Experimental study of circular hollow reinforced concrete column strengthened with partial Carbon Fibre Reinforced Polymer (CFRP) confinement

R Ismail1,2, R S M Rashid2, F A A Zakwan1 and F Hejazi2
1Faculty of Civil Engineering, Universiti Teknologi MARA, Cawangan Pulau Pinang, 13500 Permatang Pauh, MALAYSIA.
2Dept. of Civil Engineering, Faculty of Engineering, Universiti Putra Malaysia, 43400 Serdang, MALAYSIA.

E-mail: ruqayyah812@uitm.edu.my

Abstract. Structural strengthening with Carbon Fibre Reinforced Polymer (CFRP) confinement has been widely used in civil engineering applications. However, the use of CFRP has always triggered environmental and sustainable issues due to its hazardous manufacturing and disposal process. By using partial CFRP confinement, the use of CFRP as the strengthening material could be reduced. The circular hollow reinforced concrete column is commonly used in seismic zones due to its self-weight reduction and better structural efficiency of strength/mass and stiffness/mass ratios properties. However, up until today, the understanding of circular hollow reinforced concrete column behaviour still lacks, especially with CFRP partial strengthening confinement. Therefore, this paper is testing a 6 full-scale circular hollow reinforced concrete columns with 2 m height, 250 mm of outer diameter, and 110 mm of inner diameter. The behaviour of the unconfined circular hollow column will be compared with partial CFRP confinement under axial load. The circular hollow reinforced concrete column with partial CFRP confinement is proven to be able to strengthen circular hollow column effectively through this study.

1. Introduction

CFRP strengthening technique is one of the most used technique nowadays, especially for concrete column structure confinement. CFRP strengthening has become one of the main options in structural strengthening due to its ease of installation and lesser time consumption compared to concrete or steel jacket strengthening. Regardless of the benefit of using CFRP full-confinement, it does come with several limitations. Full CFRP confinement experienced sudden failure explosion without early warning, since no initial crack or spalling can be seen. Furthermore, common issues such as air voids and de-bond between CFRP and concrete surface [1] happened when the improper full CFRP confinement is installed. The use of full CFRP confinement will increase the cost unnecessarily and caused an extreme hazard to the environment due to toxic gasses released during the manufacturing of CFRP. It is harmful not only to the environment but to any people who are directly in contact with this material either during the manufacturing or installation stages [2]. Therefore, the partial CFRP confinement is considered as a reasonable option compared to the full CFRP confinement due to its faster and easy installation, also it is suitable for structures that require moderate strength enhancement [3].
1.1. Circular hollow RC column with CFRP strengthening

The previous research that has been conducted on hollow reinforced column is commonly discussed the application of either confined or unconfined CFRP strengthening. Han et al. [4] have reported that confined circular hollow concrete column does show larger strength and enhanced ductility compared to unconfined concrete. Currently, CFRP is in vogue for reinforced concrete column structures. Several researchers [5–8] have shown that CFRP composite jackets significantly enhance flexural and shear strengths, as well as the ductility of bridge piers. Even though the advantages of CFRP as strengthening material for a reinforced concrete column is no doubt proven to be effective, the effect of CFRP strengthening to circular hollow reinforced concrete column is also effective as well. However, there's not been enough understanding due to the limited research work conducted on this subject. Karbhari & Seible [9] has reported that in strengthening circular hollow RC column, CFRP is able to enhance the column ductility without any traffic disruption efficiently, this has been proven to prolong the structure durability and reduce the life-cycle costs. The amount of CFRP and the tensile strength are the main parameters which increase the strength and ductility of reinforced concrete structures.

The research on hollow reinforced concrete with CFRP confinement is still considered few compared to any section of solid column [10]. CFRP confinement has proven to be able to enhance concrete strength and ductility, and delays the buckling of reinforcing bars and concrete cover spalling [11]. The application of CFRP confinement not only able to increase the ductility of the hollow column, but it's also able to avoid any slippage caused by insufficient overlapping. Kusumawardaningsih & Hadi, [12] has compared the confinement of circular hollow reinforced concrete column with and without CFRP. The study has proven to be a significant finding. Whereby reinforced columns without CFRP confinement show brittle failure mechanism, while the ones with CFRP show a more sustained higher ultimate load and larger axial deflection.

The previous study by [13–16] reported that the implementation of CFRP on circular hollow reinforced concrete column had increased its strength capacity, but its triaxial stress confinement turned out to be very weak. Wong et al. [17] have reported that the presence of an inner void reduces the effect of external FRP confinement, but this loss of confinement effects could be compensated by using an appropriate steel tube as the inner confinement. Chin et. al [18] has reported that CFRP confinement has significantly strengthened the shear-critical hollow bridge columns and able to transform shear failure to flexure. This finding was also supported by Yeh et al. [19] where the experimental study on seismic performance of CFRP confinement has effectively improved both ductility and shear capacity of hollow reinforced concrete piers. However, the performance of these CFRP jackets when applied to hollow columns is still considered uncertain due to limited experimental work available.

2. Experimental program

2.1. Specimen preparation

In preparing the specimen, 2 phases of concrete works were conducted. The first stage is preparing the foundation part of the column to create a rigid base to the specimen. Wooden formwork with 800 x 800 mm were prepared with 4 holes for the anchor bolts. The column reinforcement is prepared as well before the casting of the first stage of concrete works. A local supplier supplied a 30 MPa nominal compressive strength concrete with a 130 mm slump. During the concrete work process, a vibrator is used to ensure the compactness of the concrete. Before the second phase is carried out, strain gauges for the reinforcement were installed in the front and back of the column at three positions every 500 mm height. To cast circular hollow reinforced concrete column, two diameter PVC pipes, 250 and 114 mm for the outer and inner circular hollow column were used. The same process which involved the use of vibrator and the curing process as the first phase were repeated. A 30 MPa concrete was supplied by the same local supplier from the previous first phase concrete work. Details of the dimensions and reinforcement are given in figure 1.
2.2. \textit{FRP wrapping and curing process}

Carbon fibre sheets from MBrace CF 130 was bought as a single layer unidirectional fabric. This material was supplied by BASF Chemical Company with a thickness of 0.165 mm/ply and 300 g/m² area weight. To determine the properties of the used CFRP material, a tensile test was carried out on two layers of three CFRP coupon strips. The testing was conducted by using Universal Testing Machine: Instron ESH at Lightweight Structural Laboratory, Universiti Teknologi MARA, Shah Alam. During the tests, specimen dimension, loading, and strain measurement for each CFRP coupon was in accordance with ISO-10406-2, (Fibre-Reinforced Polymer (FRP) Reinforcement of Concrete - Test Methods). All data recorded were taken from the average of three prepared CFRP coupon strip for the tests, and considering the actual width and the nominal thickness of the CFRP.

\begin{table}[h]
\begin{center}
\begin{tabular}{|l|c|c|c|}
\hline
CFRP Specimen & Tensile Strength (MPa) & Elastic Modulus (GPa) & Ultimate Strain (%) \\
\hline
CFRP Strip 1 & 3065.60 & 224.90 & 1.66 \\
CFRP Strip 2 & 3108.27 & 230.71 & 1.43 \\
CFRP Strip 3 & 3405.93 & 223.30 & 1.70 \\
Average & 3193.27 & 226.30 & 1.60 \\
\hline
\end{tabular}
\end{center}
\caption{FRP coupon test results.}
\end{table}

Before the CFRP strips were installed, a layer of primer was applied to the whole specimen and 24 hours of setting time is required before the CFRP strips installation could be carried out. The CFRP
adhesive were then mixed with 2 provided epoxy resin and slow hardener. Ratio 4:1 were used as recommended by the manufacturer.

2.3. Testing specimen
All circular hollow reinforced concrete column specimen compression was tested at Structural Laboratory, Department of Civil Engineering, Faculty of Engineering, Universiti Putra Malaysia, Serdang. A total of 6 column specimens were prepped with strengthening material each time before every test is carried out. Vertical load is applied by connecting a hydraulic jack with a 1500 kN capacity attached to a manual hydraulic pump. The hydraulic pump is equipped with a 38.1 mm piston stroke with the capacity of 38 MPa at the 1st stage and 38.1 MPa at 2nd stage. A 1500 kN capacity of load cell was placed on top of the column steel cap. Data from the LVDTs and strain gauges were recorded digitally through microcomputer, which is connected to the data logger. During the testing, each pump is pressed with 10 kN increment and 5 minutes pause are taken before the next pump proceeds. The pause is to avoid any premature failure and to ensure uniform load distribution through the height of the column. After each pump is pressed, structural observation will be conducted to mark any appearing cracks. When the structure almost reached the failure load, 15 minutes pause are taken to prevent any sudden rupture.

| Specimen Notation | Loading Position | Confinement Material | Strip Spacing (mm) |
|-------------------|------------------|----------------------|-------------------|
| CHC-(1)-A         | Concentric       | Unconfined           | -                 |
| CHC-(2)-A         | Concentric       | Unconfined           | -                 |
| CHC-(3)-A         | Concentric       | Unconfined           | -                 |
| CF-(1)-A          | Concentric       | CFRP                 | 50                |
| CF-(2)-A          | Concentric       | CFRP                 | 50                |
| CF-(3)-A          | Concentric       | CFRP                 | 50                |

3. Results and discussion

3.1. Behaviour of unconfined specimen
For the unconfined circular hollow reinforced concrete column, the failure behaviour and performance were evaluated. The load and displacement relationships were analysed along with the stress and strain relationship. The effect of 3 different loading conditions was investigated to further understand the

![Figure 2. Testing set-up (a) Unconfined specimen (b) Partially confined specimen.](image)

3. Results and discussion
behaviour of the unconfined circular hollow reinforced concrete column. For every loading parameter, 3 column specimens were tested to ensure the accuracy of the presented result. However, to simplify the data presentation for this chapter, only the maximum results are presented for each parameter comparison.

For all tested columns, the dominant failure is located near the top part of the column. Comparison of before and after testing of specimen for each different loads can be seen in Figure 3. All specimens for the unconfined columns failed due to concrete failure. Generally, unconfined column experienced failure with spalling of concrete cover. This commonly will be followed by the outwards buckling of longitudinal reinforcement which causes the concrete to further fractures severely.

![Figure 3. Crack Observation (Unconfined)-Concentric.](image)

3.2. Behaviour of CFRP partially confined specimen

In this observation, all CFRP confined column specimens did not experience any bending failure. Compression failure on the top of the column occurred on all tested specimens. The rupture of the CFRP strip happened only on the top of the column, which reflects the massive failure that occurred on the top of unconfined column specimen. There was no substantial failure in the specimen except for a rupture in the CFRP strip. The highest initial crack occurred was the CFRP confined column specimen under 160 kN concentric loading from back to the right side. The concentric CFRP confined specimen had a rupture and spalling on the concrete cover. The CFRP strips for most of the column specimens experienced similar rupture near the top of the heading load cap.

![Figure 4. Crack Observation (CFRP)-Concentric.](image)

3.3. Unconfined vs CFRP Partial Confinement

A comparison has been made between unconfined specimen with CFRP partial confinement for concentric loads. Through the plotted results, it can be observed that all CFRP partial confined
specimens are following the same linear increment as the unconfined specimen up until it reached the ultimate capacity strength of the unconfined specimen. The strength of CFRP partial confined specimen then continue to utilize the strength capacity of CFRP until failure. The similar increment up until it reached unconfined specimen strength capacity shows passive confinement behavior where the concrete started to fail and dilated laterally, it will activate the function of CFRP strips confinement in holding the column from continuously dilating. Lateral displacement is observed to increase by more than 50% increment. At the maximum load of the unconfined column (690.54 kN), the maximum lateral displacement recorded was 2.37 mm at failure, while in the CFRP partially confinement receiving the same load, the lateral displacement increased up to 4.49 continually up to 8.70 mm at maximum load (940.32 kN). For the vertical displacement of CFRP partial specimen concentric load, 41.7% increment in comparison with the unconfined column can be observed. With CFRP partially confined column, the maximum load increased up to 38% compared to the unconfined column, which proves that the use of CFRP partial confinement is sufficiently able to strengthen circular hollow reinforced concrete column.

Figure 5. Load vs Displacement Behavior.

A comparison between the unconfined column and CFRP partially confined column has been made to describe the for stress-strain relationship. Both conditions of unconfined and partially confined column specimens are showing bilinear relationship of stress versus strain; axial and transverse. The maximum stress recorded by unconfined column is 17.5 MPa with 0.012 of maximum lateral strain, while for the CFRP partially confined at the same maximum unconfined stress, the recorded lateral strain is 0.005. With 58.33% reduction of lateral strain, the CFRP partial confinement has proven to be sufficient in reducing the dilation of the concrete and further delaying the failure of the column specimen. The dilation of column increased linearly for both the unconfined and partially confined columns up to 13.13 MPa, where it can be seen in Figure 6, the unconfined column is started to increase nonlinearly up to failure, while the partially confined column continues to increase up to 47.26% more than unconfined maximum stress until failure. As shown in the previous study, this condition is prevalent for the fully confined CFRP column [20–23], where the existence of CFRP strip acted similarly as the full CFRP confinement in delaying the failure.
4. Conclusion
From the experimental work carried out in this study, the following points can be concluded;

- Failure mechanism experienced by the unconfined circular hollow reinforced concrete column showed severe cracks rupture at 500 mm from the top part of the column, while the partially confined CFRP columns experienced cracks rupture at 150 mm from the top of the column. This shows that the partially confined CFRP can reduce cracks and ruptures.
- A comparison between unconfined CFRP and CFRP shows a bilinear relationship for stress versus strain; axial and transverse. It has been noted that the partially confined CFRP specimens were able to provide sufficient lateral confinement, which reduced the dilation of the concrete and further delayed the failure of the column specimen.
- The strength of the partially confined CFRP column is larger up to 47.26% than the unconfined column. Even with the partially confined circular hollow column, the specimen is sufficiently strengthened.
- The recorded 0.012 lateral strain at the maximum stress in the unconfined column is 58.33% higher than the partially confined column at the same stress value (0.005). This has significantly proved the efficiency of the partially confinement CFRP for circular hollow RC column.

Acknowledgement
This work was fully sponsored by the Universiti Putra Malaysia (UPM) research grant under Putra Grant initiative (Grant Reference No: 9439300). The authors would like to express their deepest appreciation to UPM for providing all facilities and manpower during the laboratory work phase. Full gratitude is also dedicated to Universiti Teknologi MARA (UiTM), Cawangan Pulau Pinang.

References
[1] Park T W, Na U J, Chung L and Feng M Q 2008 Compressive behavior of concrete cylinders confined by narrow strips of CFRP with spacing Compos. Part B Eng. 39 1093–1103 (doi:10.1016/j.compositesb.2008.05.002)
[2] Sen T and Paul A 2015 Confining concrete with sisal and jute FRP as alternatives for CFRP and GFRP Int. J. Sustain. Built Environ. 4 248–64 (doi:10.1016/j.ijsbe.2015.04.001)
[3] Zeng J J, Guo Y C, Gao W Y, Li J Z and Xie J H 2017 Behavior of partially and fully FRP-confined circularized square columns under axial compression Constr. Build. Mater. 152 319–32 (doi:10.1016/j.conbuildmat.2017.06.152)
[4] Han T-H, Yoon K Y and Kang Y-J 2010 Compressive strength of circular hollow reinforced concrete confined by an internal steel tube Constr. Build. Mater. 24 1690–9
[5] Seible F, Priestley M J N, Hegemier G a and Innamorato D 1997 Seismic Retrofit of RC Columns with Continuous Carbon Fiber Jackets J. Compos. Constr. 1(2) 52–62 (doi:10.1061/(ASCE)1090-0268(1997):1:2(52))

[6] Xiao Y 2000 Compressive behavior of concrete confined by carbon fiber composite jackets J. Mater. 12(2) 139–46

[7] Guralnick S A and Gunawan L 2006 Strengthening of Reinforced Concrete Bridge Columns with FRP Wrap Pract. Period. Struct. Des. Constr. 11(4) 218–228 (doi:10.1061/(ASCE)1084-0680(2006):11:4(218))

[8] Gajdosova K and Bilcik J 2013 Full-Scale Testing of CFRP-Strengthened Slender Reinforced Concrete Columns J. Compos. Constr. 17 239–48 (doi:10.1061/(ASCE)CC.1943-5614.0000329)

[9] Karbhari V M and Seible F 2000 Fiber Reinforced Composites – Advanced Materials for the Renewal of Civil Infrastructure Appl. Compos. Mater. 7 95–124 (doi:10.1023/A:1008915706226)

[10] Yazici V 2012 Strengthening hollow reinforced concrete columns with fibre reinforced polymers (University of Wollongong)

[11] Lignola G P, Prota A, Manfredi G and Cosenza E 2007 Deformability of reinforced concrete hollow columns confined with CFRP ACI Struct. J. 104 629–37 (doi:10.1061/(ASCE)1090-0268(2007):11:4(329))

[12] Kusumawardaningsih Y and Hadi M N S 2010 Comparative behaviour of hollow columns confined with FRP composites J. Compos. Struct. 93 198–205 (doi:10.1016/j.compstruct.2010.05.020)

[13] Hadi M N S 2006 Behaviour of FRP wrapped normal strength concrete columns under eccentric loading Compos. Struct. 72 503–11 (doi:10.1016/j.compstruct.2005.01.018)

[14] Yazici V and Hadi M N S 2009 Axial Load-Bending Moment Diagrams of Carbon FRP Wrapped Hollow Core Reinforced Concrete Columns Compos. Constr. 13 262–8

[15] Li X-X 2012 Experimental Study on Behaviour of RC Column Confined by CFRP and Steel Fibre Adv. Mater. Res. 446-449 3146–9 (doi:10.4028/www.scientific.net/AMR.446-449.3146)

[16] Albitar M, Ozbakkaloglu T, Alfonsius B and Fanggi L 2013 Behavior of FRP-HSC-Steel Double-Skin Tubular Columns under Cyclic Axial Compression 1–13 (doi:10.1061/(ASCE)CC.1943-5614.0000510)

[17] Mo Y L, Wong D C and Maekawa K 2003 Seismic performance of hollow bridge columns ACI Struct. J. 100 337–48

[18] Cheng C T, Mo Y L and Yeh Y-K 2005 Evaluation of As-Built, Retrofitted, and Repaired Shear-Critical Hollow Bridge Columns under Earthquake-Type Loading J. Bridg. Eng. 10 520–9 (doi:10.1061/(ASCE)1084-0702(2005):10:5(520))

[19] Yeh Y-K, Mo Y L and Yang Y 2001 Seismic Performance of Hollow Circular Bridge Piers ACI Struct. J. 100 337–48

[20] Fitzwilliam J and Bisby L A 2010 Slenderness Effects on Circular CFRP Confined Reinforced Concrete Columns J. Compos. Constr. 14 280–8 (doi:10.1061/(ASCE)CC.1943-5614.0000073)

[21] Xiao Y and Wu H Compressive Behavior of Concrete Confined by Carbon Fiber Composite Jackets J. Mater. Civ. Eng. 12 139–46

[22] Lim J C and Ozbakkaloglu T 2015 Influence of concrete age on stress-strain behavior of FRP-confined normal- and high-strength concrete Constr. Build. Mater. 82 61–70 (doi:10.1016/j.conbuildmat.2015.02.020)

[23] Ozbakkaloglu T and Lim J C 2013 Axial compressive behavior of FRP-confined concrete: Experimental test database and a new design-oriented model Compos. Part B Eng. 55 607–34 (doi:10.1016/j.compositesb.2013.07.025.)