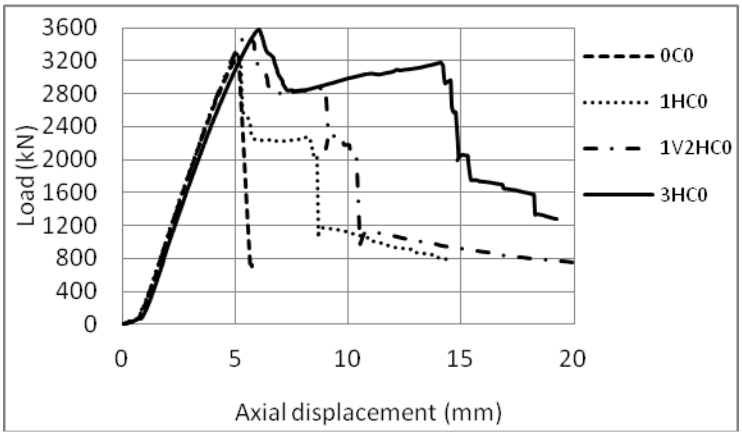


**Figure 1. Load-displacement curves for columns tested under concentric loading.**

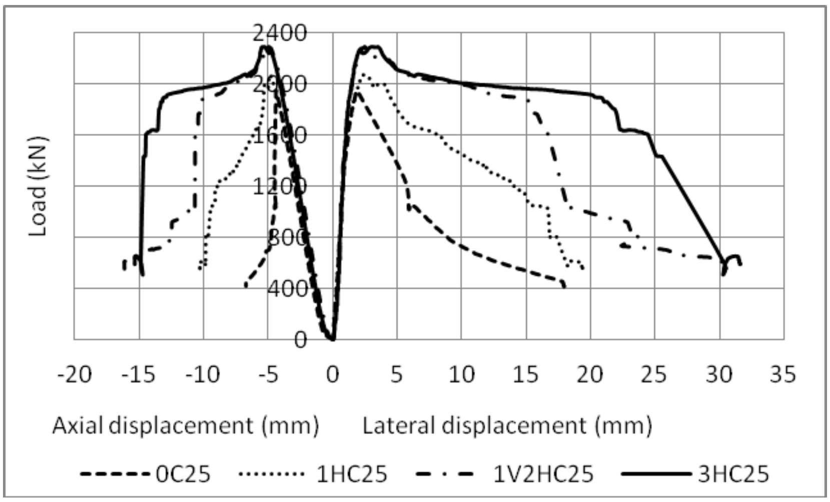


**Figure 2. Load-displacement curves for columns tested under 25 mm eccentricity.**

Figure 3 shows the axial and lateral displacements versus the applied load curves for columns tested under 50 mm eccentric loading. Failure in compression was also observed in all columns with cracks in the tension face near the mid height of the columns. FRP rupture occurred and followed by an increase in displacement after the maximum load was reached. Similar increases of maximum load of 14.8% was achieved for Columns 1V2HC50 and 3HC50, however Column 1V2HC50 had a better performance than Column 3HC50. Column 1HC50 had 7.3% increase in maximum load and a better performance than the unwrapped column.

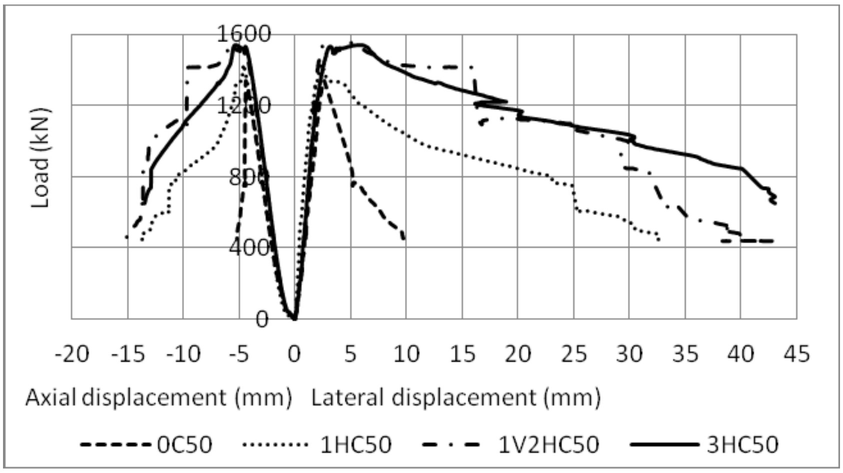


**Figure 3. Load-displacement curves for columns tested under 50 mm eccentricity.**

From testing the twelve specimens, wrapping columns with CFRP increased the maximum load of the columns. A more important advantage was achieved that was all wrapped columns showed a better performance than the unwrapped columns. The performance of column can be indicated with ductility which was reported in Table 3. From the load-displacement curves of the columns, it can be seen that the displacement increases with the increasing the load until approaching the maximum load. Then, for unwrapped columns the load suddenly dropped with peeling of concrete cover. For wrapped columns, FRP rupture occurred when the maximum load was reached and followed by the decrease of load and a sharp increase of displacement. At this stage, the effect of confinement was active to control the behaviour of the columns. Following FRP rupture the applied load was decreased, and the displacement increased until the column failed.

A four-point loading test by means of pure bending test was conducted in order to determine the maximum flexural capacity of the four tested beams. All beams were tested to failure. Figure 4 shows the load-midspan deflection of the tested beams wrapped with different number of CFRP layers. It can be seen that wrapping the beam in the hoop direction with CFRP did not improve significantly the performance of the beam under flexural loading. However, the presence of CFRP straps that were applied longitudinally in Beam 1V2HB produced a large improvement in the load carrying capacity of the beam.

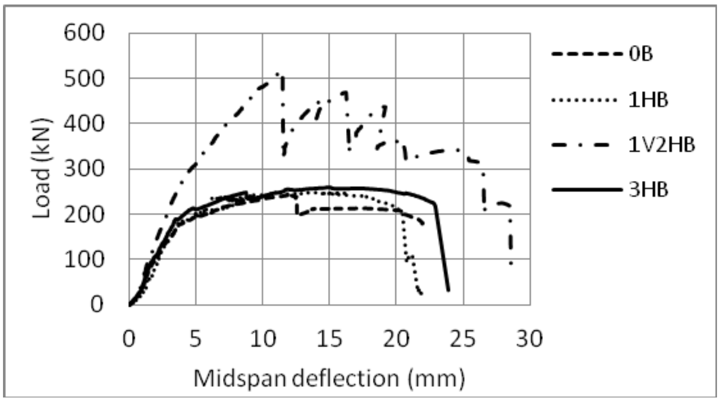


**Figure 4. Load-midspan deflection curves of beams tested under flexural loading.**

Table 4 summarizes the analysis results of the beams. It can be seen that Beam 1V2HB has the highest load and ductility of the four beams. Wrapping the beam in the hoop direction with one layer of CFRP had no influence on the beam ductility. On the other hand, wrapping with three-layers of CFRP increased the beam ductility slightly. The calculations of the ductility of the beams were done using similar methods that were explained for axially loaded columns.

**Table 4. Testing results of beams tested under flexural loading**

| SPECIMEN | 0B | 1HB | 1V2HB | 3HB |
|---|---|---|---|---|
| Ultimate load (kN) | 240.846 | 246.856 | 518.031 | 259.737 |
| Deflection at ultimate load (mm) | 11.940 | 11.029 | 11.847 | 14.952 |
| Yield deflection (mm) | 4.057 | 4.202 | 4.154 | 3.890 |
| Maximum deflection (mm) | 20.328 | 20.236 | 25.472 | 22.778 |
| Ductility, Method 1* | 5.01 | 4.82 | 6.13 | 5.88 |
| Ductility, Method 2* | 9.74 | 10.41 | 15.12 | 12.50 |
| Failure mode | Yield | Yield | Yield | Yield |

*Refer to Section 3.2 for definition of the methods

## 4. Conclusions

Sixteen square reinforced concrete columns with CFRP wrapping were tested in this study to investigate the influence of eccentricity and number of layers on their behaviour and load carrying capacity. Twelve columns were tested under compressive loading and four specimens (as beams) were tested under flexure. The compressive loading test results of the columns indicate that wrapping columns with CFRP increased the load carrying capacity of the columns. An important advantage that was achieved is CFRP wrapping enhanced the performance of the columns by postponing the rupture of the concrete and reinforcement. It increased the column ductility. Similar results were obtained in beams tested in flexure. Increasing the number of the CFRP layers resulted in increasing the load and the performance of the columns. It was revealed that in columns with a large eccentricity, which means with a large bending moment, the presence of CFRP straps produced higher load and ductility than that in columns wrapped horizontally with similar number of CFRP layers. It was also obtained from this study that the eccentricity of loading reduces the load carrying capacity and performance of the columns. Finally, it was proven that wrapping square RC columns with CFRP enhanced the performance of the columns. Wrapping with a minimum of three layers would be suggested to achieve significant results.

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