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# Compressive Strength and Behaviour of Full and Partial CFRP Confined Concrete Columns

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**ABSTRACT**

*Concrete columns encased in carbon fibre reinforced polymer (CFRP) have been extensively explored for usage in civil engineering constructions in recent years. However, the performance of these CFRP concrete systems is still questionable since CFRP application is relatively costly. The study focuses on the axial compressive loadings and strength of two different types of CFRP confinement configurations. Fifteen (15) cylindrical concrete column samples of 1 m height and 200 mm diameter were fabricated, including three (3) control samples (without CFRP) and twelve (12) CFRP cylindrical concrete columns. Two layers of CFRP confinement gave more additional support and strength to the column's samples for both full and partial confinement. Full 2-layers confined columns obtained 65.53% and partial 2-layers confined columns obtained 48.35% higher than the unconfined samples (control samples) on average. The load-displacement and stress-strain results are also discussed in this paper. A full layer of CFRP gave higher compressive strength in this study but partial CFRP confinement gave enough strength to the column which was more than 35% higher compressive strength compared to the control samples on average. The knowledge in this research field can be used as the basis for future structural rehabilitation work.*

**Keywords:** *carbon fibre reinforced polymer (CFRP); reinforced concrete column; compressive strength; partial confinement; fully confinement.*

## 1. INTRODUCTION

A fibre-reinforced polymer (FRP) is a composite material consisting of a polymer matrix and fibre reinforcement. FRPs such as carbon fibre-reinforced polymers (CFRP), basalt fibre-reinforced polymers (BFRP), aramid fibre-reinforced polymers (AFRP) and glass fibre-reinforced polymers (GFRP) have been massively produced around the world [1-2]. FRP composites have been widely utilised for the confinement of existing concrete columns over the past three decades. FRPs had frequently been utilised to upgrade concrete columns in older buildings and bridges. Numerous researchers had proven the significance of this topic, and their study revealed that by employing the FRP wrapping system, the axial compression strength and ductility of concrete columns under pure concentric loading are significantly enhanced. The confinement mechanics and stress-strain properties of FRP-confined concrete had been the subject of much investigation. The results of the study showed that FRP confinement might improve the strength and deformation capacity of circular concrete columns substantially [3-6]

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FRPs had gained popularity as viable options for reinforcing and retrofitting concrete buildings due to their major benefits over traditional construction materials such as steel and concrete for retrofitting and strengthening concrete structures [7-8]. These composites were commonly used as "externally bonded" systems to raise the axial sectional, flexural, torsion and shear capabilities of reinforced concrete structural components, improved structural member stability, serviceability and offered extra confinement [9-10].

Structures should be able to maintain their stability and strength throughout their service life, and fire resistance should be factored into the design. Weather, the climate, natural disasters, excessive loads, poor craftsmanship and other factors can all contribute to structural degradation over time. Retrofitting and strengthening have traditionally been popular options for repairing and reinforcing deteriorating buildings.

Continuous fibre reinforced materials with polymeric matrix (FRP) can be seen as composite, heterogeneous and anisotropic materials having a mostly linear elastic behaviour up to failure. Normal reinforcement materials for FRP include glass and carbon fibres [11]. CFRP is the most popular material used to retrofit and strengthen column structures in civil engineering [12]. Its potential to improve the structure's bending, compressive strength and ductility drew the attention of many academics and industries who wanted to use it. It is well known that reinforced concrete makes up the vast bulk of Malaysian housing constructions.

In recent years, concrete columns confined with CFRP have been widely studied for their use in civil engineering structures. However, the application of these CFRP concrete systems is still limited since the CFRP material is quite expensive. Most researchers and construction industries usually applied full confinement of CFRP or other FRPs on the structures [13-18]. Therefore, this research focuses on partial confinement which is expected to perform well and leads to cost savings. Few previous researchers had used partial confinement in their studies with different configurations [12-14]. Previous researchers such as [19] studied the behaviour of short concrete cylinders partially confined but they used GFRP in their study. CFRP partial confinement had been found to have a great potential in improving concrete strength [20]. Furthermore, debonding can also be decreased by partial confinement. Trapped air can be removed thus improving the bonding between the CFRP, adhesive, and concrete surface. [21] found that the partial CFRP horizontal strip confinement's strength and spacing parameters significantly increased concrete strength. A similar study was carried out by [22] with differences in the CFRP spacing and width. These studies show the promising potential of partial CFRP confinement. The strip spacing and breadth, however, were different from those employed by Barros & Ferreira [22].

In this study, 15 specimens were fabricated and then tested under axial compression loading. The two types of CFRP wrapping used were full wrap and partial wrap. Each type of confinement consisted of 1-layer and 2-layers of confinement. The objectives of this study are to investigate the enhancement in compressive strength of the CFRP confined specimen and to evaluate the behaviour and the failure mode of each specimen.

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*ESTEEM Academic Journal*
Vol. 18, September 2022, 41-54

## 2. MATERIALS AND METHODS

### *2.1 Materials*

Fifteen (15) numbers of reinforced concrete columns of 1m in height and 200mm in diameter were fabricated. Three (3) samples were used as control samples, six (6) samples were fully wrapped and six (6) samples were partially wrapped. The confined samples were divided into two categories which were one-layer CFRP confinement and two-layers CFRP confinement. The sample categories are shown in Table 1. The partial confinement underwent only one type of configuration only and full confinement underwent the configuration as shown in Figure 1 below. The method of confinement was referred to [23-24].

Table 1: Sample Categories

| Sample Type | Confinement | |
|---|---|---|
| | 1-Layer | 2-Layers |
| Control | - | - |
| Partial | 3 | 3 |
| Full | 3 | 3 |

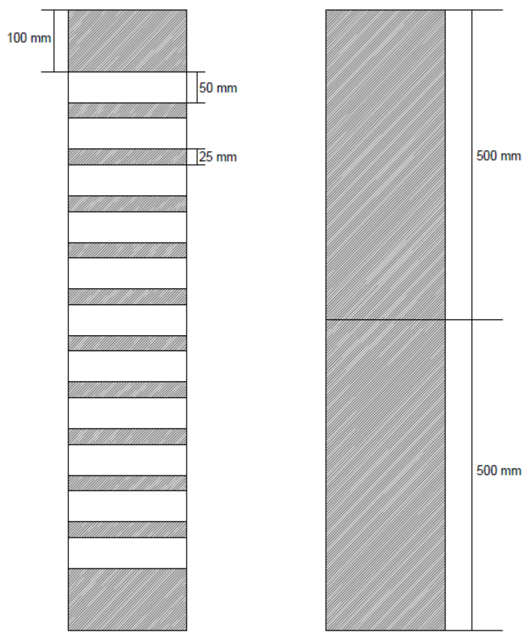


Figure 1: Configuration of Confined Specimens

#### *2.1.1 Concrete*

One batch of ready-mixed concrete was prepared using ordinary Portland cement (OPC) and with a target compressive strength of 30MPa in the concrete factory of Hanson Building Materials Malaysia Sdn Bhd by Guar Bakti Enterprise. The procedure of the concrete mixing was carried out according to the British Standard (BS EN-206-1) [25] for the compressive strength to reach approximately 30 MPa. Table 2 shows the mixed quantities needed for casting the concrete columns with sizes of 1m in height and 200mm in diameter. Moreover, the

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selection of raw materials such as gravel and sand is very important to achieve the targeted strength.

Table 2: Concrete Mix Design

| Component | Quantity (kg/m$^3$) |
|---|---|
| Cement | 300 |
| Water | 172 |
| Fine Aggregate | 878 |
| Coarse Aggregate | 970 |

### *2.1.2 Epoxy Resin and Primer*

Epo Resin Wrap is used as adhesive to bind the concrete columns and CFRP sheet [26]. There are several advantages of Epo Resin Wrap, which are good in high-temperature properties, easy to mix, excellent bond to structural, high tear resistance and harden without shrinkage. The adhesive consists of two components Part A (liquid epoxy) and Part B (liquid hardener). As an adhesive, a two-part epoxy resin that was combined at a certain ratio was mixed [27]. Part A and Part B were mixed at a weight ratio of 100:30 by weight to ensure that the reaction of epoxy was successfully acting as the binding agent. Saturant and hardener are vigorously mixed for five minutes to ensure that all of the components are evenly distributed same as [11]. The layer thickness of epoxy applied to the surface of the concrete column is approximately less than 5mm. Meanwhile, Epo Bond Primer has been used as a primer coating. The detailed properties of epoxy resin and primer provided by LaMaCo System Sdn Bhd are shown in Table 3.

Table 3: Properties of Epoxy Resin and Primer

| Type | Properties | Value |
|---|---|---|
| Epo Resin Wrap | Mixing Ratio | 100: 30 (weight) |
| | Mix Viscosity (25 $^0$C) | 4000(±550) mPa.s |
| | Density | 1.02 g/cm$^3$ |
| | Tg | 90 $^o$C |
| | Compression Strength | 50 N/mm$^2$ |
| Epo Bond Primer | Mix Viscosity (25 $^0$C) | 3500(±250) mPa.s |
| | Density | 1.02 g/cm$^3$ |
| | Compression Strength | 48 N/mm$^2$ |
| | Elongation | 2 % |

### *2.1.3 Carbon Fibre Reinforced Polymer (CFRP)*

LaMaCo System Sdn Bhd produced the carbon fibre-reinforced polymer (CFRP) sheet used in this experiment. CFRP is a high-strength material that is attached to structures for structural reinforcement. The benefits of being able to adapt to practically any complicated or geometric shape, such as the cylinder shape have complied. The use of CFRP by LaMaCo gives several unique benefits such as ease of handling, high strength, lightweight, effectiveness for both wet and dry lay-up applications and significant gain in load-bearing capacity. The properties of CFRP are shown in

Table 4, while Figure 2 shows the CFRP sheet used in this study.

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Table 4: Properties of CFRP

| Properties | Value |
|---|---|
| Tensile Strength | 2900 MPa |
| Max. Tensile Load | 12525 kN |
| Tensile Modulus | 165 GPa |
| Elongation | 1.6% |
| Thickness | 0.167 mm |

Figure 2: CFRP Sheet Roll

### *2.1.4 Specimen Preparation*

The surface concrete preparation phase was taking place before the concrete columns were wrapped with CFRP. The concrete surface had to be cleaned and smoothed at this step. The concrete surface was buffed using sandpaper. Additionally, the surface must be solid and devoid of oil laitance. Before applying epoxy primer, all water ponding must be wiped dry. Epoxy resin was then applied after a thin coating of epoxy primer. Before using epoxy resin, the epoxy primer was allowed to dry for two to four hours. The two-component of the epoxy resin system which consists of Part A and Part B were mixed by hand for at least 5 minutes at a slow speed (25-30 cycles of a stir in a minute) to avoid unnecessary air inclusion. One layer of CFRP sheet was then wrapped around the specimens. Special care was taken during the CFRP confinement process to achieve the perfect bonding between CFRP and the concrete surface. All entrapped air in between the surface and CFRP was removed using a roller. Lastly, a thick layer of epoxy resin was applied to the top surface of CFRP and rolled around the CFRP sheets attached to the column's surface with the roller. All specimens were stored at room temperature for 4 hours to cure the epoxy. However, for the most efficient curing time,x the wrapped samples were cured for 24 hours.

## *2.2 Methods*

### *2.2.1 Experimental Setup and Instrumentations*

Four linear variable differential transformers (LVDTs) were used to measure the horizontal deformations of the column in the mid-height region. Four LVDTs were installed in four opposite locations for each column sample. One LVDT was used to measure the vertical deformation of the column and was placed vertically at the top of the column. The gauge lengths were determined as 200mm for all the samples. Four unidirectional strain gauges (SGs) were

p-ISSN 1675-7939; e-ISSN 2289-4934

installed on each column's surface at the mid-height to monitor the strains of the samples. The concrete SGs were used for the unconfined samples while the CFRP SGs [28] were used for the confined samples. CFRP SGs were installed on the CFRP's sheet surface at the mid-height. There was a difference between the concrete SG and the CFRP SG. The use of these correct SGs must be well monitored as different type-function of SG gave different results. The four SGs were attached to the front side and left side of the samples. Two SGs were installed in the horizontal direction and another two SGs were installed in the vertical direction. These SGs were installed in such a direction so that they can measure both horizontal (hoop) and vertical (axial) strains. The locations of the SGs are shown in Figure 3. The LVDTs and SGs were also used for physical centring adjustment before actual compression loading.

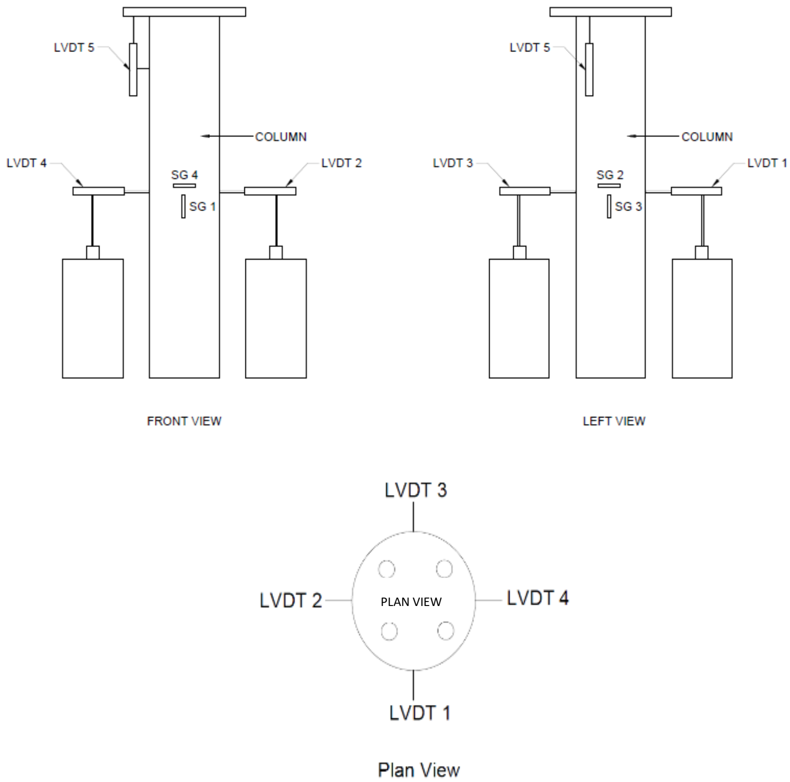


Figure 3: Schematic of LVDTs and SGs Setup

### *2.2.2 Compression Testing*

Fifteen (15) specimens including control samples, full CFRP confined concrete column and partial CFRP confined concrete column were tested by using a compression machine to determine the compressive strength of concrete for 28 days. The specimen was placed on the adjusted platform of the compression machine. A few parameters were programmed into the machine such as the dimension of concrete (1m height x 200mm diameter), the pacing rate (0.01 mm/s) and the coefficient of each LVDT. The pacing rate was the rate of the quantity of loading applied to the specimens. The loading was applied slowly without shock and it was increased continuously.

p-ISSN 1675-7939; e-ISSN 2289-4934

*ESTEEM Academic Journal*
Vol. 18, September 2022, 41-54

## 3. RESULTS AND DISCUSSION

The following experimental results cover the compressive strength, load-displacement curve, stress-strain curve and mode of failure of concrete column specimens obtained from the test.

### *3.1 Compressive Strength*

All samples were tested after 28 days based on previous researchers [28-29]. The compressive strength and result details of all tested specimens are tabulated in Table 5. The average compressive strength of control (unconfined) samples was 23.82 kN/mm$^2$ and the highest compressive strength was the third sample labelled CF-03 which obtained 26.47 kN/mm$^2$. 1-layer fully CFRP wrapped samples recorded 23.35 kN/mm$^2$ on average and the highest compressive strength was the first sample labelled CF-01-1 which was 25.14 kN/mm$^2$. The strength of the 1-layer fully confined specimen was lower than the strength of the control sample. The strength was 1.97% lower than the unconfined sample on average. The highest compressive strength for 1-layer fully wrapped was 5.02% lower than the highest compressive strength for the control sample. 1-layer partly CFRP wrapped samples recorded 33.32 kN/mm$^2$ on average and the highest compressive strength was the second sample labelled CP-02-1 which was 34.73 kN/mm$^2$. The strength for the 1-layer partly confined specimen was higher than the strength of the control sample. The strength was 39.88% higher than the unconfined sample on average. The highest compressive strength for 1-layer partly wrapped was 31.21% higher than the highest compressive strength for the control sample. Meanwhile, 2-layers fully CFRP wrapped samples recorded 39.43 kN/mm$^2$ on average and the highest compressive strength was the first sample labelled CF-01-2 which was 46.91 kN/mm$^2$. The strength of the 2-layers fully confined specimen was higher than the strength of the control sample based on average. The strength was 65.53% higher than the unconfined sample on average. The highest compressive strength for 2-layers fully wrapped was 77.22% higher than the highest compressive strength for the control sample. 2-layers partly CFRP wrapped samples recorded 35.34 kN/mm$^2$ on average and the highest compressive strength was the third sample labelled CP-03-2 which was 36.51 kN/mm$^2$. The strength for the 2-layers partly confined specimen was higher than the strength of the control sample. The strength was 48.36% higher than the unconfined sample on average. The highest compressive strength for 2-layers partly wrapped was 37.93% higher than the highest compressive strength for the control sample.

This could be concluded that the more the layers of the CFRP sheets wrapped around the column, the higher the strength of the column under compression loadings. Partial CFRP confinement gave enough strength to the column which was more than 35% higher compressive strength compared to the control samples on average. Different layers of CFRP sheets gave different amounts of strength to the column. Compared to unconfined specimens, either partial or full CFRP confinement greatly enhances the final compressive strength of specimens.

p-ISSN 1675-7939; e-ISSN 2289-4934

Table 5: Result of Tested Specimens

| Specimen | | Max. Load (kN) | Compressive Strength/ Max.Stress ($kN/mm^2$) |
|---|---|---|---|
| Unconfined | C-01 | 608.60 | 19.37 |
| | C-02 | 804.69 | 25.61 |
| | C-03 | 831.58 | 26.47 |
| | Average | 748.29 | 23.82 |
| 1-layer Fully Wrapped | CF-01-1 | 789.40 | 25.14 |
| | CF-02-1 | 625.98 | 19.93 |
| | CF-03-1 | 784.36 | 24.97 |
| | Average | 733.25 | 23.35 |
| 1-layer Partly Wrapped | CP-01-1 | 1056.85 | 33.64 |
| | CP-02-1 | 1090.96 | 34.73 |
| | CP-03-1 | 992.58 | 31.59 |
| | Average | 1046.80 | 33.32 |
| 2-layers Fully Wrapped | CF-01-2 | 1473.63 | 46.91 |
| | CF-02-2 | 1003.73 | 31.95 |
| | CF-03-2 | - | - |
| | Average | 1238.68 | 39.43 |
| 2-layers Partly Wrapped | CP-01-2 | 1082.76 | 34.47 |
| | CP-02-2 | 1100.47 | 35.03 |
| | CP-03-2 | 1147.03 | 36.51 |
| | Average | Average | 35.34 |

### *3.2 Load-Displacement Curve*

The load-displacement relationship for horizontal and vertical displacement showed the output of RC column specimens subjected to compressive load with various confinement methods. The data was plotted based on the highest load capacity obtained from the samples of each type of confinement. All horizontal LVDTs were positioned in the middle of the samples and a vertical LVDT was placed at the top of the column as shown in the schematic diagram in Figure 3 above in clause *2.1.5*. Based on the graph obtained in Figure 4, for load-displacement LVDT 1, the curve pattern for each type of specimen was the same. The positivity of values defined that all the samples were expanded and moved towards the front view.

Based on the graph plotted in Figure 4, for load-displacement (vertical) LVDT 5, the curve pattern for each type of specimen was all same but for a fully 2-layers confined sample, the displacement was dropped to null at a loading of 1216.87 kN (red circle in Figure 4). The concrete was spalled and the displacement was dropped to null. The other samples were resulting in a positive curve until failure but the fully 2-layers confined were resulting in a negative curve at the end of the graph. All samples were compressed until failure. From this graph, it could be observed that a fully 2-layer confined sample recorded the least value of displacement but higher loading capacity before failure.

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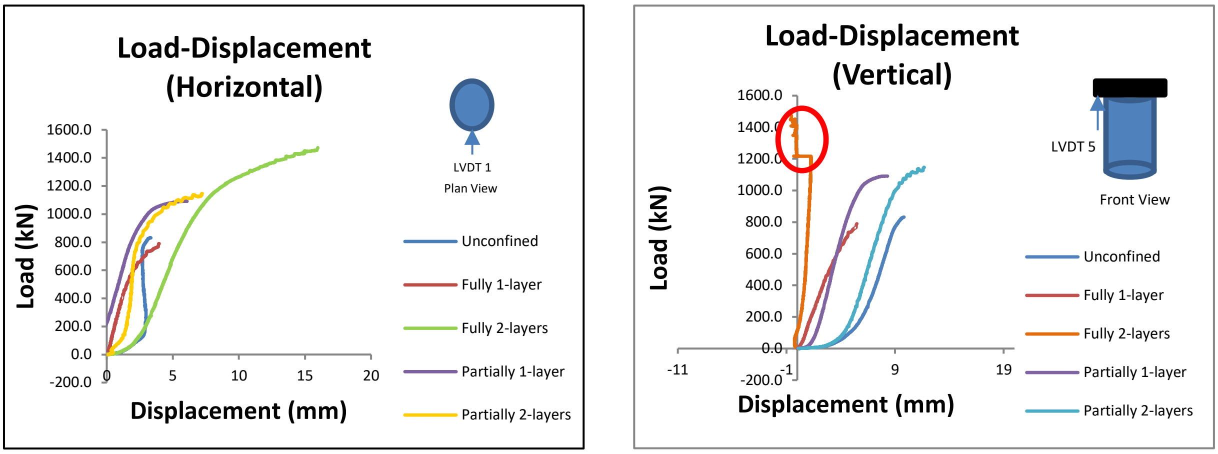


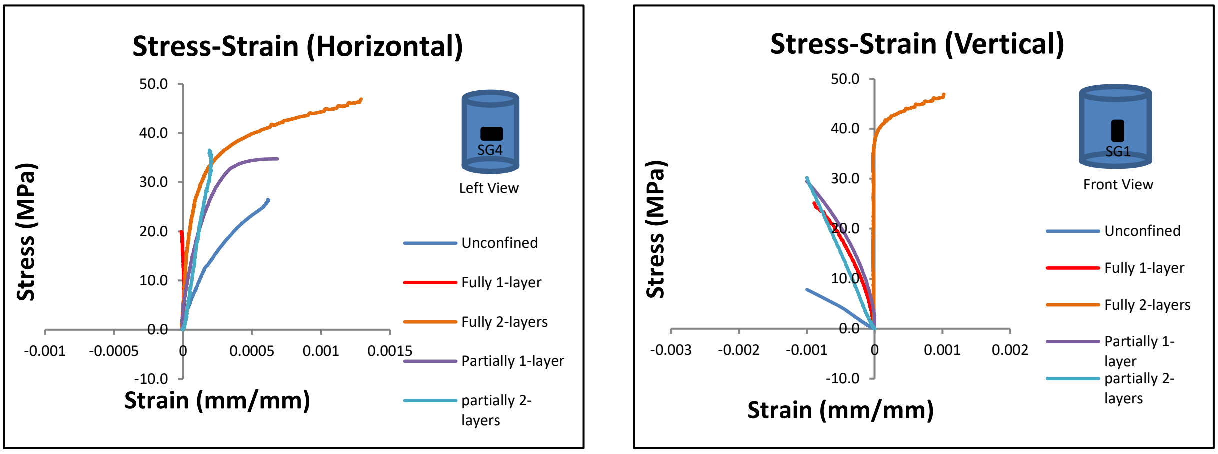

(a)Load-Horizontal Displacement

(b) Load-Vertical Displacement

Figure 4: (a) Load-Horizontal Displacement Curve (b) Load-Vertical Displacement Curve

### *3.3 Stress-Strain Curve*

Figure 5 displays the stress-strain curve (horizontal) SG4 and stress-strain curve (vertical) SG1 for all confinements. All strains of each type of sample were in positive values from the beginning of the test until failure. In Figure 5(a), the fully 2-layers sample recorded the highest value which was 0.00129 and the lowest strain recorded was -0.000013 which is for a fully 1-layer sample. The positive sign of the strain determined that the column was in a horizontal tension state on the left side and the negative sign indicated that the column was in a horizontal compression state on the left side. For the vertical part, all strains of each type of sample were in negative values from the beginning of the test until failure except for the fully 2-layers sample which the strain in positive values at the end of the test. In Figure 5(b), the fully 2-layers sample recorded the highest value, which was 0.001023 and the lowest strain recorded was –0.000569 for the fully 1-layer sample. The positive sign of the strain determined that the column was in a vertical tension state at the front side and the negative sign indicated that the column was in a vertical compression state at the front side.




(a) Stress-Strain (Horizontal)

(b)Stress-Strain (Vertical)

Figure 5: Stress-Strain Curve (a) Horizontal (b) Vertical

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ESTEEM Academic Journal
Vol. 18, September 2022, 41-54

### *3.4 Mode of Failure*

All specimens that had been contained with CFRP displayed typical CFRP rupture brought on by hoop stress at or around the top of the specimens. After the carbon sheet ruptured, all specimens under compression force showed a sudden and catastrophic failure. The shear diagonal split failure occurred in the majority of CFRP partial confinement specimens. Multiple specimens from explosions were seen being held by intact strips. Figure 6 to Figure 10 show several failure types in which partial and full containment CFRP rupture occurred.

#### *3.4.1 Unconfined Specimens*

The cracks of the specimens were observed and noted after being compressed under axial loading. The cracks for the unconfined specimen are shown in Figure 6 below. Each tested sample was experiencing concrete spalling either at the top or bottom of the column in overall observation with naked eyes. Minor cracks like hair cracks occurred at the mid-section of the column. Columns labelled C-01 had a quite big concrete spalled area at the top of the column. C-02 and C-03 experienced minor concrete spalling at the bottom of the column and a line of crack occurred at the top of both columns.

(a) C-01 (b) C-02 (c) C-03

Figure 6: Cracks Observation (Unconfined)

#### *3.4.2 Confined Specimens*

All concrete columns that were wrapped with CFRP both in the full and partial configuration were observed carefully and in detail. All fully 1-layer confined samples were experiencing cracks at the top of the columns. The cracks could clearly be seen from the left side of the columns. The concrete spalling could be seen along with the ruptured of the CFRP sheet as shown in Figure 7.

(a) CF-01-1 (b) CF-02-1 (c) CF-03-1

Figure 7: Cracks Observation (Full 1-Layer)

p-ISSN 1675-7939; e-ISSN 2289-4934

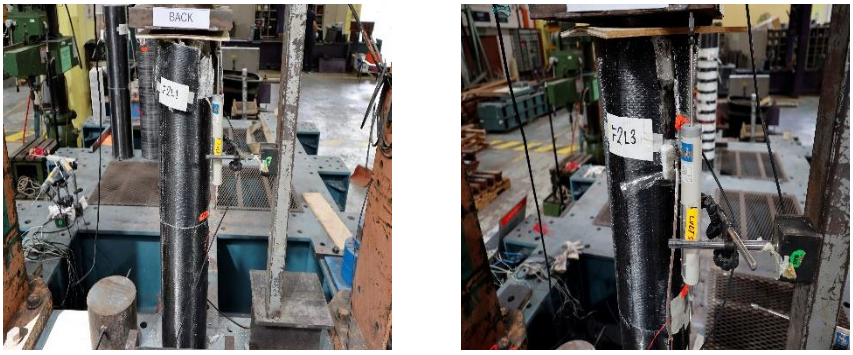
*ESTEEM Academic Journal*
Vol. 18, September 2022, 41-54

Partial 1-layer confined samples were experiencing cracks at the top of the columns. The cracks were visible from the back and right sides of the columns. Two out of three samples were experiencing concrete deterioration at the top-back side of the columns, which were CP-01-1 and CP-03-1 meanwhile the concrete spalled for CP-02-1 was at the top-right side of the column. The concrete spalling could be seen along with the ruptured of the CFRP sheet as shown in Figure 8.

(a) CP-01-1 (b) CP-02-1 (c) CP-03-1

Figure 8: Crack Observation (Partial 1-Layer)

Fully 2-layers confined samples were experiencing cracks at the top-back of the columns. The concrete spalling could be seen along with the ruptured of the CFRP sheet as shown in Figure 9. The third sample was not observed and analysed in this study as the sample was facing a technical error during the compression testing.




(a) CF-01-2 (b) CF-02-2

Figure 9: Cracks Observation (Full 2-Layers)

All partial 2-layers confined samples were experiencing cracks at the top of the columns. The cracks were visible from the left and front sides of the columns. Two out of three samples were experiencing concrete deterioration at the top-front side of the columns, which were CP-02-2 and CP-03-2 meanwhile the concrete spalled for CP-01-1 was at the top-left side of the column. The concrete spalling could be seen along with the ruptured of the CFRP sheet as shown in Figure 10.

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*ESTEEM Academic Journal*
Vol. 18, September 2022, 41-54


(a) CP-01-2 (b) CP-02-2 (c) CP-03-2

Figure 10: Cracks Observation (Partial 2-Layers)

## 4. CONCLUSION AND RECOMMENDATIONS

### *4.1 Conclusion*

The result obtained proved that both fully and partially CFRP confinement significantly enhanced the axial loading capacity of the RC columns. The fully 2-layers CFRP confined sample was the best CFRP confinement to increase the axial static loading for this study. Based on the best specimen of each configuration, fully 2-layers confinement gave a huge increment percentage of axial load (77.22%) compared to the unconfined sample determined that the confinement could be used to give additional strength to the RC column and supported the reinforcement bars along with the concrete to reach maximum loading until failure. Both 1-layer and 2-layer partial confinement configurations also gave a higher percentage of the axial load than the unconfined samples which were 39.88% and 48.36%, respectively. Besides, based on specimens' average compressive strength, full 2-layers confined columns obtained 65.53% and partial 2-layers confined columns obtained 48.35% higher than the unconfined samples (control samples) on average. Two layers of CFRP sheets provided more axial compression load support for the column's sample, hence the more layers of CFRP sheets used, the higher the compressive strength achieved. The CFRP confinement was able to withstand and gave additional support to the RC column once the RC column reached its axial loading limit up to 39% to 77% in range based on this research.

When analysing the data, there was a problem where the compressive strength of the third full 2-layers confined sample was lower than the unconfined sample. The specimens were painted white before the axial compression test was running. The paint was used to cover the rough surface and tiny holes of the circular RC columns.

During the axial test, the CFRP sheets could not contribute their strength to support and sustain the loading as the CFRP sheets were detached from the surface of the columns earlier. This occurred because the paint that was experiencing paint dated. Once the paint was dated, it would spread to the entire painted column. Hence, when this happened, the bonding between the CFRP sheet and the surface of the column through the epoxy resin would get weaker and easily detached before the CFRP could give out the strength to withstand the loading. This had happened to the third sample of full 2-layers confined specimen, and this was the reason why the result of the specimen was neglected in this study.

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### 4.2 Recommendations

The samples are better in plain condition with no paint to avoid the detachable CFRP sheet from the samples' surface in future research. Moreover, future research can consider different concrete grades, the different number of CFRP wrapping layers, different spacing for partial confinement and different types of strengthening methods. Besides, future research can be done by exposing the confined samples to high temperatures and testing the samples under axial compression loading or/and lateral loadings.

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## CONFLICT OF INTEREST

The authors declare that there is no conflict of interest regarding the publication of this paper.

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