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BEHAVIOUR OF WRAPPED HSC COLUMNS UNDER ECCENTRIC LOADS

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ABSTRACT

With the technology development on the compressive strength of concrete over the years, the use of high strength concrete has proved most popular in terms of economy, superior strength, stiffness and durability due to many advantages it could offer. However, strength and ductility are inversely proportional. High strength concrete is a brittle material causing failure to be quite sudden and 'explosive' under loads. It is also known that true axial compression of structural concrete columns (axially compressed) rarely occurs in practice.

The stress concentrations caused by the eccentric loading further reduce the strength and ductility of high strength concrete. This paper presents results of testing eccentrically loaded columns externally wrapped with different types of materials. The experimental results show that external reinforcement can enhance the properties of high strength concrete columns.

Keywords: high strength concrete, columns, ductility, wrapped, eccentric loads, FRP

1. INTRODUCTION

The use of high-strength concrete columns has proved most popular in terms of economy, superior strength, stiffness and durability. With the increase of concrete strength, the ultimate strength of columns increases, but a relatively more brittle failure occurs. The lack of ductility of high strength concrete can result in sudden failure without warning in some structural members. Previous studies have shown that addition of compressive reinforcement and confinement will increase the ductility as well as the strength of the material section. Concrete, confined by transverse ties, develops higher strength and ductility. Studies conducted by some investigators on the improvement of the ductility of high strength concrete members have proven that the use of the spiral confinement is more effective and beneficial in the improvement of performance of concrete members [1].

In recent years, FRP wrapping in lieu of steel jacket has become an increasingly popular method for external reinforcement in which FRP offers improved corrosion and fatigue resistance compared to the steel reinforcement. The high tensile strength and low weight make FRP ideal for use in the construction industry. Another attractive advantage of FRP over steel

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straps as external reinforcement is its easy handling, thus minimal time and labour are required for installation [2]. However, research studies conducted to date on external confinement of concrete columns have mainly concentrated on concentric loading. In practice, very few structural concrete columns are concentrically loaded. Even in a column nominally carrying only axial compression, bending action is almost always present due to unintentional load eccentricities and possible construction error. Also, there are many columns where an eccentric load is deliberately applied. Therefore, studies of concrete columns under eccentric loading are essential for its practical use.

This study investigates the benefits of external confinement using FRP and steel straps on high strength concrete columns under eccentric loading and compares the effectiveness of the types of external reinforcement.

2. EXPERIMENTAL PROGRAM

2.1 Objective

The objective of the experimental program in this study is to investigate the behaviour of external reinforced high strength concrete columns (no internal reinforcement) subjected to eccentric loading and to evaluate the effectiveness of external confinement. Internally reinforced columns are cast and tested as reference. Proven by previous studies, the major parameters affecting the behaviour of concrete columns confined with external reinforcement are the type of fibres; the number of layers and the shape of cross-section. As the influence of cross section is already well known, this study is limited to circular columns under eccentric loading.

The testing variables selected for this study are: (1) the type of reinforcement: internal and external and (2) the type of wrapping materials: unidirectional Carbon, Kevlar, plain weave E-glass and steel straps. Two sets of experiments were undertaken and this paper presents a description of these tests.

2.2 Column Details

2.2.1 Set 1

In the first set of experiments, six circular concrete columns (205 mm diameter and 920 mm height) were cast and tested. Three of the columns were wrapped with three layers of unidirectional fibre reinforced polymers. Two were externally reinforced with galvanised steel straps, each steel strap was 20 mm wide and 0.5 mm thick. Two spacings for the steel straps were used: 10 mm and 20 mm. The final column was internally reinforced with steel helix and longitudinal reinforcement. All the columns were eccentrically loaded until failure with an eccentricity of 50 mm. The testing matrix is summarised in Table 1. As shown in Figure 1, two plates were designed and manufactured in order to apply eccentric loading on the columns. These plates were used on either end of the columns during loading.

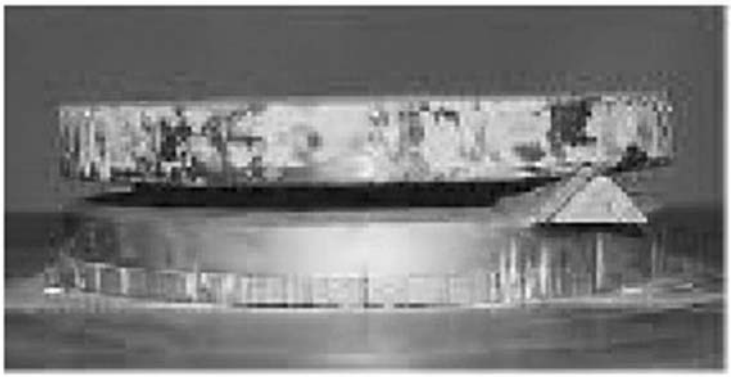

Figure 1. Eccentric Loading Configuration for Set 1

Table 1: Testing matrix for Set 1

Col.	Reinforcing Type	Reinforcing Material
1	External	Three-layered Carbon
2	External	Three-layered E-glass
3	External	Three-layered Kevlar
4	External	Steel Straps at 10 mm Spacing
5	External	Steel Straps at 20 mm Spacing
6	Internal	6 N12 Bars and N10 Helix

2.2.1 Set 2

In the second set of experiments, seven high strength concrete columns were designed for testing. Each column was designed to have a diameter, *D*, of 235 mm for both the haunched ends and 150 mm in the test region, and an overall height, *H*, of 1400 mm. The clear distance between the ends was 620 mm. The dimensions were selected to be compatible with the capacity of the testing machine. There were two major amounts of reinforcement designed for the two internally reinforced specimens. Six RW10 bars were equally spaced around the inside circumference of 110 helix with a pitch of 60 mm through the entire length of specimens and three RW8 bars were confined by equally spaced circular ties at both ends. The geometry, dimension and internal reinforcement details of the column specimens are shown Figure 2.

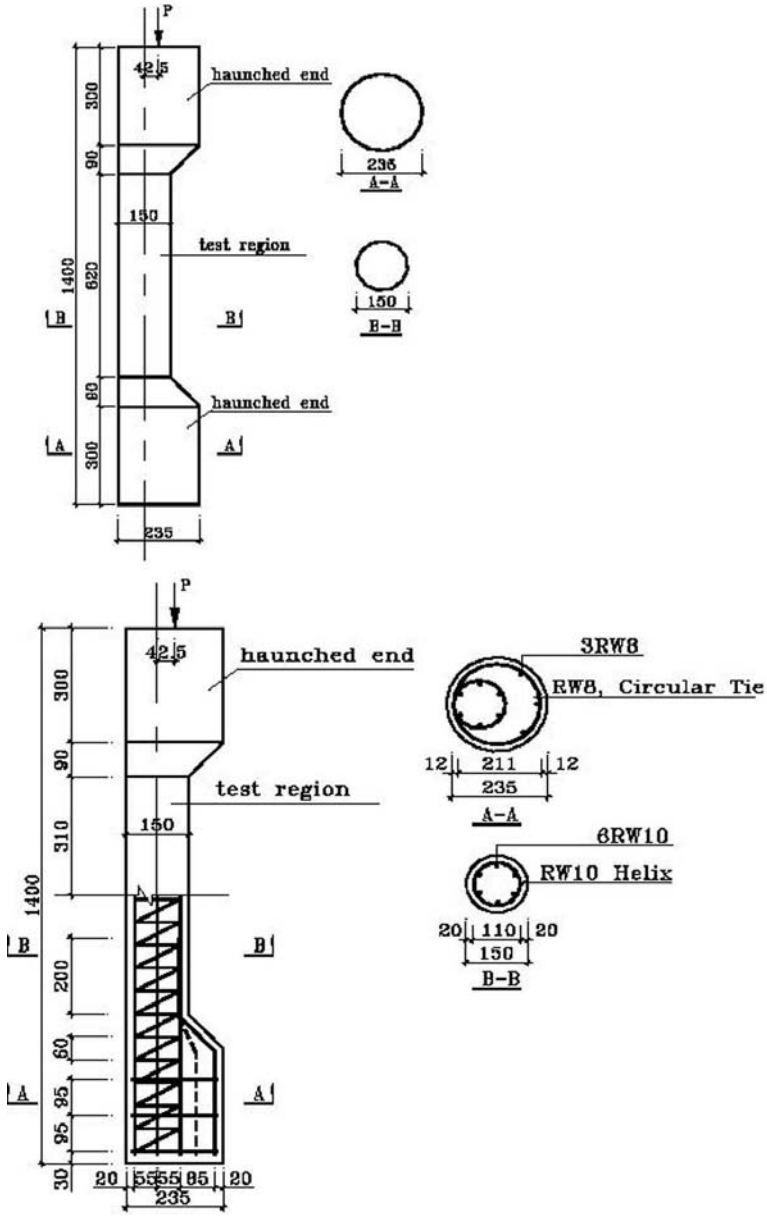

Figure 2. Set 2 column details

Five specimens wrapped continually with FRP had the following configurations: one-layered and three-layered Carbon fibres and one-layered, three-layered and five-layered E-glass. The other two specimens were internally reinforced. The only difference between these two columns was that one specimen was continually wrapped with three-layer E-glass fibres as this specimen was damaged during construction. The testing matrix is summarised in Table 2.

Table 2: Testing matrix for Set 2

Column	Internal Reinforcement	Wrapping Configurations
C1-1	Yes	3-layer Carbon (ends only)
C1-2	Yes	3-layer E-glass
C1-3	No	3-layer E-glass
C1-4	No	5-layer E-glass
C1-5	No	3-layer Carbon
C2-6	No	1-layer E-glass
C2-7	No	1-layer Carbon

All seven columns were tested under eccentric loading, which was achieved by the introduction of haunched ends to each column. This is shown in Figure 2. When concentric loading was applied to the haunched ends of the column specimen, an eccentricity, *e*, of 42.5 mm, was achieved in the test region of each column. The large haunched ends were introduced in the configuration of the column specimens in order to prevent premature failure and to allow for eccentric loading. A steel plate and a knife edge was used at each end of the column in order to provide an accurate concentric loading to the haunched end and to facilitate the adjustment of the direction of loading. See Figure 3.

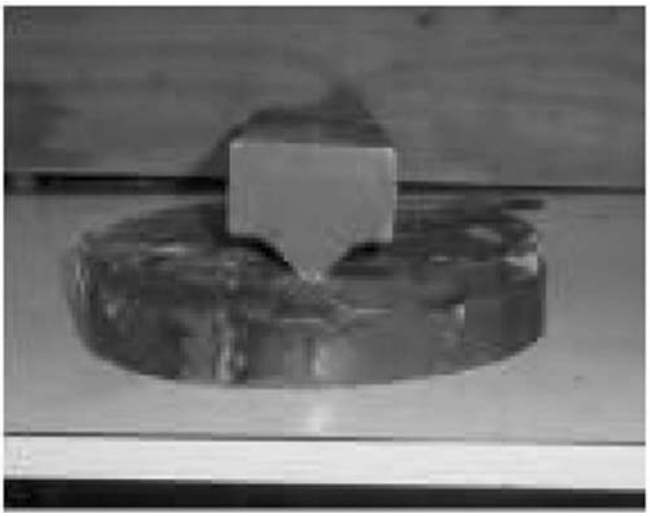

Figure 3. Eccentric loading configuration for Set 2

2.3 Specimen Preparation

All column specimens were cast in the Civil Engineering Laboratory at the University of Wollongong. For the first set of experiments the unconfined compressive strength of concrete was 51 MPa. For the second set of experiments 103.1 MPa was achieved for batch C1 and 95.9 MPa for batch C2.

For the first set of experiments, the three types of fibre reinforced polymers used were Carbon, Kevlar and E-glass. An epoxy system consisting of two parts, resin and slow hardener, was used to bond the FRP to the surface of the concrete columns. The process of applying the FRP is known as the wet lay up method and was used to wrap all the columns with external FRP confinement. The band-it method was employed to apply the galvanised straps on the two concrete columns in this study. The galvanised steel straps (hoops) were placed along the length of the column at 20 mm spacing for one column and 10 mm spacing for the second column.

For the second set of experiments, resin was prepared by mixing it with slow hardener in a 5:1 ratio and applied to the concrete surface. Then, the first layer of FRP was applied to the column with an overlap of 25 mm in each revolution. After wrapping the first layer, the second coating of epoxy was applied on the surface of the first layer to allow the second layer of FRP to be applied. This process was repeated until the desired number of layers of FRP were wrapped. A final layer of epoxy resin was applied on the surface of the wrapped specimens. The wrapped column specimens were left at room temperature for about 2 weeks for the epoxy system to harden adequately before testing.

2.4 Testing of Specimens

A hydraulically operated 5000 kN Denison compression testing machine, located in the Engineering Laboratory at the University of Wollongong was used to test the Set 1 columns. All the columns were tested to failure. In the second set, the seven columns were tested to failure using a 900 kN Strong Floor testing machine in the Civil Engineering Laboratory at the University of Wollongong. The load eccentricity was 42.5 mm, which resulted in large *e/r* (eccentricity/column radius) ratio of 0.57.

3. TEST RESULTS

The failure of the columns in all cases was brittle and in the case of the plain (non-wrapped, internally reinforced) specimen, a very explosive failure occurred. In the case of the FRP confined columns, the snapping of the fibres could be heard throughout the loading as the concrete tried to expand. For the two galvanised steel strap reinforced columns, failure was sudden and soundless. In each case the straps may have yielded but did not break. This suggests that the failure of the columns was a direct result of cracking of the concrete in tensile flexure. Table 3 presents the test results for the eccentrically loaded Set 1 columns.

All Set 2 columns showed similar behaviour under the eccentric loading. Although noises of snapping of the fibres could be heard near the failure load, the failure of the column specimens in all cases was characterised by a very loud and explosive failure. The results from experiments conducted on the seven column specimens are shown in Table 4.

Table 3: Set 1 test results

Col.	Ultimate Load (kN)	Axial Deflection (mm)
1	840.0	5.20
2	630.8	4.38
3	906.0	5.50
4	720.0	4.22
5	704.9	3.94
6	636.8	--

Table 4: Set 2 test results

Column	Ultimate Load (kN)	Axial Deflection (mm)
C1-1	836.4	0.753
C1-2	525.5	1.983
C1-3	601	2.4
C1-4	736.8	1.45
C1-5	791.5	1.405
C2-6	669	1.771
C2-7	644.6	--

4. OBSERVED BEHAVIOUR

4.1 Set 1

The internally reinforced specimen exhibited brittle failure under the eccentric loading. The concrete cover started to fall away due to lateral dilation under the loading. However, even after the concrete cover had spalled, the confined core continued to carry an increasing load. Failure

of the Carbon fibre jacketed column was marked by brittle rupture of the hardened fibres at the bottom of the column. Failure was sudden and quite explosive. During various stages of loading, snapping sounds could be heard, which were attributed to the cracking of the concrete and the stretching of the hardened fibres. The test results show that this column could withstand much higher ultimate load than the internally reinforced column. This reveals that carbon confinement could provide significantly greater confining pressure to the high strength concrete column.

Failure of the E-glass wrapped column specimen was marked by fibre rupture at the top of the column. Although it was sudden, the failure could be predicted by the appearance of white patches at the top of the column as the result of the fibre stretching. Layers of E-glass were torn as a result of the eccentric load applied to the column. As the external E-glass confinement tried to prevent the concrete from expansion under loading, it was ruptured when the tensile stress, applied by the concrete lateral expansion, became too large. The results show that the load carrying capacity of this column wrapped with E-glass was slightly lower than the internally reinforced column.

One sheet of Kevlar, 920 mm wide (rather than the roll of tape) was used to wrap the Kevlar wrapped column. The failure mode of this column was similar to that of E-glass specimen: fibres were ruptured at the top end of the column. Cracking of Kevlar fibre could be heard throughout the testing with the failure of the column signified by a loud snap of the Kevlar jacket. The largest load carrying capacity was achieved by this column compared to other eccentrically loaded columns. This is contributed to the external confinement in terms of continuous sheet. Also, the failure was sudden and loud.

It was found that the galvanised steel strapped column (10 mm spacing) failed in the tensile bending region under eccentric load. Failure occurred in the space between two straps. This can be explained as a result of there being no reinforcement in this region. However, the crack was much narrower and failure occurred closer to the bottom of the column when compared to the column with steel straps at 20 mm spacing. The failure was brittle and soundless.

Failure of the 20 mm spaced galvanised steel strapped column was similar to that of the other galvanised steel strap wrapped column, in that the cracking of the concrete on the tension side marked the failure. Also evident is that the failure, again occurred in the region between the galvanised steel straps and the straps themselves, again, did not show any sign of failing. As the increased spacing of straps resulted in a larger area of the column being unreinforced, the column failure occurred with a substantial crack in the concrete. The results shown in Table 3 confirm that larger spacing between the straps results in a lower load carrying capacity.

4.2 Set 2

The loading on the internally reinforced specimen (C1-1) wrapped with Carbon at both ends resulted in the spalling of the concrete cover. The final sudden failure of this column was due to the yielding of steel reinforcement. Although defects existed in the haunched ends of this column, the failure of this column did occur in the unwrapped test region as designed, which proved the effectiveness of wrapping using Carbon fibres at the ends.

The internally reinforced column (C1-2) was damaged during construction and hence it was patched and then wrapped with E-glass. Ultimate failure occurred in the patched location of the column. This confirmed that the final failure was marked by the fracture of the E-glass fibres as a result of lateral expansion under axial eccentric loading, preceded by the crushing of concrete in the patched part. The results shown in Table 4 confirm that the influence of defects on the load carrying capacity, which is much lower than that of the internally reinforced column

with similar configuration.

The failure of all unreinforced E-glass wrapped specimens was marked by the rupture of the E-glass fibres. However, the externally wrapped E-glass was ruptured in the hoop direction only for 3-layered E-glass column, while for 1-layered and 5-layered specimens, the fibres were torn multi-directional and in the longitudinal direction besides hoop direction, respectively.

Approaching failure load, the appearance of white patches could be discerned, which indicated the yielding of E-glass and resin. Snapping noises were heard before the ultimate failure, revealing the yielding of FRP composites and debonding between the layers of wrapping.

For the one-layered E-glass wrapped column (C2-6), the inner side of the wrapping remained bound together with concrete even after failure, indicating that this column achieved the best bond between the concrete and FRP. This is a possible explanation for this column having a higher ultimate load carrying capacity than the single layered Carbon column (C2-7).

For the unreinforced columns, the final failure of the two Carbon wrapped columns was more explosive and sudden when compared to the E-glass wrapped specimens. This is due to delamination of fibres between layers which was accompanied by a simultaneous fracture of Carbon fibres and the concrete core.

The experimental results from the six wrapped columns show that the Carbon wrapped columns generally out-performed the E-glass wrapped columns. The three-layered Carbon specimen exhibited 7% and 23% increase over the five-layered and three-layered E-glass specimens, respectively. The three-layered and single layered Carbon columns exhibited 7.4% and 7.2% increase in ultimate load over the five-layered and three-layered E-glass columns, respectively. This proves that Carbon fibres are more effective than E-glass for external confinement.

However, the single layered E-glass column achieved higher ultimate load than the single layered Carbon column due to the better bond.

The comparison made between the two Carbon wrapped columns shows that increasing the number of layers from 1 to 3 increased the ultimate load by 23%. This again indicates that higher ultimate load could be achieved by increasing the number of layers.

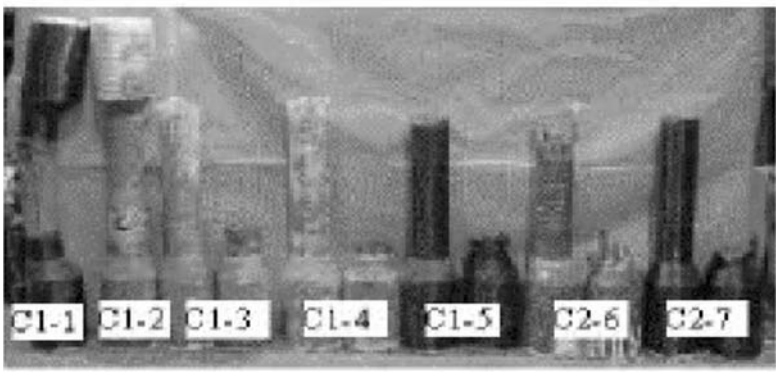

Figure 4. Set 2 columns after failure

In order to evaluate the effectiveness of external confinement under eccentric loading as opposed to the internal reinforcement, a comparison between C1-1, C1-3, C1-4, C1-5 and C2-7

was made. Although C1-2 is one of the internally reinforced columns, it was not used here for comparison due to the significant defects that existed in this column. The three-layer Carbon wrapped column achieved the ultimate load of 791.5 kN, which is just 5% lower than the high strength concrete column internally reinforced with high strength steel. This confirms that the external confinement with three-layer Carbon is nearly as effective as the internal reinforcement with high strength steel. For the E-glass wrapped columns, the ultimate load achieved by the single layered Carbon wrapped column was decreased by 23% compared to the internally reinforced column. Figure 4 shows Set 2 columns after failure.

5. CONCLUSIONS

The work carried out in this study involved two sets of testing: six circular columns where eccentric loading was applied through especially designed loading mechanism and seven columns with a geometry to allow the application of eccentric loading. The objective was to evaluate the effectiveness of the various types of external reinforcement. The results from both sets of tests allow the following conclusions to be drawn:

- The experimental results clearly demonstrate that composite wrapping can enhance the structural performance of concrete columns under eccentric loading to some extent. However, the enhancement is not as significant as that of columns under concentric loading as suggested by previous studies.
- The test results also indicated that the Carbon fibres provided the greatest amount of confinement, and had significantly better results, if the external confinement was achieved by the application of FRP in tape.
- The external confinement with galvanised steel straps improved the strength of the column to a certain extent. The brittle, sudden, soundless failure of the galvanised steel strap wrapped columns showed that the galvanised steel straps had very little effect on improving the ductility of the columns.
- The E-glass proved to be the weakest reinforcing material in this study. The ultimate load achieved by the E-glass wrapped specimen was even lower than that of the internally reinforced column.

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