# Strengthening of Compression Members with Glass Fiber Reinforced Polymer Wraps

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**Abstract**

Strengthening, repairing and retrofitting of structures for safe usage of the community is becoming a must. Columns are structural members that resist vertical compression loads and they may experience severe damage due to low deformability and axial capacity. One way of strengthening this structural part is confining concrete columns by wrapping with glass fiber reinforced polymer (GFRP) around the perimeter of column sections. This strengthening technique confines the column cores, increases load carrying capacity and ductility. In this study, strengthening of concrete cylinders by GFRP confinement is experimentally investigated. Plain concrete, concrete restrained laterally by steel ties, and concrete restrained by both steel ties and GFRP wrap of various layers are examined for both circular and square sections. An axial centric compressive load was applied to all the specimens. The results showed that GFRP of three layers improved compression resistance of test specimens by 77%. In addition, some theoretical models were used to associate with the experimental results.

**Keywords:** Strengthening, Concrete columns, Confinement, Axial load, GFRP

# 1 Introduction

The reliable use of FRP sheets for the confinement of reinforced-concrete (RC) columns requires a proper understanding of material properties and the capability of accurately modeling the stress-strain behavior of FRP-confined concrete Hadi et al (2016). Many researchers have focused their study on determining the effect of FRP confinement and attempt to come up with stress-strain models. Moreover, numerous numerical tools have been developed to model the structural behavior of FRP-confined columns and to strengthen flexural members (Megalooikonomou, 2007; ACI, 2008; Khalifa et al. , 1998). But understanding and modeling the structural behavior of FRP-confined RC columns is still a very active research field, mainly due to the complexity of the problem.

The data available for columns of square or rectangular cross-sections have increased over recent years but are still limited. This field remains in its developmental stages and more testing and analysis are needed to explore its capabilities, limitations, and design applicability. This study deals with a series of experimental tests on circular and square concrete confined with stirrup and glass fiber reinforced polymer (GFRP) wraps.

The demand of structural members may increase due to provisions of new design codes (structures built in the past are currently utilizing higher seismic loads), lower material quality, construction error or change in use. To sustain these higher loads, different strengthening techniques are available and one of them is confining with GFRP wraps. Before applying this technique, a detail study on its effectiveness is required.

# 2 Literature Review

Strengthening uses for RC members can range from a restore of deteriorated members so that their original load carrying capacity is returned, to adding elements to improve their strength. From the most traditional techniques of strengthening of RC structures, increase in the reinforced concrete cross section and increase area of reinforcements are some of the conventional examples.

In the field of structural strengthening, in recent years, the use of externally applied fiber-reinforced polymers (FRP) has gained significant popularity. FRP composites have been used successfully for rehabilitation and upgrading of deficient reinforced-concrete structures such as buildings and bridges (Dash , 2009).

## 2.1 **FRP Material Properties**

Composite materials are made by bringing together two or more separate fundamental materials, where one or more materials act as reinforcements and the other ones materials perform as the matrix (Dash, 2009).

Fiber Reinforced Polymer (FRP) can be described as a polymer (plastic) matrix, that is reinforced (combined) with a fiber or other reinforcing material with an adequate aspect ratio (i.e., a length to thickness ratio) to provide a noticeable supporting function (Megalooikonomou, 2007). Thus, by definition, FRP composite has some resemblances to reinforced concrete with a fiber (such as glass, carbon, etc.) as the reinforcement and a polymer (polymer resin matrix such as epoxy, polyester) as concrete for RC. The fiber reinforcement supports the load in the premeditated directions and the polymer matrix operates as a binder. Recent FRP composite materials typically have high strength and high-stiffness because structural fibers embedded in lightweight, low-cost, and environmentally resistant polymers consequently have better mechanical and durability properties than either of the constituents alone Mega- looikonomou (2007). Fig. 1 below shows comparison of stress-strain curve for different FRP, high performance and mild steel (Nicolae et al., 2008).

The composites designer can modify the performance of the end product with a proper selection of materials.

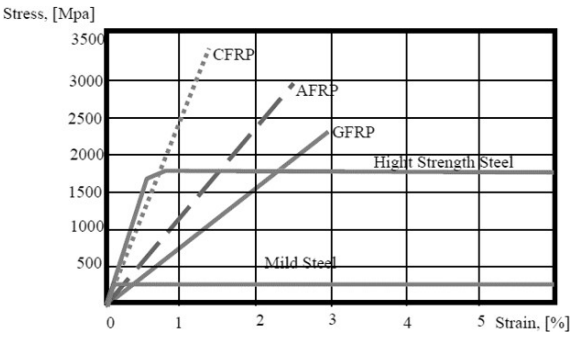



**Figure 1:** Stress-Strain Curve for Different FRP and Steel [Nicolae et al (2008)]

Some of the main benefits of FRP materials based on Megalooikonomou (2007) are summarized as follows:

- Lightweight
- High strength-to-weight ratio
- Corrosion and weather resistances
- low thermal conductivity and coefficient of thermal expansion
- Non-magnetic High impact strength
- High dielectric strength (insulator)

But these materials have disadvantages. These include Megalooikonomou (2007):

- High cost
- Brittle materials. Their performance is linear elastic until failure, albeit this happens at a high deformation level.
- The non-compatible coefficient of thermal expansion of the constituent materials. They are vulnerable to fire and generally too high temperatures.
- Reduction of tensile strength and Young Modulus when they are under continuous drench or alkaline environment.

## 2.2 FRP Confinement of Columns

To get strength and ductility improvement, confining concrete columns is one of the most significant techniques which has been used by numerous researchers and engineers from many years ago. Generally, there are two different methods of confining concrete: active and passive confinements.

In active confinement method, there is a constant pressure applied to the concrete under prestressing forces. In the case of passive confinement, lateral expansion is restricted by confining concrete with certain elements, for instance, steel jackets or wrapping with FRP sheets (Benzaid et al , 2013). Therefore, tension due to the axial forces is developed in these confining elements.

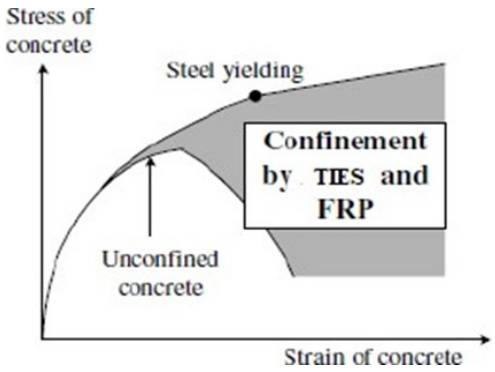



**Figure 2:** Lateral Expansion and Confining Effect due to Axial Load (Benzaid et al., 2013)

The increase of axial load in the column, increases the level of confinement and this type of confinement is activated due to the bulging effect of concrete as a result of Poisson's effect. Close stirrups in concrete columns also provide a kind of passive confinement. The stirrups keep a tight reinforcement on the lateral expansion of concrete leading to tensile stress in stirrups (Benzaid et al , 2013). Lateral expansion and confining effect of concrete column due to axial load is shown in Fig. 2.

Different from steel, the stress-strain relationships of FRP-confined concrete steadily increase and abruptly drop down when FRP composites rupture these is because FRP exhibits a stress-strain curve of a single stage when subjected to a tensile force that is it goes linear elastic up to final brittle rupture and the corresponding stress-strain relations of concrete confined by both FRP and steel ties is shown in Fig. 3 (Lee et al , 2004).

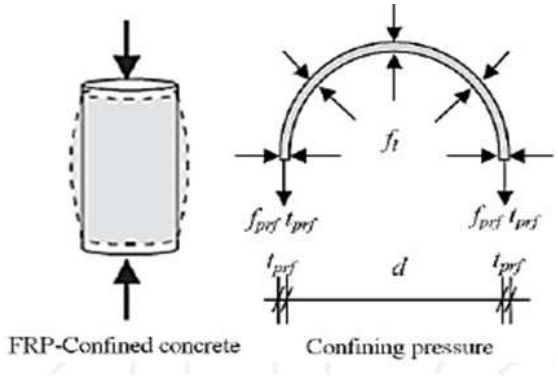



**Figure 3:** Stress-Strain Relations of Concrete Confined by both FRP and Steel Ties (Lee et al., 2004).

Researchers on confinement of compression members have been conducted and results showed that FRP-confinement can significantly enhance the ultimate strengths

plain and RC columns (Lee et al, 2004; Mahdy , 2016; Benzaid et al , 2013; Ilki et al , 2006; Khaloo et al , 2008). In recent research, experimental investigation of different RC columns with cylindrical shapes and externally confined with FRP subjected to concentric and eccentric loadings were carried out and the effectiveness of two confinement materials (carbon and glass fibers) were evaluated. According to the results, failure of strengthened columns was brittle and very explosive (Mahdy , 2016).

### 2.3 Confinement Models of RC Columns

Various models for the confinement of concrete with FRP have been developed. The majority of these models were performed on plain concrete specimens' (Mander et al , 1998). A limited number of tests have been reported in the literature on the axial compressive strength and strain of reinforced concrete specimens confined with FRP. Most of the existing strength models for FRP confined concrete adopted the concept of Frank et al. (1929) and Richart et al. (1929). Different confinement models for RC columns are summarized as follows Lam et al (2003); Pellegrino and Modena (2010):

i) Lim and Teng (2003)

$$f'_{cc} = f'_{co} + 3.3 f_1^{0.7} \quad (1)$$

$$\frac{f'_{cc}}{f'_{co}} = 1 + 3.3\left(\frac{h}{b}\right)^2 \frac{A_e}{A_c}\frac{f_1}{f'_{co}} \quad (2)$$

where: $f_1$ - lateral confining pressure

$A_e$ and $A_c$ - effective confinement area and total area of concrete

b and h - width and length of the rectangular section

$f'_{cc}$- compressive strength of FRP-confined concrete

$f'_{co}$ - compressive strength of concrete

ii) Pellegrino and Modena (2010)

$$f_{1f} = 1/2 k_f \rho_f E_{frp} \varepsilon_f^{eff} \quad (3)$$

$$\rho_f = \frac{2 n_f t_f (b+h)}{bh} \quad (4)$$

$$k_f = 1 - \frac{(b-2r)^2 + (h-2r)^2}{3bh} \quad (5)$$

where: $E_{frp}$ - elastic modulus of the FRP strengthening

$k_f$ - coefficient of efficiency of the confinement

$\varepsilon_f^{eff}$ - effective hoop FRP strain; $\rho_f$ - FRP strengthening ratio

Fig. 4 below shows effective confinement areas of smooth and sharp corner concrete sections confined with FRP (Richart et al., 1929).

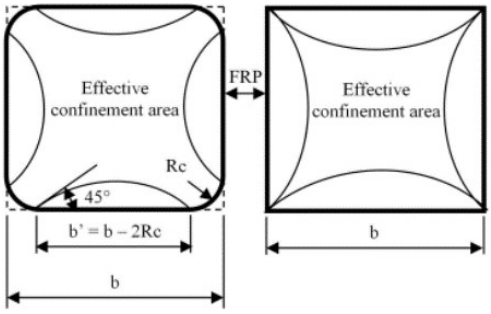



**Figure 4:** Effective Confinement Areas (Richart et al., 1929).

## 3 Materials and Methods

### 3.1 Materials

**1. Cement**

Pozzolanic Portland Cement (PPC) of 32.5grade cement with a specific gravity of 3.15 is used.

**2. Fine Aggregate**

The fine aggregate used in this research was natural siliceous sand. The physical properties of the fine aggregate were tested based on the procedures given by Dinku (2002) and fulfils the requirements set on ACI-E107 ACI (2007). The results are summarized in Table 1.

**Table 1:** Physical and Mechanical Properties of Fine Aggregates

| Properties | Values |
|---|---|
| Fineness modulus | 3.4 |
| Specific gravity | 2.23 |
| Absorption capacity | 1.61 |
| Silt Content | 3.8 |

**3. Coarse Aggregate**

The coarse aggregate used in this research was gravel, clean, free from organic silts, loam, injurious matter, and clay. Nominal aggregate size of 25 mm is used in the mix. The main physical and mechanical properties of the coarse aggregate was tested based on the procedures given by Dinku (2002) and fulfils the requirements set on ACI-E1-07 ACI (2007). Properties of coarse aggregate is shown in Table 2.

**Table 2:** Physical Properties of Coarse Aggregates

| Properties | Values |
|---|---|
| FRP type | E-Glass |
| Tensile strength | 772.95MPa |
| Young's modulus | 21.6GPa |
| Thickness | 0.69mm |
| Fiber orientation | Uni-directional |
| FRP Weight | 168g/m$^2$ |

**4. Reinforcement Bar**

As transverse ties, diameter 6mm bars are used for the circular specimen while 8mm diameters are used for the square ones. After the tensile test for both bars, the yield and ultimate tensile strength together with test summary are listed in Table 3.

**Table 3:** Experimental Data for Yield and Ultimate Stress of Reinforcing Bars

| Diameter (mm) | Average Yield stress (MPa) | Average Ultmate Tensile stress (MPa) |
|---|---|---|
| 8 | 439.64 | 550.12 |
| 6 | 171.73 | 298.65 |

**5. GFRP**

The unidirectional GFRP is a non-corrosive and high alkali resistance fabric produce by VITRULAN company with behavior given in Table 4 is used (Meried, 2016).

**Table 4:** Summary of GFRP Properties (Meried, 2016)

| Properties | Values |
|---|---|
| Specific gravity | 2.87 |
| Absorption capacity | 1.24 |

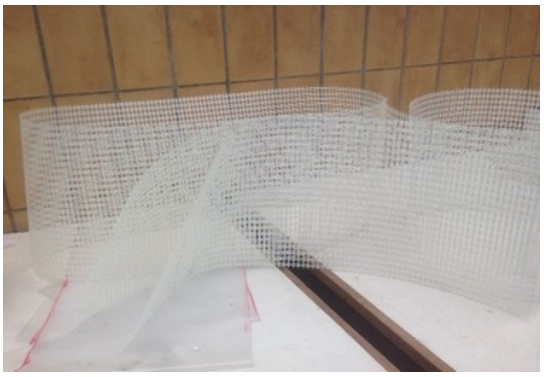


**Figure 5:** Sample of GFRP

**6. Adhesive**

An epoxy-based adhesive (Sika -161) is used to bond the FRP with the concrete. Mixing is done as per manufacturer's recommendation Sika (2019). The main properties of the adhesive are listed in Table 5.

**Table 5:** Summary of Adhesive Proper Ties (Sika, 2019)

| Properties | Values |
|---|---|
| Compressive strength | > 45 MPa |
| Tensile strength | 15 MPa |
| Tensile Adhesion Strength | 1.5MPa (concrete failure) |
| Density | 1.4kg/l |

**7. Prime**

The prime is used to penetrate the surface of concrete providing an improved adhesive bond for the saturating risen or adhesive. Gel-coat, all-purpose resin, and Butanox M-50 (as a catalyst) have all been used as adhesive materials.

**8. Concrete Mix Proportion**

C25 grade concrete was intended and prepared using ACI mix design procedure (ACI, 1991) with a water-to-cement ratio of 0.45. The $28^{th}$ days average cubic compressive strength of concrete was found to be 25.1 MPa.

### 3.2 Methods

**1. Test Specimens**

The test specimens are mainly divided into two groups based on their shape: circular and square. Circular specimens have a diameter of 150mm and height of 300mm. Diameter 6mm ties in a hoop form at a spacing of 65mm are used. Square specimens with a dimension of 150mm and a height of 300mm are prepared. The transverse reinforcements were arranged with a center to center spacing of 67.5mm and were tied with 2.5mm wire (there are no longitudinal bars). These wires help to keep the transversal bars in place. In this study, 10 different cases, a total 30 specimens (3 for each case) are prepared and the average values are reported. The clear cover of the concrete is 15mm. The concrete was mixed by a mechanical mixer and compacted using a vibrator following standard mixing procedures of Teychenné et al (1975).

The designation, dimensions and ties arrangement of test specimens are summarized in Tables 6 and 7. To study the

effect of confinement only, in all cases, no longitudinal bars have been used. Fig. 6 shows rebar arrangement of square and circular specimens.

**Table 6** Designation of Circular Test Specimens

| Designation | Dimension | Remarks |
|---|---|---|
| **CPC** | Circular specimens 150mm in diameter and 300mm height | Plain concrete |
| **CSC** | | confined by steel ties |
| **CSFC1** | | confined by steel ties and 1 layer of GFRP sheet |
| **CSFC2** | | confined by steel ties and 2 layers of GFRP sheet |
| **CSFC3** | | confined by steel ties and 3 layers of GFRP sheet |

**Table 7** Designation of Square Test Specimens

| Designation | Dimension | Remarks |
|---|---|---|
| **SPC** | Square specimens with a dimension of 150mm and a height of 300mm | Plain concrete |
| **SSC** | | confined by steel ties |
| **SSFC1** | | confined by steel ties and 1 layer of GFRP sheet |
| **SSFC2** | | confined by steel ties and 2 layers of GFRP sheet |
| **SSFC3** | | confined by steel ties and 3 layers of GFRP sheet |

In the above tables, for instance, the notation CSFC2 stands for circular concrete specimen confined both with transversal steel ties and 2-layers of FRP sheet. SSFC2 stands for square concrete specimen confined both with transversal steel ties and 2-layers of GFRP sheet.



**Figure 6:** Rebar Arrangement of Specimens

To avoid de-lamination of GFRP from the concrete, quarter of the perimeter length (100 150 mm) were added as an overlap. Before the GFRP is attached to the concrete, surface preparation was done. Thus, the specimens were washed, dried with air blow and coated with prime.

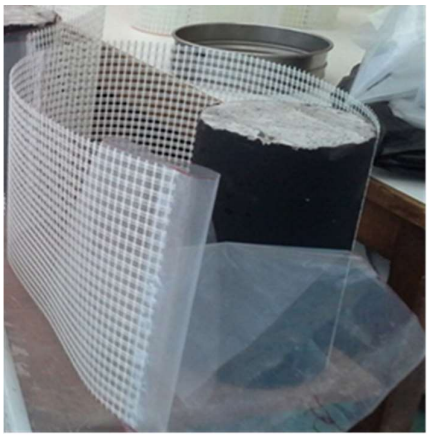


**Figure 7:** Wrapping of Specimen with GFRP

**2. Test Setup & Experimental Procedure**

After the test specimens were cured for 28 days under a temperature of 20C and relative humidity of 70%, the GFRP layers were bonded using epoxy adhesive and allowed to

cure for 10 days. The specimens were tested in the compression testing machine which has a maximum loading capacity of 3000kN. To have accurate data and post-peak behaviors of the specimens, a load cell (with maximum capacity of 1000kN) was placed under the specimen and the grid sensor on the machine was raised to 500kN.

The load rate used during the test was set to 0.25MPa/sec. Linear variable displacement transducer (LVDT) is used to measure the deflection of the specimens. The test setup is shown in Fig. 8.



**Figure 8:** Test Setup

## 4 Results and Discussions

The test results of unconfined and confined specimens are presented. Finally, comparison between the different types of confinement and strengthening methods on circular and square specimens are put and are briefly discussed. Theoretical models from different researchers are used to estimate the analytic capacities of GFRP wrapped specimens and their results are compared with the experimental ones.

### 4.1 Circular Concrete Columns

Failure of circular concrete specimens is shown in Fig. 9. In the figure, for the plain concrete member, crushing of concrete is observed. On the other hand, for strengthened member, the confinement of the member was assured, and lately rupture of GFRP has been occurred.



(a) Plain concrete (b) with GFRP

**Figure 9:** Circular Specimen Failures

Stress-strain relationship of circular specimens is shown in Fig. 10. As shown in Fig. 10, the GFRP wrapped circular samples showed an increase in peak strength. The one layered specimen reached their peak stress earlier than the two or three-layered specimens. Thus, as the layer increased the strain at the peak stress also increased. But, the one layered specimen has sustained a load after they reached their peak stress better than the two or three-layered specimens, so we can say as the number of layers increase the failure of the

specimen become more sudden. The initial stiffness of the specimens is different as the GFRP sheet may experience stress concentrations that lead to premature failure Pellegrino and Modena (2010).

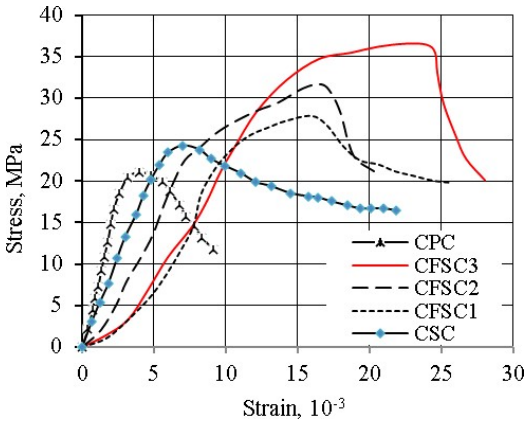



**Figure 10:** Stress-Strain Comparison of Circular Specimens

As the specimens were about to reach their peak stress, they started to make crunching sound and continued until failure. This was accompanied by a small popping off the outer plaster epoxy. A summary of comparison of compression resistance of specimens is given in Table 8.

**Table 8** Comparison of Compression Resistance Square Specimen

| Designation | Average Stress (MPa) | Ratio to Plain Specimen |
|---|---|---|
| SPC | 17.36 | 1.00 |
| SSC | 18.24 | 1.05 |
| SSFC1 | 21.03 | 1.21 |
| SSFC2 | 22.66 | 1.31 |
| SSFC3 | 24.78 | 1.43 |

The three-layer specimen performed better as expected with an increase of 77% in comparison to the control specimen.

### 4.2 Square concrete columns

Failure of square concrete specimens is shown in Fig. 11. Moreover, Fig. 12 shows the stress-strain relationship of different types of square concrete specimens. As shown in Fig. 12, the FRP wrapped square samples showed an increase in peak strength than the plain and the reinforced specimens. Like circular specimens, similar properties have been observed; as the specimens were about to reach their peak stress, they started to make stretching sound and continued until failure and this was accompanied by rupture of the GFRP as shown in Fig. 11 (b).



(a) Plain concrete (b) with GFRP

**Figure 11:** Square Specimen Failures

A summary of compression resistance comparison of square specimens is given in Table 9. As shown in the table, the cross sectional shape of the compression member affects the effectiveness of GFRP wraps.

**Table 9** Comparison of Compression Resistance of Circular Specimens.

| Designation | Average Stress (MPa) | Ratio to Plain Specimen |
|---|---|---|
| CPC | 20.80 | 1.00 |
| CSC | 23.55 | 1.13 |
| CSFC1 | 27.68 | 1.33 |
| CSFC2 | 31.14 | 1.50 |
| CSFC3 | 36.90 | 1.77 |

The increment was significantly higher in the circular specimens than in the square ones. For instance, a 77% improvement in compression resistance over plain concrete was achieved for the three-layer circular specimen. While the increase for square one was found to be 43%. This is because failure occurred after the strain reached its maximum value in square portions, where the corners are sharp and the stresses are highly concentrated at the edges.

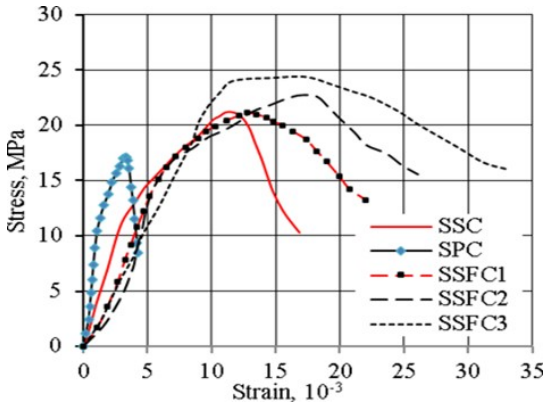



**Fig. 12** Stress-Strain Comparison of Square Specimens

### 4.3 Comparison of Test Results with Theoretical Models

The experimental test results of concrete compression test specimens are compared with the existing models and the results are shown in Table 10.

| Cases | Test Results (1) | Lam & Teng Model (2) | Ratio (1)/(2) | Pellegrino & Modena (3) | Ratio (1)/(3) |
|---|---|---|---|---|---|
| CSFC1 | 27.68 | 29.78 | **0.93** | 26.38 | **1.05** |
| CSFC2 | 31.14 | 35.42 | **0.88** | 35.02 | **0.89** |
| CSFC3 | 36.9 | 40.22 | **0.92** | 45.64 | **0.81** |
| SSFC2 | 22.66 | 23.87 | **0.95** | 19.44 | **1.16** |
| SSFC3 | 24.78 | 27.13 | **0.91** | 20.65 | **1.20** |

**Table 10** Comparison of Theoretical and Experimental Results

In Table 10, it is shown that the experimental test results of concrete compression. The two models can predict the confined concrete strength with a good accuracy. However, for the Pellegrino and Modena model (2010), accuracy decreased with increasing layers.

The models are found to be better in predicting compression resistance of circular section than square ones.

## 5 Conclusions

Based on the experimental investigation, the following conclusions are drawn.

- The peak stress capacities of the circular GFRP wrapped concrete with steel ties improved by 33% for one layer 50% for two layers and 77% for three layers compared to plain concrete.
- The peak stress capacities of the square FRP wrapped concrete with steel ties improved by 31% for two layers and 43% for three layers than plain concrete.
- Increasing the number of layers of fibers were found to have a significant effect in improving compressive resistance of concrete members, especially for 3 layers.
- The comparisons made between theoretical calculations and experimental results showed that the models prepared by Lim & Teng (2003) and Pellegrino & Modena (2010) can be used to estimate the peak stress of externally wrapped GFRP concrete columns with internal steel ties under pure uniform pressure.

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