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Compression Behaviour of Concrete Cylinder with Carbon Fibre Reinforced Polymer (CFRP) Confinement

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ABSTRACT

Carbon fibre reinforced polymer (CFRP) confinement has always been one of the strengthening methods available for a vulnerable concrete column. This paper presents the compressive behaviour of nine circular concrete cylinders with CFRP confinement. Three different specimen conditions considered; full CFRP confinement, partial CFRP confinement, and unconfined (control specimen). Nine concrete cylinders with lOO mm x 200 mm were tested under compression load. It is discovered that full and partial CFRP confinement had improved concrete cylinder ultimate load capacity by 3OO% and l5O% respectively when compared to the unconfined concrete cylinder. With 150% strength enhancement achieved by partial CFRP confined specimen, it is proven that partial CFRP confinement does provide sufficient confinement in enhancing concrete column strength as full CFRP confinement. This finding has led to remarkable discoveries which with lesser CFRP used the functionality of CFRP as strengthening material can still be utilized. Therefore, could contribute significant input to the construction industry in using lesser CFRP for more sustainable material approach.

***Keywords**: CFRP, concrete confinement, strengthening, compression behaviour*

INTRODUCTION

A column is a structural element that supports loads from beams and slabs, then transferring the loads to the foundations. Failure in a column can be catastrophic as it can destroy the whole building. Maintaining an existing structure for its intended purpose for an extended period is a huge challenge since it can be exposed to natural disasters, environmental impacts, or overloading which deteriorating the structures and consequently causing structural failure. Therefore, strengthening and rehabilitation works are needed for deteriorated structures in maintaining and prolong their service life.

Iacobucci *et al.*[1] has reported that carbon fibre reinforced polymers (CFRP) confinement method able to enhance the seismic performance of the concrete column. This finding has led to more research works in utilising CFRP as confinement material in column strengthening [2]–[5]. Further investigation by Elsayed *et al.* [6] and Mahdi *et al.* [4] has also proved that CFRP confinement can improve column ductility and increase the axial load capacity of column structure. Therefore, with these findings and CFRP remarkable advantages such as lightweight, corrosion resistance, fire resistance, adjustable shape, durable, high strength-to-weight and high tensile strength has made it become one of the most preferable confinement materials in strengthening column structure.

Previous research mainly focusing on fully confinement column with CFRP layers, and the effect of the amount of CFRP layers to the concrete column behaviours [3], [5]. The increment of CFRP layers has proven could improve the ultimate strength, the axial strain and the energy dissipation capacity of CFRP-confined concrete column. However, the advantage of using CFRP as confinement material is overwhelmed by its high cost, which indeed increasing the entire cost of the project. Thus, reducing the CFRP confinement area of a column is seen as more economical to the strengthening method, which can be beneficial to the current construction industry. Furthermore, CFRP area reduction could also decrease the effect of CFRP production and disposal issues as sustainable material [7]. Even though the effectiveness of CFRP partial confinement is discovered not as high as the full confinement performance, but it is proven able to strengthen a column structure [8]. However, there is still limited information about partially CFRP-confined concrete structures behaviour available in the literature. Therefore, this has urged more researcher to explore more in this research field.

This paper presents a report on experimental studies of CFRP-confined concrete columns subjected to compression load. This study aims to investigate the behaviour of cylinder concrete strengthened with a different method of confinement; unconfined, partially confined and fully confined. From this research work, the ultimate load, vertical and horizontal displacement, stress-strain relationship and failure modes of the specimens were evaluated.

EXPERIMENTAL PROGRAMME

Specimens

Nine circular concrete cylinders with a diameter of 100 mm and 200 mm in diameter and height were casted and tested under axial compression. Three different conditions of concrete cylinder specimens as illustrated in Figure 1 were used in this study which; unconfined, partially CFRP confined, and fully CFRP confined of concrete cylinders with three specimens for each group. The unconfined specimens were acted as the control specimen to evaluate the ultimate load enhancement of the concrete cylinders through CFRP fully and partially confinement. CFRP was wrapped horizontally around the circumference of the concrete cylinders. Only one layer of CFRP was used to wrap the concrete cylinder for both partially and fully confined concrete cylinder conditions. The partially confined concrete cylinder was wrapped with four strips of 25 mm height of CFRP with a clear spacing of 20 mm each, as shown in Figure 1.

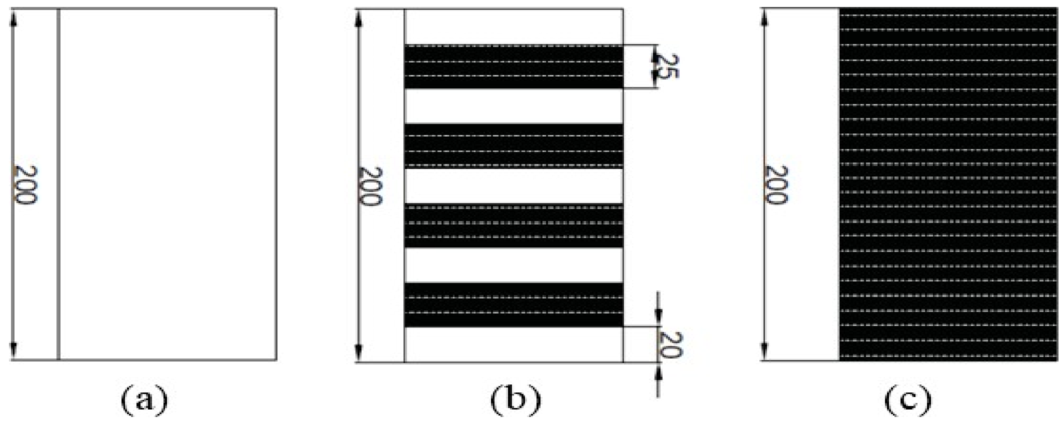


Figure 1: Details of Concrete Cylinder Confinement for; (a) Unconfined Concrete Cylinder, (b) Partially Confined Concrete Cylinder and (c) Fully Confined Concrete Cylinder

The specimens were casted with ready mix concrete prepared by the local supplier of targeted concrete strength grade C30/37. The maximum aggregate size used in the mix was 20 mm. The Wet-layup technique was used to install CFRP to the concrete cylinder [2], [9]. For this technique, the cylinder surface was first coated with adhesive, and then the CFRP layer was attached to the cylinder on top of the adhesive. The adhesive used was a mixture of epoxy resin with hardener at a ratio of 5:1. The CFRP layer was arranged perpendicular to the longitudinal axis of the cylinder specimens. The specimens were placed at room temperature for seven days to dry up the adhesive. The mechanical properties of the CFRP and the epoxy resin used in the confinement process are presented in Table 1 and Table 2, respectively.

Table 1: Mechanical Properties of the CFRP

Ultimate tensile strength (MPa)	Modulus of elasticity (GPa)	Ultimate tensile strain (%)	Nominal thickness (mm)	Unit mass (gm^2)
4354.7	219.0	1.77	0.167	300

Table 2: Mechanical Properties of Epoxy Resin

Ultimate tensile strength (MPa)	Modulus of elasticity (GPa)	Elongation (%)	Compressive Strength (MPa)	Shearing strength (MPa)	Bonding Strength (MPa)	Non-volatile material content (%)
49	2701	2.7	97	16	5.1	99.2

Test Setup

The cylinder specimens were subjected to compression test using 2500kN capacity Universal Testing Machine (UTM) with load increment of 20 kN/mins. Loading was continued until the specimens fail to determine its ultimate load capacity. Figure 2 shows the experimental setup and detailed configuration on the position of strain gauges (SG) and linear variable displacement transducers (LVDT). Horizontal displacement (at the circumference of the concrete cylinder) during compression test were measured using two LVDT (LVDT 1 and LVDT 2) placed at the middle of the cylinder specimen. While for the vertical displacement (vertical deformation on the cylinder length direction) measurement, LVDT 3 was vertically placed parallel to the cylinder length, as shown in Figure 2. Two strain gauges (SG1 and SG2) were attached at the mid-span to measure the horizontal strain and vertical strain of the concrete cylinder specimen. Automatic data logger unit was used to record and store data of strain gauges and LVDTs.

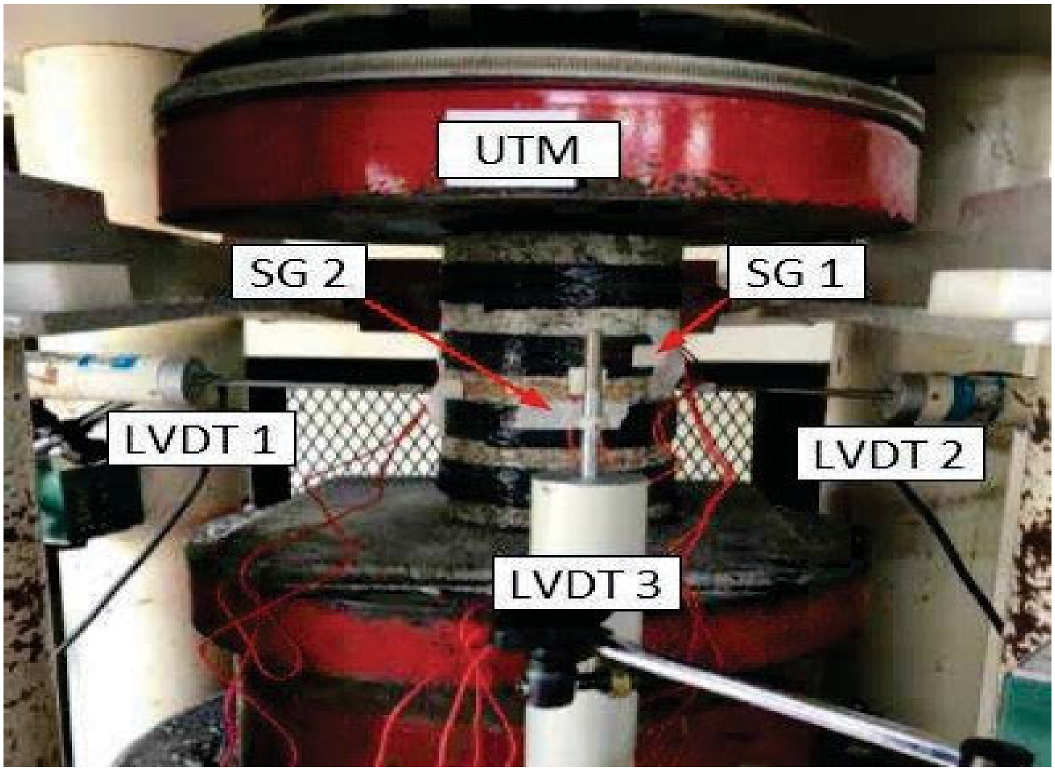
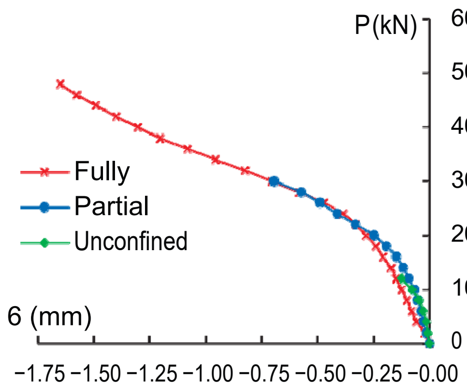


Figure 2: Experimental Setup

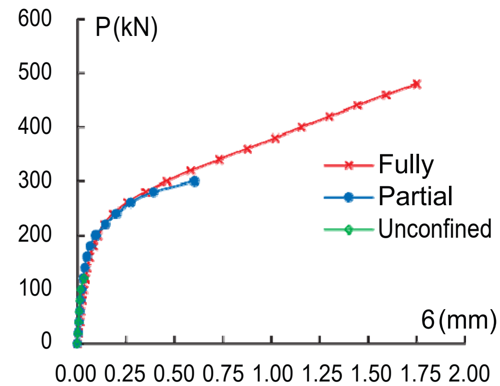
RESULTS AND DISCUSSION

Load vs Displacement

The performance of concrete cylinder specimens subjected to compressive load with different confinement methods can be seen from the load-displacement relationship for vertical and horizontal displacement shown in Figure 3.



a) Load vs vertical displacement



b) Load vs horizontal displacement

Figure 3: Load Against Displacement

The load-displacement relationships of the unconfined, fully confined and partially confined concrete cylinders were slightly different due to the action of the CFRP layer. As been discovered in [6] and [4], the axial load capacity of the fully confined concrete cylinder has increased to 480 kN load, 300% higher than the capacity of the controlled specimen that failed at 120 kN. Table 3 shows the results summary of the experimental test, taken from the average results of three specimens for each condition.

Table 3: Results Summary from the Compression Test

Conditions	Ultimate load (kN)	Compressive strength (MPa)	Displacement		Strain	
			Vertical (mm)	Horizontal (mm)	Vertical (mm/mm)	Horizontal (mm/mm)
Unconfined (control)	120	15	0.13	0.04	6.3×10^{-4}	1.2×10^{-4}
Partially confined	300	38	0.69	0.60	34.7×10^{-4}	19.3×10^{-4}
Fully confined	480	61	1.65	1.75	82.6×10^{-4}	56.7×10^{-4}

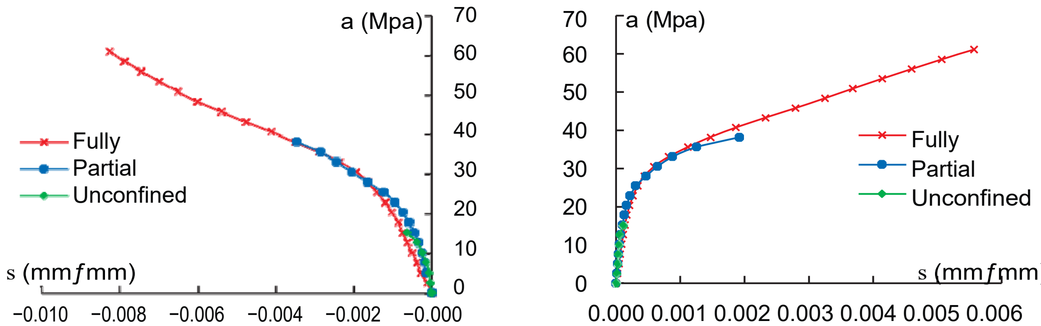
From the testing, it is discovered full CFRP confinement has significantly enhanced the ability of concrete cylinder to sustain load due to the effect of CFRP layer acted as reinforcement in delaying cracking of the concrete cylinder. The CFRP layer also provides additional strengthening after the crushing of the internal concrete by actively confined the cylinder until the CFRP itself ruptured. This was resulting in the higher maximum vertical and horizontal displacements experienced by fully confined concrete cylinders compared to others as listed in Table 3. The vertical displacement response is 1.52 mm bigger than the unconfined concrete cylinder. This large-displacement response exhibits the specimen's endurance in absorbing the load applied with the impact of CFRP confinement.

Partial CFRP confinement had improved the ultimate capacity of the concrete cylinder by 150% higher than the unconfined specimen when it failed at a 300 kN compressive load. That was half of the ultimate capacity of a fully confined concrete cylinder, and high enough for strengthening mechanism. While, the vertical displacement at failure is 0.56 mm greater than the control concrete cylinder, which is more than one-third of the displacement response of a fully confined concrete cylinder.

Reduction in crack propagation contributes to a greater horizontal displacement of CFRP confined concrete cylinder. This is due to the high load absorption capacity by these specimens. Figure 3(b) illustrates the horizontal displacement response with a load applied where a fully confined concrete cylinder has the highest horizontal displacement with 1.75 mm, followed by partially confined specimens with 0.6 mm and the unconfined specimens with 0.04 mm.

Compressive Stress-Strain Curve

Figure 4 illustrates the stress-strain curves (in a vertical and horizontal direction) of the concrete cylinder specimens in diRerent conditions. Stress was calculated by dividing the axial load with the cross-sectional area of the cylinder specimen. The positive value of the strain was assumed for shortening in vertical strain and expansion in horizontal strain. In Figure 4(a) fully CFRP confined concrete cylinder had the highest vertical strain response of 82.6 x 10^{-4} mm/mm followed by partially confined concrete cylinder with 3.5 x 10^{-4} mm/mm, respectively 1211% and 450% higher than the vertical strain of the unconfined concrete cylinder. The strain corresponded to the ultimate compressive stress of 61 MPa and 38 MPa for fully and partially confined concrete cylinder, respectively, significantly higher compared to the unconfined concrete cylinder capacity of 15 MPa. This finding has proven that CFRP confinement could enhance the structural integrity of a concrete cylinder by its capability to sustain high compression stress with significantly large vertical strain.



a) Stress vs vertical strain b) Stress vs horizontal strain

Figure 4: Stress-Strain Relationship

Most of the horizontal strains developed at the middle height of the concrete cylinder as it is the weakest part when encounter compression stress. The horizontal strain delivers confinement pressure that can be sustained by the concrete cylinder under compression to restrain the internal core cracking. High horizontal strain responded to high stress applied to indicate the endurance of the concrete cylinder to sustain high compression stress. Figure 4(b) shows large horizontal strain developed by the fully confined concrete cylinder with 56.7 x 10^{-4} mm/mm followed by partially confined concrete cylinder with 19.3 x 10^{4} mm/mm and unconfined concrete cylinder with 1.2 x 1^{0-4} mm/mm. The partially confined concrete cylinder is less efficient than a fully confined concrete cylinder due to the existence of the exposed areas between the CFRP layer, as shown in Figure 1(b). The arching action of the partially confined area aRected the confining pressure act on the concrete cylinder.

Failure Modes

Besides the load-displacement relationships and stress-strain curves of the concrete cylinders with different confinement conditions, the fracture patterns and the failure modes of the specimens were also being observed in this study. Figure 5 shows pictures of concrete cylinder specimens grouped according to the confinement conditions after the compression test. The specimens categorised by its failure modes according to the fracture pattern seen on the pictures.

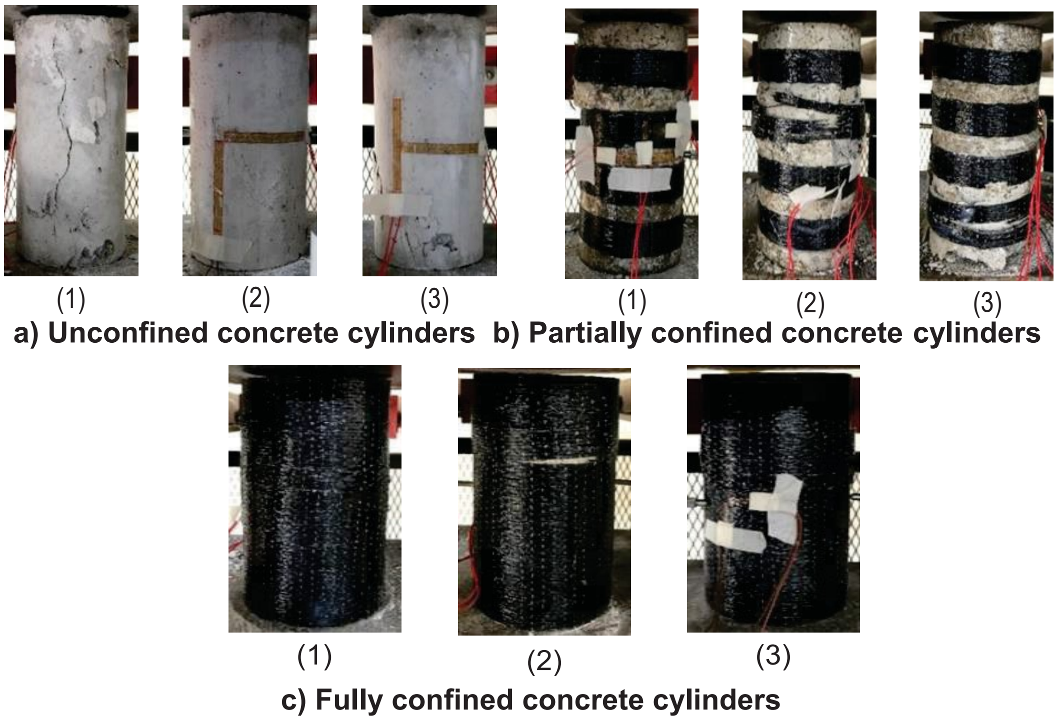


Figure 5: Fracture of the Concrete Cylinders

The failure mode of the specimens was categorised according to the schematic report of typical failure pattern given in [10] and [11]. British Standard Institution [10] asses the compression test of cylinder specimens according to two types of failures; satisfactory and unsatisfactory failures. Unsatisfactory failure might occur because of equipment faulty, the wrong specimen positioning during test or testing procedure not well performed. Typical fracture patterns of cylinder specimens are classified into six types of patterns by ASTM C39 [12]. The description of each type is given as follows:

Type 1: Cone is reasonably well-formed on both ends
Type 2: Cone is well-formed only on one end with vertical cracks existence
Type 3: Columnar pattern of vertical cracking through both ends
Type 4: Diagonal fracture without cracking through ends
Type 5: Top or bottom side fractures
Type 6: Top or bottom side fractures with a pointed end

The two standards had been referred in [13] to classify the failure mode of specimens in their study about the size and shape eRect of concrete specimens subjected to compressive stress. For cylinder specimens, Hamad [13] simplified the category given in [12] into five types of cylinder fractures; (1) cone, (2) cone and split, (3) cone and shear, (4) shear and (5) columnar. The summary of fracture patterns and failure modes classification for the specimens in this study are listed in Table 4.

Table 4: Summary of the Mode of Failure

Specimens	Types of failure by British Standard Institution [10]	Types of fracture by ASTM C39 [12]	Types of fracture by Hamad [13]
a) Unconfined			
- specimen (1)	Unsatisfactory	Type 3	Columnar
- specimen (2)	Unsatisfactory	Type 4	Shear
- specimen (3)	Unsatisfactory	Type 5	-
b) Partially confined			
- specimen (1)	Satisfactory	Type 1	Cone
- specimen (2)	Satisfactory	Type 1	Cone
- specimen (3)	Unsatisfactory	Type 5	-
c) Fully confined			
- specimen (1)	Unsatisfactory	-	-
- specimen (2)	Unsatisfactory	-	-
- specimen (3)	Unsatisfactory	-	-

Unconfined Concrete Cylinder

Figure 5(a) shows three specimens of the unconfined concrete cylinder after failure. All the specimens didn't fail exactly as described in standard due to different concrete cylinder sizes used in this research work compared to the size used in the standard. However, most of the concrete cylinders experienced the same failure preference, as mentioned in [13]. Error in the compression test procedure that could lead to a premature failure of the specimens before achieving the designed compression strength is also considered in presenting these findings.

Specimen 1 was failed with a Type 3, columnar fracture pattern where vertical cracks were observed propagated from one edge to the other. While Specimen 2 undergoes a different pattern of crack propagation where it began at the mid-span and slanting down reaching the lower side edge of the specimen. Specimen 2 failed due to shear with Type 4 fracture pattern. For Specimen 3, which failed with a Type 5 fracture pattern, cracks occur only at the side corner of the edge.

Partially CFRP-Confined Concrete Cylinder

The failure modes of partially CFRP-confined specimens can be seen in Figure 5(b). Two specimens (1 and 2) were failed satisfactorily exhibit Type 1 failure where the cone was reasonably well-formed. Cracking was propagated from the unconfined area near the middle height of both specimens and pieces of concrete were fall off, forming the cone pattern. Specimen 2 was also failed due to the rupture of the second CFRP strip that making an explosive sound. Large concrete crushing occurs, and it falls off when the failed CFRP was removed. Looking at the failure mode ofthese two specimens, CFRP confinement is proven could enhance the performance of concrete cylinder from failing as experienced by the unconfined concrete cylinder.

However, specimen three was failed unsatisfactorily with a Type 5 fracture pattern. The side fractures occur at the left corner, as shown in Figure 5(b). Similar with Specimen 2, the CFRP layer was failed, but for specimen three it was the fourth strip, near the fractured area at the bottom of the specimen. The CFRP rupture happened because it was no longer able to sustain the localised confining pressure that acts around the circumference of the CFRP. However, before failing, the CFRP has delayed thecracking on the concrete by helping it to sustain higher compressive stress.

Fully CFRP-Confined Concrete Cylinder

The final specimens group is a fully CFRP-confined concrete cylinder which can be seen in Figure 5(c). The CFRP layer for all specimens was still intact with the concrete even after failures. There was no apparent concrete damaged seen as the full CFRP confinement has prevented the crack propagation and maintained the solid features of the specimens.

Specimen 1 and 2 experienced CFRP ruptured and concrete damaged at the mid-span and upper part area. The CFRP layers have overlapped due to the shortening of the concrete cylinder subjected to compression load. While specimen three was slightly swollen at the upper part caused by the expansion of the concrete cylinder. This might due to larger compression stress experienced at that part of the area than others. The other possibility might be due to the CFRP layer was at the weakest strength around that area which caused by the confining pressure has reached beyond the CFRP's tensile strength.

CONCLUSION

The performance of a short concrete cylinder partially and fully confined with CFRP has been studied by comparing the results with the unconfined specimens. Full CFRP confinement has increased the ultimate load capacity of the concrete cylinder to 300% compared to the unconfined cylinder. In contrast, the capacity for partially CFRP-confined cylinder had 150% higher than the unconfined cylinder, which still can be considered high enough for cylinder strengthening.

Most of the cylinder specimens were undergone an unsatisfactory type of failure that might result due to equipment faulty or errors in the testing procedure, except for two partially CFRP-confined specimens that failed satisfactorily with a well-formed cone fracture pattern. The unconfined concrete cylinders were failed due to concrete crushing while partially and fully CFRP-confined concrete cylinders mostly failed because of the CFRP rupture. The vague fracture patterns exhibit by the specimens, causing difficulty in relating the failure mode with the confinement conditions.

The use of fully CFRP confinement method for cylinder strengthening can be costly to a particular construction project. Thus, partial CFRP confinement of concrete cylinder offers a more economical alternative to a strengthening project and can be beneficial to the current construction industry. Although its performance is not as high as the full CFRP-confined concrete cylinder, it had proven strong enough for strengthening the concrete cylinder.

LIMITATIONS AND FUTURE WORKS

The tests were conducted to a cylinder type of specimens only due to the fund limitation. Thus, the study only covers the efficiency of the CFRP confinement on the concrete cylinder specimens and application on the other type of structure was not further discussed. The size of the cylinder specimens was designed to facilitate the loading capacity of the Universal Testing Machine in UiTM Cawangan Pulau Pinang.

Further studies should be done on the actual size of column structures typically being used in the construction field. Also, extensive research is required to estimate the long-term capability of the CFRP confinement in providing structural strengthening. This includes studies on other parameters that could affect the performance of any confined structures. For example, is the variation of void ratio to estimate the optimum spacing of the CFRP confinement and contribution of the CFRP thickness to the performance of the confined structures.

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