

ADDIS ABABA UNIVERSITY
ADDIS ABABA INSTITUTE OF TECHNOLOGY
SCHOOL OF CIVIL AND ENVIRONMENTAL ENGINEERING

**STRENGTHENING OF CONCRETE COLUMNS BY CONFINING WITH
FIBER REINFORCED POLYMER WRAPS**

A Thesis in Structural Engineering

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A Thesis

Submitted in Partial Fulfillment of the Requirements for the Degree of Master of Science in
Civil Engineering

The undersigned have examined the thesis entitled '**Strengthening of Concrete Columns by Confining with Fiber Reinforced Polymer Wraps**' presented by **Alazar Nigussie**, a candidate for the degree of **Master of Science** and hereby certify that it is worthy of acceptance.

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UNDERTAKING

I certify that research work titled “Strengthening of Concrete Columns by Confining with Fiber Reinforced Polymer Wraps” is my own work. The work has not been presented elsewhere for assessment. Where material has been used from other sources it has been properly acknowledged.

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ABSTRACT

Large numbers of structures turn out to be unsafe to use because of changes of design code, changes in use, lack of quality building material and construction error every year. Thus, strengthening, repairing and retrofitting of these structures for safe usage of the community is becoming a must. Columns are member of structure that resist vertical compression loads and these members may experience severe damage due to low deformability and axial capacity. One way of strengthening this structural part is confining concrete columns by wrapping fiber reinforced polymer (FRP) around the perimeter of column sections. This strengthening technique confines the column cores and increases their load carrying capacity and ductility. In this study, strengthening of concrete cylinders by FRP confinement is experimentally investigated. Two group of concrete sections which are circular and rectangular with a subdivision of plain concrete, concrete confined laterally by steel ties and concrete confined by both steel ties and FRP wrap of different layers are considered. An axial centric compressive load was applied to all the specimens. The results of the experiment show that FRP confinement is capable of increasing axial load carrying capacity and can be used to strengthen deficient columns. In addition, some theoretical models were used to associate with the experimental results.

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NOTATION

f'_{cc} - compressive strength of confined concrete
 f'_{co} - compressive strength of unconfined concrete
 f_l - lateral confining pressure
 k_1 - confinement effectiveness coefficient for Richart et al
 ϵ_{frp} - ultimate strain of FRP
 $\epsilon_{h,rupt}$ - hoop rupture strain of FRP
 ϵ_{cu} - ultimate concrete axial strain of uniformly confined concrete
 ϵ_{co} - ultimate concrete axial strain of unconfined concrete
 D - diameter of circular specimens
 k_s - shape effectiveness for rectangular section
 b - width of the rectangular section
 h - length of the rectangular section
 A_e - effective confinement area of the rectangular section
 A_c - total area of concrete
 A_g - gross area of the column section with rounded corners
 f_{lf} - confinement pressure due to FRP wrapping
 ρ_f - FRP strengthening ratio
 ϵ_f^{eff} - is the effective hoop FRP strain
 k_e - coefficient of efficiency of the FRP strengthening
 ρ_{st} - transverse steel ratio
 $f_{y,st}$ - yield stress of the transverse steel reinforcement
 P_u - total confining pressure

1. INTRODUCTION

1.1. General Background

A civil engineer could be faced with a challenge for an already constructed structures due to many reasons. One is if the structures constructed in the past using the older design codes are structurally unsafe according to the new design codes or another maybe if there is a need for changing the usage of the structure to a heavier one (e.g. from an office to a storage). To this problem, there are two solutions. The first one is the replacement of such deficient elements of structures, but this incurs a huge amount of public money and takes a massive amount of time, thus strengthening has become an acceptable way of improving the load carrying capacity and extending the service lives of structures. One of the challenges in the strengthening of concrete structures is a selection of a strengthening technique that will enhance the strength and serviceability of the structure while dealing with limitations such as constructability, building operations, and cost.

There are many techniques for strengthening reinforced concrete structures. From them, one is strengthening reinforced concrete structural members with the externally bonded fiber reinforced polymer (FRP). This technique has been usually acclaimed as an efficient method to increase the strength, ductility, and durability of structural members. The use of FRP composites in strengthening solutions has become an efficient alternative to some of the existing traditional methods due to some advantages such as their features in terms of strength, lightness, corrosion resistance and ease of application. FRP can be used for beams to increase the flexural capacity and improve the ductility and for columns to increase the axial load carrying capacity and ductility.

The capability of FRP jacket to increase the axial load carrying capacity and ductility of columns derives from their confinement property. Confinement of columns is done with FRP by wrapping around its perimeter. To properly use this strengthening technique the engineer requires to be able to precisely and capably predict the values of the enhanced performance of the FRP-confined columns based on the explicit geometry, material properties, and quantity of FRP utilized. Confinement of RC columns with FRP has been widely used, in particular for retrofit or strengthening of structures located in earthquake-prone regions.

The reliable use of FRP plates or sheets for the confinement of RC columns requires a proper understanding of and the capability of accurately modeling the stress-strain behavior of FRP-confined concrete. Many researchers have focused their study on determining the effect of FRP confinement and attempt to come up with stress-strain models. Also, numerous numerical tools have been developed to model the structural behavior of FRP-confined columns. 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.

Several studies on the performance of FRP wrapped columns have been conducted, using both experimental and analytical approaches. Such strengthening technique has proved to be very effective in enhancing their ductility and axial load capacity. However, the majority of such studies have focused on the performance of columns of circular cross-section. 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 compression tests on circular and rectangular concrete confined with both stirrup and glass fiber reinforced polymer (GFRP)wraps.

1.2. Statement of the Problem

Due to change in code, lower material quality, construction error or change in use, buildings are subjected to a higher load than their capacity. To solve these problems different strengthening techniques are available and one of them is confining with FRP wraps. Before applying this technique for strengthening of columns a detail study on its effectiveness is required.

1.3.Objective

The main objective of this thesis is to clearly demonstrate the effectiveness of FRP wraps in increasing the axial capacity of confined concrete. In addition, it also covers the difference in the efficiency of these FRP wraps for circular rectangular cross-section specimens.

1.4.Scope

The scope of this thesis is limited to a concentric axial pressure which means eccentric load is not included. The FRP type used is only glass type and it doesn't include carbon or aramid types. The shapes of the specimens are only limited to circular and rectangular cross-section. The layers of FRP used are up to three layers.

1.5.Thesis Outline

This thesis is composed of five chapters. The first chapter is about the introduction to structural strengthening using FRP and states the objective and scope of the research. The second chapter is literature review on previous research about strengthened concrete columns by confinement of FRP and studies about confinement models for FRP confined columns. The third chapter is materials, methods and test setup which describes the properties of materials used in the experiment, the experimental setup, and the test procedure. The fourth chapter is experimental result and discussion which shows the results from the experiment and briefly explains them and compare them with a theoretical model from literature. The final chapter gives a conclusion for the thesis and recommends ideas for further investigation.

2. LITERATURE REVIEW

2.1. General

Strengthening uses for reinforced structure (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 the RC structures are increase the reinforced concrete cross-section and increase the reinforced concrete reinforcement are examples. In the field of structural strengthening in recent years, the use of externally applied fiber-reinforced polymers (FRP) has gained significant popularity. The FRP composites have been used successfully for rehabilitation and upgrading of deficient reinforced-concrete (RC) structures such as buildings and bridges.

FRP composite materials have progressed into economically and structurally feasible construction materials for load bearing elements in buildings and bridges in recent years. Today there is a wide range of available types of FRP composites comprised with polyester, epoxy or vinyl-ester as matrices and reinforced with glass, carbon and aramid fibers with suitable properties for different applications in civil and structural engineering. One significant application of this composite strengthening technology is the use of FRP jackets to provide external confinement to RC columns when reinforcement that already exists is insufficient.

RC columns should be confined laterally in order to ensure large deformation under load before failure and to provide an adequate resistance capacity for the case of seismic events. Confinement may be beneficial in non-seismic zones too, where, for instance, survivability of explosive attacks is required, or the axial load capacity of a column must be increased due to higher vertical loads (e.g., increased traffic on a bridge). FRP sheet encasement is used to increase the axial load carrying capacity of the column with minimal increase in the cross-sectional area. Confinement in their case consists of wrapping the column with FRP sheets, prefabricated jacketing, or in situ cured sheets with fiber running in circumferential direction. The use of FRP confinement increases the lateral resistance pressure on the member which results in more ductility and higher load carrying capacity thus enabling the structure to withstand the effect of the seismic actions.

2.2.FRP Composite Material Properties

Composite materials as the name indicates are made by bringing together at least two separate fundamental materials, where one or more materials act as reinforcements, and the other one or more materials perform as the matrix [1]. From this definition the composite 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 in one or more directions [2]. Thus, we can say FRP composite has some resemblances to reinforced concrete (RC) by definition, with a fiber (such as glass, carbon or aramid) as the reinforcement (bars for RC) and a polymer (polymer resin matrix such as epoxy, polyester) i.e. concrete for RC. The fiber reinforcement supports the load in the premeditated directions and the polymer matrix operates as a binder, i.e. as a medium to transfer loads between adjoining fibers and to offer protection for the fiber. 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 [2].

FRP composites are anisotropic (properties appear in the direction of the applied load) making them different from customary construction materials such as steel or aluminum for the reason that steel or aluminum is isotropic (uniform properties in all directions, independent of applied load) [3]. The mechanical and physical properties of FRP are dictated by its constituent properties and by structural arrangements at the micro level. Therefore, the design and analysis of any FRP structural member require a good knowledge of the material properties, which are dependent on the manufacturing process and the properties of constituent materials. The figure below shows how FRP composites are formed.

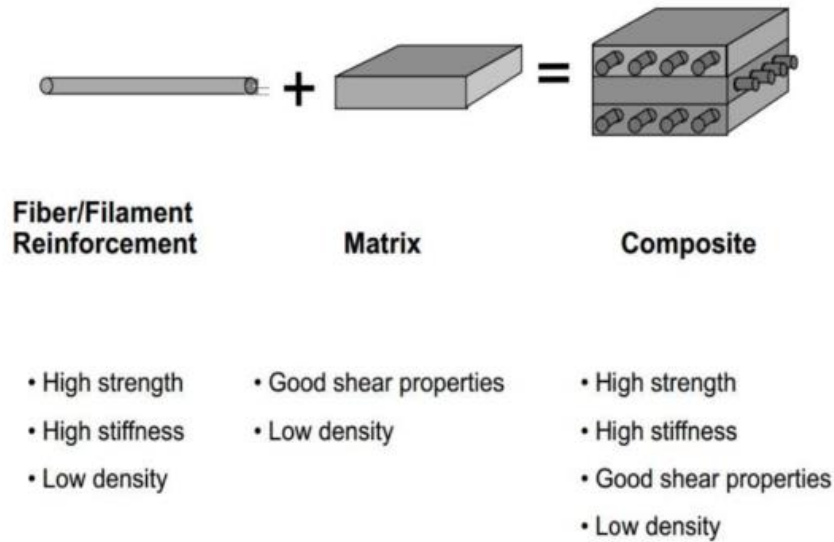


Figure 2-1 Formation of FRP

FRP composite properties are directional, meaning that the best mechanical properties are in the direction of the fiber placement and are composed of reinforcing part and matrix part. Straightway let us look at these parts in detail:

Risen: - the stresses that come to the fiber are safely transferred between them because they are glued together by risen. In addition, the presence of epoxy helps to protect the fibers from mechanical and environmental damage [2]. The capacity of the matrix dictates the ability of the fibers to resist load up to their maximum potential. Meaning a low strength matrix can lead to a premature failure. The most common resins used in the production of FRP attaching are epoxy and polyesters.

Reinforcements: - As mentioned earlier the fundamental function of reinforcements or fibers is to support load along the length of the fiber to provide strength and stiffness in that direction. Reinforcements are able to be placed in order to provide desired behaviors to which they are manufactured in a direction to carry the load for their practical use [2]. Now let us look at fiber in detail.

A fiber is a material made into a long strand with a diameter generally in the order of 10 micrometer. This makes the aspect ratio of length and diameter to go from thousand to infinity in

continuous fibers. To achieve these desirable functions, the fibers in FRP composite must have the following general properties [1]:

- High modulus of elasticity for use as reinforcement;
- high ultimate strength
- low variation of strength among fibers;
- high stability of their strength during handling; and
- High uniformity of diameter and surface dimension among fibers.

The most common types of fibers used in fiber reinforced polymer composites are:

- ❖ Glass fibers
- ❖ Carbon fibers
- ❖ Aramid fibers

Since a glass fiber type is used in this thesis, next we will see more detailed properties of this type of fiber.

Glass fibers: - Glass is principally made from silicon (SiO_2) with a tetrahedral structure (SiO_4). Some aluminum oxides and other metallic ions are then added in many proportions for making working operations easier or modify a few properties (e.g., from various glass fiber grades which differed in Composition, S-glass fibers exhibit a higher tensile strength than E-glass) [1]. These fibers frequently used in the naval and industrial fields to make composites of medium to high performance. The production technology of fiberglass is essentially based on spinning a batch made of sand, alumina, and limestone. FRP composites based on fiberglass are usually denoted as GFRP.

Glass fibers are heavier than carbon or aramid. Glass fibers have outstanding features, equal to or better than steel in some ways. lower modulus requires special design treatment where stiffness is critical. Their ability to withstand impact can be categorized as good [1]. Composites made from this material exhibit very good electrical and thermal insulation properties. Glass fibers are also transparent to radio frequency radiation and are used in radar antenna applications. The properties of different types of fibers are summarized in the next table.

Table 2-1 Properties of Different Fibers [1]

Material	Density (g/cm ³)	Tensile Modulus(E) (GPa)	Tensile Strength(σ) (GPa)	Specific Modulus (E/ σ)	Specific Strength	Relative cost
E-glass	2.54	70	3.45	27	1.35	Low
S-glass	2.50	86	4.5	34.5	1.8	Moderate
Graphite, high modulus	1.9	400	1.8	200	0.9	High
Graphite, high strength	1.7	240	2.6	140	1.5	High
Kevlar 29	1.45	80	2.8	55.5	1.9	Moderate
Kevlar 49	1.45	130	2.8	89.5	1.9	Moderate

From the table above, we can see that glass fibers typically have a Young modulus of elasticity lower than carbon or aramid fibers and their abrasion resistance is comparatively weak; therefore, attention in their use is essential. In addition, it has been observed that they are susceptible to creep and have low fatigue strength. To improve the bond between fibers and matrix, in addition to protecting the fibers itself against alkaline agents and moisture, fibers undergo sizing treatments acting as coupling agents. Such treatments are advantageous to enhance durability and fatigue performance (static and dynamic) of the composite material [1]. The stress-strain diagram of the fibers and the composite material can tell us a lot about their properties, the graph is shown below [3].

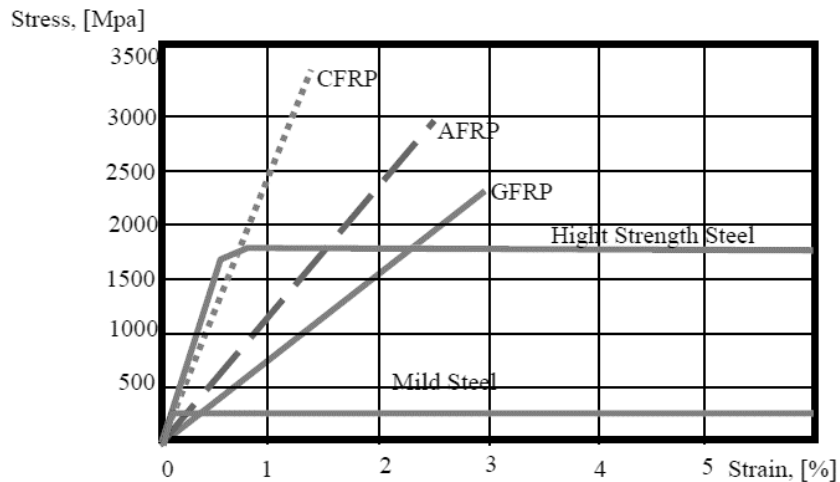


Figure 2-2 Comparison of Stress-Strain curve for Different FRP and Steel Types [3]

2.3. Advantage and Disadvantage of FRP

One of the most important things in FRP is for the end-user to be aware of the application environment, load performance and durability requirements of the product and apply this information on to the design of strengthened structural component. FRP composites have many benefits to their selection and use. The selection of the materials depends on the performance and intended use of the product. The composites designer can modify the performance of the end product with a proper selection of materials. The main benefits of FRP materials are summarized as follows [2].

- ✓ Lightweight
- ✓ High strength-to-weight ratio
- ✓ Directional strength
- ✓ Corrosion resistance
- ✓ Weather resistance
- ✓ Dimensional stability
- ✓ low thermal conductivity and coefficient of thermal expansion
- ✓ Non-magnetic
- ✓ High impact strength
- ✓ High dielectric strength (insulator)

- ✓ Low maintenance and long-term durability
- ✓ Small to large part geometry possible
- ✓ Tailored surface finish

And the main disadvantages of FRP materials are:

- ✓ 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 with this one of concrete and masonry.
- ✓ 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.

2.4.FRP Confinement of Columns

Confining of concrete columns is one of the most significant techniques which has been used by numerous researchers and engineers from many years ago to get strength and ductility improvement in concrete. In overall, there are two different methods for confining concrete. The first method which is known as active confinement, where there is a constant pressure applied to the concrete example for this is prestressed. The second one is passive confinement where lateral expansion is restricted by confining concrete with certain elements, for instance, steel jackets or FRP sheets. Therefore, tension due to the axial forces is developed in these confining elements. The increase of axial load in the column, in this case, increases the level of confinement, which means 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 rein on the lateral expansion of concrete leading to tensile stress in stirrups.

When an FRP confined cylinder is subject to axial compression, the concrete expands laterally, and this expansion is restrained by the FRP [4]. Due to this, stresses are developed in both concrete and FRP. The stress developed in the concrete is triaxial compression while the fiber resists a tensile stress in the hoop direction. This mechanism benefits them both, as a result, the strength

and the ultimate strain of concrete can be enhanced, while the tensile strength of FRP can be effectively utilized. Instead of the brittle behavior exhibited by both materials, FRP-confined concrete possesses an enhanced ductility [3]. For FRP wrapped, axially loaded columns the design philosophy relies on the wrap to carry tensile forces around the perimeter of the column as a result of the lateral expansion of the underlying column when loaded axially in compression. The figure below shows typical lateral expansion.

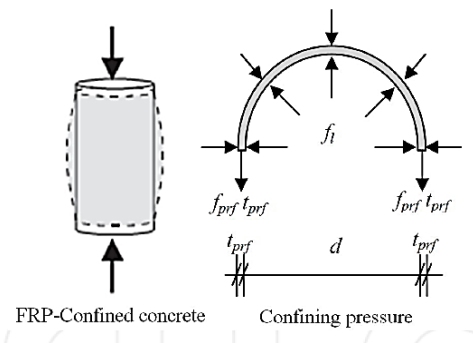


Figure 2-3 Lateral expansion and confining effect due to axial load [4]

When the columns of existing RC buildings are wrapped with FRP composites, the core concrete is restrained by using two distinct materials the metal spirals and the FRP composites. For the case of steel transverse reinforcement, the continuous confining pressure can be assumed when the steel is yielding, and the stress-strain relationships of steel-confined concrete progressively decreases after the yielding of the steel because the normal stress-strain curves of steel bars consist of three parts these are a preliminary linear elastic portion, a yield plateau in which strain increases with little or no increment in stress, and a strain-hardening range. 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 the single stage when subjected to a tensile force that is it goes linear elastic up to final brittle rupture [5].

The stress-strain curves of concrete confined with both steel and FRP composites are influenced with the lateral confining pressures of both confining materials. in the case of the lateral confining pressure of steel is smaller than the lateral confining pressure of FRP composites, the slope of the stress-strain curves of both material-confined concrete decreases after steel yielding. However, this slope is stiffer than that of the only steel-confined concrete [5].

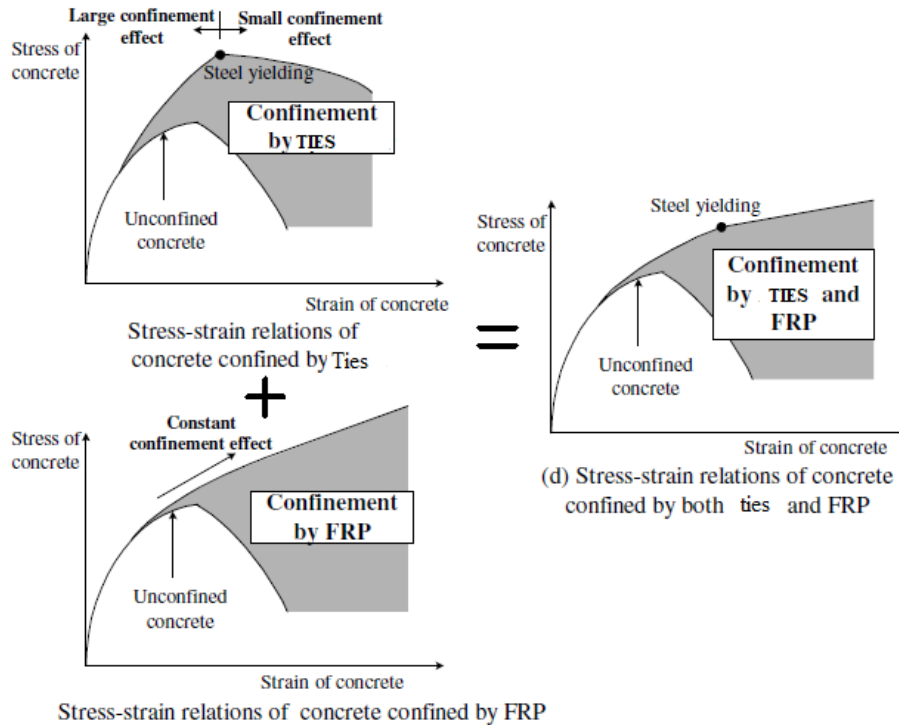


Figure 2-4 Stress-Strain Curve for Combined FRP and Steel confinement [5]

In circular sections, the radial translation caused by the applied axial load activates the confining mechanism and causes radial confining forces the same as hydrostatic confining pressure. This pressure causes a state of stress which is the same in every point of the section and at every point of the circumference, the lateral expansion of concrete is equal to the deformation of FRP [2]. In case of FRP confined rectangular sections, the concrete is non-uniformly confined, and the efficiency of confinement is much lessened. Meaning there is a smaller resistance to lateral expansion being provided by the FRP wrapped column sides [3]. That's because the confining sheet can confine the lateral displacement of corner parts but cannot confine the displacement outside the central part of the sides thus causing different stress-state in every point of the section [2]. The figure below shows the difference in effective area due to change in shape.

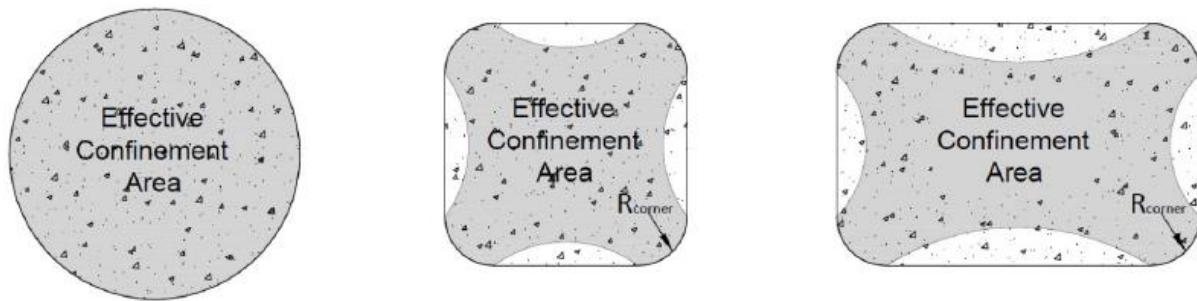


Figure 2-5 Effective confinement area in circular, square and rectangular columns

Finally, a correctly FRP confined column failure occurs when the FRP jacket ruptures as a result of tensile stresses in the hoop direction [2]. But a premature failure caused by the likes of insufficient capacity of the risen lead to slip and deboning of FRP at the overlap.

2.5. Review on Related Experimental Research

Many researchers have been done on the topics of FRP confined concrete. From these, some are concluded and presented in a brief manner. The first is from M. Mahdy [6] he presents experimental results of testing twelve reinforced concrete short columns with cylindrical (900 mm high with 190 mm diameter) shape. He reinforced all columns longitudinally with 5 ϕ 16 steel bars and transversally with helices 8 mm plain bars at 80 mm pitches externally confined with FRP subjected to loading (concentric and eccentric) and evaluates the effectiveness of two confinement materials (Carbon fiber and Glass fiber). The columns were wrapped with either carbon fiber or glass fiber with a different number of layers.

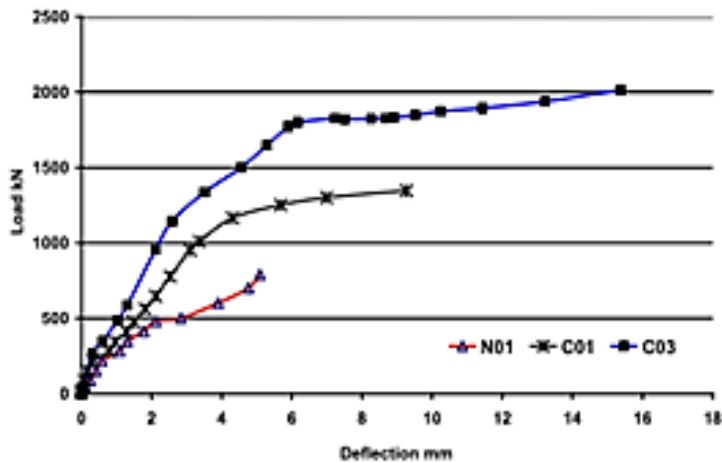
In his conclusion, the author reported that failure of strengthening columns was brittle, a very explosive failure. He reported that the snapping of fibers could be heard throughout the loading as the concrete tried to expand. It is of significance to note that he reported the column was appeared to be fully intact after failure as shown in the Figure below. This meant that after failure the column still had the ability to withstand load and still maintain its integrity.



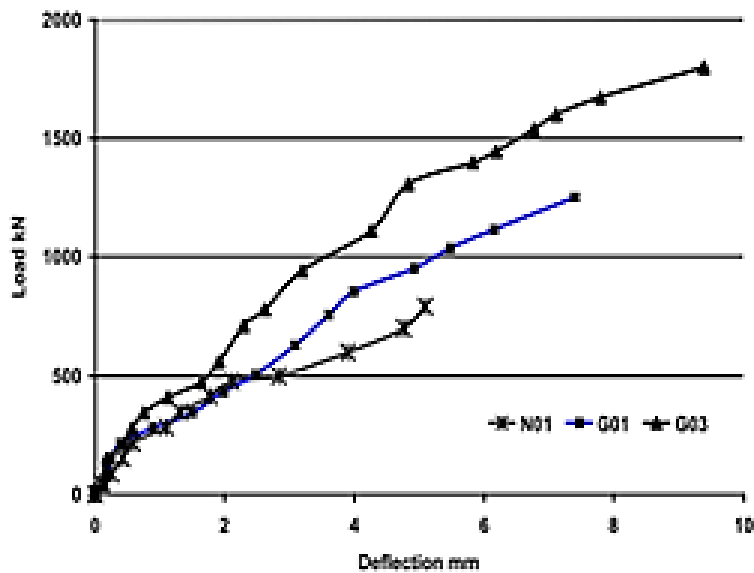
Figure 2-6: Mode of failure for columns under concentric load [6]

For the case of glass fiber confinement, he shows it also achieving higher strength and ductility. However, he reported there was not as much excess deflection achieved as the carbon fiber confinement. The specimen also remained intact after failure except for presence some fracture in the glass fiber. The values of ultimate loads increase for all fiber confinement columns by values ranged (70-155) % for Carbon confinement and (58-128) % for Glass fiber confinement compared with control columns (without fiber confinement).

For Fiber confinement column he showed there is an increase in deflection values ranged from (82-200) % for carbon confinement and (45-80) % for Glass fiber confinement, compare with control column (N01). Moreover, his Comparison among the concentrically loading columns confirmed that the confinement significantly enhanced the strength, ductility of concrete, in particular when applied in multiple layers, as shown in Fig 2-7.



Load-deflection of columns N01, C01 and C03



Load-deflection of columns N01, G01 and G03

Figure 2-7 Load-deflection comparison between results of test specimens

Another study from Riad Benzaid and Habib-Abdelhak Mesbah [4] deals with a series of tests on circular and square plain concrete (PC) and reinforced concrete (RC) columns strengthened with carbon fiber reinforced polymer (CFRP) sheets. In their experimental program included unconfined concrete strength (26, 50 and 62MPa), they present the mechanical properties of CFRP as thickness (per ply) 1 mm, modulus of elasticity 34GPa, Tensile strength 450MPa and Ultimate strain 14 %.

Their test specimens were short cylindrical specimens (with a diameter of 160 mm and a height of 320 mm) and short square columns specimens (with a square cross-section of 140x140 mm and a height of 280 mm). For all RC specimens, they used the diameter of longitudinal and transverse reinforcing steel bars of 12 mm and 8 mm respectively. They make the longitudinal steel ratio constant for all specimens and equal to 2.25%. The yield strength of the longitudinal and transversal reinforcement was reported to be 500 MPa and 235 MPa; respectively.

Their test results indicate that CFRP-confinement can significantly enhance the ultimate strengths and strains of both plain and RC-columns. As reported for normal-strength RC specimens (26Mpa) with circular and square cross-sections, the average increase in strength was in the order of 69% and 22% over its unconfined concrete strength for columns with 1 layer, 141% and 46% for columns with 3 layers of CFRP jackets, respectively. The axial strains they reported corresponding to CFRP-confined columns, for the normal-strength RC specimens with circular and square cross-sections, were on average 4.06 and 1.41 times that of unconfined concrete for 1 layer, 6.09 and 1.95 times for 3 layers of CFRP jackets, respectively.

The stress-strain curves they obtained, which characterize the CFRP confined concrete, were mostly bilinear. The first zone is essentially a linear response governed by the stiffness of the unconfined concrete, which indicates that no confinement is activated in the CFRP wraps since the lateral strains in the concrete are very small. The strengthening effect of the CFRP layers begins only after the concrete has reached the peak strength of the unconfined concrete: transversal strains in the concrete activate the FRP jacket. In this region little increases of load produce large lateral expansions, and consequently a higher confining pressure. In the case of circular sections, the section is fully confined, therefore the second slope is positive, showing the capacity of confining pressure to limit the effects of the deteriorated concrete core, which allows reaching higher stresses. With this type of stress-strain curves (the increasing type), both the compressive strength and the ultimate strain are reached at the same point and are significantly enhanced. Instead in the cases of square sections (sharp edges) with a small amount of FRP, the peak stress is similar to that of unconfined concrete, indicating the fact that the confining action is mostly limited at the corners, producing a confining pressure not sufficient to overcome the effect of concrete degradation. Otherwise with low levels of confinement (one CFRP layer), the second part of the

bilinear curve shifts from strain hardening to a flat plateau, and eventually to a sudden strain softening with a drastically reduced ductility.

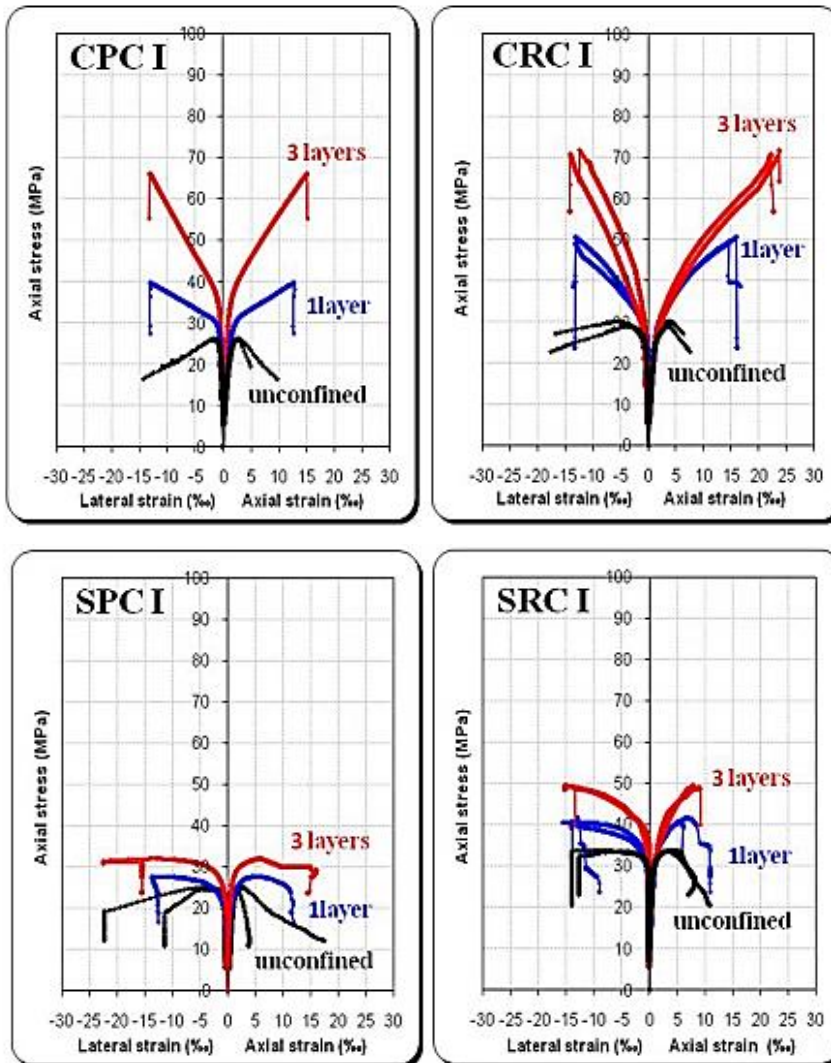


Figure 2-8 Experimental stress-strain curves of normal-strength concrete specimens (26MPa) [4]

The figures below illustrate the failure modes for circular and square columns wrapped with CFRP sheets. All the CFRP-wrapped cylinders were reported to fail by the rupture of the FRP jacket due to hoop tension; the confined specimens failed in a sudden and explosive manner and were only preceded by some snapping sounds. They added that, many hoop sections formed as the CFRP ruptured and were either concentrated in the central zone of the specimen or distributed over the entire height. The wider the hoop, the greater the section of concrete that remained attached to the

inside faces of the delaminated CFRP. Regarding confined concrete prisms, the reported failure initiated at or near a corner, because of the high stress concentration at these locations. The reported collapse occurred almost without advance warning by sudden rupture of the composite wrap. For all confined specimens, they say delamination was not observed at the overlap location of the jacket which confirmed that there was adequate stress transfer over the splice.

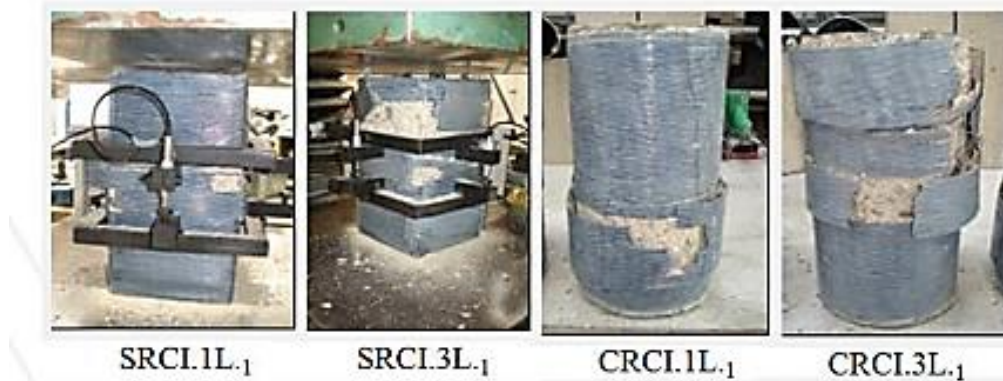


Figure 2-9 Typical failure modes for the tested specimens [4]

Experimental performed by Jung and et al. [5] consisting of 24-cylinder specimen with a height of 300mm and a diameter of 150mm. He classified his specimen in three steel group these are plain and a pitch size of 20, 40 and 60mm and 5 FRP layers from zero up to five layers. The compressive strength of concrete was 33.2MPa. In his finding he concluded the compressive strength of concrete confined with both carbon FRP and steel spiral was approximately the same to the sum of increments of the compressive strength of carbon FRP-confined concrete and spiral confined concrete.

He also implied that the stress-strain curve of concrete confined with both carbon FRP and steel spiral was influenced by the ratio of lateral stress by steel to lateral stress by FRP and the stress-strain curves of lateral confining materials. The slope of the stress-strain curve of both material-confined concrete that had more lateral stress by steel than lateral stress by FRP decreased after steel spiral had yielded. Thus, in order to predict with accuracy, the stress-strain curve of both material-confined concrete, it is needed to propose a model considering the effects of the ratio steel to FRP and the stress-strain curves of lateral confining materials. The maximum axial strain of concrete confined with both carbon FRP and steel spiral was approximately the same to the larger

maximum strains between CFRP-confined concrete and spiral-confined concrete. The current models, that depends on the sum of the lateral confining pressures overestimated the maximum strains of both material-confined concrete when their sum is high.

Experimental program conducted by Alper Ilki and et al. [7] consists of 15 columns having low transverse reinforcement with combination of the types low and normal strength concrete (15.9 and 31MPa), circular (diameters of 250mm and height of 500mm) and rectangular (side length of 250mm and height of 500mm) and different reinforcement ratio for longitudinal (bar diameter used are 10,12 and 14mm) and transverse bars (bar diameter used is 8mm).

In their conclusion they stated the carbon FRP jackets increased the compressive strength and corresponding axial strain of the columns with circular, square and rectangular cross-sections. For the normal strength specimens, confined concrete compressive strength and corresponding axial strain increased between 1.5 to 3.6 times and 16.5 to 26.0 times, respectively. For the low strength specimens, they increased between 2.8 to 6.3 times and 21.5 to 34.5 times, respectively While the strength enhancement was more pronounced for circular cross-sections, deformability enhancement was greater for rectangular cross-sections. The increase in deformability was significant even in the case of rectangular cross-sections with h/b ratio of 2.

Although the spacing of transverse bars in the test zone and the diameter of longitudinal bars were chosen for allowing buckling of the longitudinal bars, in the case of carbon FRP, jacketed specimens, the premature buckling of the longitudinal reinforcement was prevented and the contribution of longitudinal reinforcing bars to the axial resistance and ductility was maintained until very large axial strains. It is apparent that the possible tendency of longitudinal bar buckling did not have a negative influence on the behavior of carbon FRP sheets.

Independent of the jacket thickness, the measured maximum transverse deformations of carbon FRP jackets for normal strength and low strength specimens were between 0.012 to 0.015 and 0.013 to 0.015, respectively. The test results showed that carbon FRP jackets were more effective in the case of low concrete strength in terms of strength and deformability enhancement.

A research by Alireza Khaloo an et. al. [8] on thirty small-scale column specimens of 400 mm height and 120 mm diameter were tested. Based on the result of their extensive experimental study they concluded that at a low level of internal confinement, strength and ductility enhancements due to FRP confinement are considerable. However, in case of relatively high level of internal confinement, External FRP strengthening has limited influence on strength and ductility increase.

The studies showed that FRP is effective in strengthening concrete columns. Most of them tested on short column where buckling of longitudinal bar doesn't occur. One test was performed using only spiral transverse reinforcement for circular section. Here the tests are performed using only circular and rectangular hoops.

2.6. Review on Confinement Models of Reinforced Concrete

Various models for the confinement of concrete with FRP have been developed. The majority of these models were performed on plain concrete specimens' tests. 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 Richart et al. [9], in which the strength at failure for concrete confined by lateral pressure takes the following form:

$$f'_{cc} = f'_{co} + k_1 f_l \quad (2-1)$$

Where f'_{cc} and f'_{co} are the compressive strength of confined and the unconfined concrete respectively, f_l is the lateral confining pressure and k_1 is the confinement effectiveness coefficient. In applying their model to steel-confined concrete, Richart et al. [9] assumed that k_1 is a constant equal to 4.1. However, several studies revealed that existing models for the axial compressive strength of steel-confined concrete are un-conservative and cannot be used for FRP-confined concrete. Many authors have raised towards the steel-based confinement models the objection that they do not account for the profound difference in uniaxial tensile stress-strain behavior between steel and FRP. According to these authors, while the assumption of constant confining pressure is still realistic in the case of steel confinement in the yield phase, it cannot be extended to FRP materials which do not exhibit any yielding and therefore apply on the concrete core a continuously

increasing inward pressure. However, a number of strength models have been proposed specifically for FRP-confined concrete which employs the above equation with modified expressions for k_1 . Most of these models used a constant value for k_1 (between 2 and 3.5) indicating that the experimental data available in the literature show a linear relationship between the strength of confined concrete f'_{cc} and the lateral confining pressure f_l . Other researchers expressed k_1 in the nonlinear form in terms of f_l/f'_{co} or f_l .

When talking about the confinement of RC elements with FRP in order to increase strength and ductility is complex problem and not completely solved especially for circular and rectangular columns with existing steel reinforcement. In fact, interaction mechanisms between internal steel reinforcement and external FRP are not sufficiently studied especially in relation to the efficiency of FRP confinement technique. Analytical models actually present in the literature e.g. Ilki and Kumbasar [7]; Lam and Teng [10]; Li et al [11]; are principally calibrated with experimental studies without taking into account the effect of the existing steel reinforcement on the structural performance of the FRP confined element.

According to most of the researches and codes the confinement pressure is taken equal to that of due to FRP only neglecting the subsequent contribution of the internal transverse steel reinforcement correlating the increase of strength and ductility with the confinement pressure, whereas only some of the most recent analytical models Li et al. [11]; Ilki et al. [7] takes the total confinement pressure as the sum of the confinement pressure due to the external FRP jacketing, and the confinement pressure due to the internal transverse steel reinforcement i.e. stirrups or spirals, eventually present. In these models, the interaction between FRP and steel confinement actions and its influence on the effectiveness of the FRP confinement technique are not explicitly considered. In the coming sections will see the literature that only considers the effect of the FRP only and literature that consider both the steel and FRP confinement.

2.6.1. Lam & Teng Model

Lam & Teng proposed a design-oriented model which describes the stress-strain relationship of FRP-confined concrete [10]. This model is only for uniformly confined concrete. The compressive strength of FRP-confined concrete (f'_{cc}) is predicted using

$$f'_{cc} = f'_{co} + 3.3f_1^{0.7} \quad (2-2)$$

$$f_1 = \frac{2E_{frp}\epsilon_{h,rupt}}{D} \quad (2-3)$$

$$\epsilon_{h,rupt} = k_e \epsilon_{frp} \quad (2-4)$$

k_e is the FRP efficiency factor and has a value of 0.586. Lam & Teng proposed that the ϵ_j should be taken as the actual hoop rupture strain $\epsilon_{h,rupt}$ measured in the FRP jacket and not the ultimate FRP tensile strain ϵ_{frp} as is assumed ideally. The ultimate concrete axial strain of uniformly confined concrete, ϵ_{cu} is given by:

$$\frac{\epsilon_{cu}}{\epsilon_{co}} = 1.75 + 12 \frac{f_1}{f'_{co}} \left(\frac{\epsilon_{h,rupt}}{\epsilon_{co}} \right)^{0.45} \quad (2-5)$$

Here, the axial strain (ϵ_{co}) at the compressive strength of unconfined concrete is taken as 0.002. For rectangular columns since the area of confinement decreases the model is modification is next.

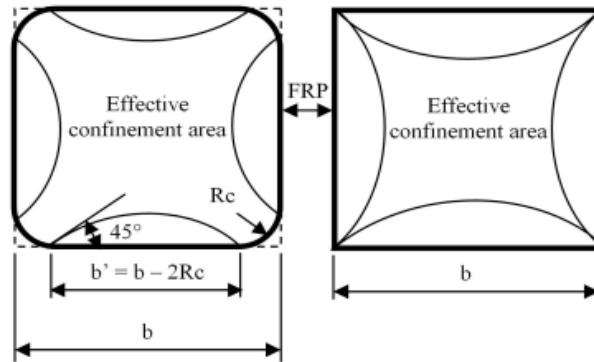


Figure 2-10 Effective confinement area

$$\frac{f'_{cc}}{f'_{co}} = 1 + k_1 k_s \frac{f_1}{f'_{co}} \quad (2-6)$$

The lateral confining pressure f_1 is the same as the circular one with the exception of D being the diameter of an equivalent circular column. In Lam's model k_1 is taken as 3.3 and k_s is the shape effectiveness and is given by:

$$k_s = \left(\frac{b}{h}\right)^2 \frac{A_e}{A_c} \quad (2-7)$$

Where, b and h are width and length of the rectangular section, respectively. A_e/A_c is effective confinement area ratio.

$$\frac{A_e}{A_c} = \frac{1 - \frac{\left(\frac{b}{h}\right)(h-2R_c)^2 + \left(\frac{h}{b}\right)(b-2R_c)^2}{3A_g} - \rho_s}{1 - \rho_s} \quad (2-8)$$

Where: - A_e and A_c are the effective confinement area and the total area of concrete.

- ρ_s is the cross-sectional area ratio of the longitudinal steel reinforcement.
- R_c is the corner radius of the rectangular section.
- A_g is the gross area of the column section with rounded corners, which can be evaluated by:

$$A_g = bh - (4 - \pi)r^2 \quad (2-9)$$

Therefore, Lam's model can be expressed as follows

$$\frac{f'_{cc}}{f'_{co}} = 1 + 3.3 \left(\frac{b}{h}\right)^2 \frac{A_e}{A_c} \frac{f_1}{f'_{co}} \quad (2-10)$$

While determining the confinement pressure (f_1), ε and D are taken as $0.85\varepsilon_{FRP}$ and $\sqrt{(h^2 + b^2)}$, respectively.

2.6.2. Research by Carlo Pellegrino and Claudio Modena

Carlo Pellegrino and Claudio Modena [12] tried to contribute a better understanding of the behavior of reinforced concrete columns confined with fiber reinforced polymer (FRP) sheets. In particular, some new insights on interaction mechanisms between internal steel reinforcement and external FRP strengthening and their influence on the efficiency of FRP confinement technique are given. In this context a procedure to generate the complete stress-strain response including new analytical proposals for:

- effective confinement pressure at failure;
- peak stress;
- ultimate axial strain; and

The computed confinement pressure f_{if} due to FRP wrapping as:

$$f_{if} = 1/2 k_f \rho_f E_{frp} \epsilon_f^{eff} \quad (2-11)$$

Where E_{frp} is the elastic modulus of the FRP strengthening, k_f is the coefficient of efficiency of the confinement and ρ_f is the FRP strengthening ratio explained in the annex. The term ϵ_f^{eff} is the effective hoop FRP strain. According to the experimental results available in the literature, this strain is less than the ultimate FRP strain. On this basis, most of the analytical models reduce the ultimate FRP strain ϵ_{fu} , for the calculation of the confinement pressure at failure, with a coefficient of efficiency of the FRP strengthening k_e .

$$\epsilon_f^{eff} = k_e \epsilon_{fu} \quad (2-12)$$

Matthys et al. [13] suggested, according to their experimental results, the value of $k_e=0.5$, whereas Lam and Teng [10] proposed various values, according to the type of composite used, between 0.6 and 0.85. For columns with internal steel stirrups or spirals, the confinement pressure due to transverse reinforcement is usually calculated as:

$$f_{is} = 1/2 k_s \rho_{st} f_{yst} \quad (2-13)$$

where ρ_{st} =transverse steel ratio; $f_{y,st}$ =yield stress of the transverse steel reinforcement; and k_s =coefficient of efficiency for the confining transverse steel. The above equation is based on the approach proposed by Mander et al. [14]. The coefficient of efficiency k_s for the confining transverse steel is described in the annex.

Effective confinement pressure at failure

The total confining pressure P_u can be computed as the sum of the contributions due to FRP wrapping f_{if} and transverse steel reinforcement f_{is} , reduced with the ratio A_{cc}/A_g , where A_{cc} =area of the cross section included in the transverse steel and A_g area of the overall cross-section.

$$P_u = f_{lf} + f_{ls} \frac{A_{cc}}{A_g} \quad (2-14)$$

Peak stress

The model for the peak stress is inspired to that of Harajli et al. [15] and those for the confinement with transverse reinforcing steel, in which peak stress of the confined concrete f_{cc} is increased with respect to that of the unconfined concrete f_{co} , proportionally to the total confining pressure at failure P_u .

$$\frac{f_{cc}}{f_{co}} = 1 + k_1 \frac{P_u}{f_{co}} \quad (2-15)$$

The coefficient k_1 , in the present analytical model, is computed as

$$k_1 = k_A \quad (2-16)$$

The coefficient k_A is computed with the same formula proposed by Harajli et al [15].

$$k_A = A \left(\frac{P_u}{f_{co}} \right)^{-\alpha} \quad (2-17)$$

but the parameters A and α are computed by means of a regression analysis of the experimental data and related to the columns with $2r/b \geq 0.3$ only. Considering separately the coefficients for circular and rectangular columns, with and without steel reinforcement, the values listed in Table in the appendix.

3. MATERIALS, METHODS AND TEST SETUP

3.1.Introduction

The main effort of this experimental program is to study the behavior of normal strength columns confined with fiber reinforced polymer. The experimental program included a total of twenty-two specimens where nine are FRP confined circular column specimens, three steel confined circular column specimens three unconfined circular column specimens, four FRP confined rectangular column specimens, two steel confined rectangular column and finally one unconfined rectangular column specimens subjected to axial compression. Detail of the material properties, test specimen, test set up and method are presented in this section

3.2.Material Property

3.2.1. Concrete

A normal strength concrete is prepared using ACI mix design procedure. The attend 28 days cubic compressive strength is 25.1mpa.

Cement: - Pozzolanic Portland cement (PPC) with a specific gravity of 3.15 is used in the concrete mix

Fine Aggregate: - The fine aggregate used in this research was natural siliceous sand. The sand used was clean, free from impurities, silt, loam, and clay. The main physical and mechanical properties of the used sand are summarized in the table 3-1 below.

Table 3-1: physical and mechanical properties of Fine Aggregate

Fineness modulus	3.4
Specific gravity	2.23
Absorption capacity	6.16
Silt content	3.8

The sieve analysis is listed in the appendix.

Coarse Aggregate: - The coarse aggregate used in this research was natural gravel, clean, free from organic silts, loam, injurious matter, and clay. Nominal aggregate size of 25mm is used in the mix.

Table 3-2 physical and mechanical properties of Coarse aggregate

Fineness modulus	7.32
Specific gravity	2.87
Absorption capacity	1.24

The sieve analysis and gradation curve are listed in the appendix.

3.2.2. Reinforcement Bar

Diameter 6mm bars are used in for the circular specimen while 8mm diameters are used for the rectangular ones as transverse ties. After the tensile test for both bars, the yield and ultimate tensile strength together with test summary are listed in the table 3-3 below.

Table 3-3 Experimental Data for Yield and Ultimate stress of Reinforcing Bars

Sample	Average Diameter (mm)	Area (mm ²)	Yield Load (kN)	Failure Load (kN)	Yield Stress (MPa)	Tensile Stress (MPa)	Ultimate Strain (%)	Average Yield Stress(MPa)	Average ultimate Tensile Stress(MPa)
F6,1	5.84	26.79	4.6	8	171.73	298.66	18.00	154.93	276.43
F6,2	5.38	22.73	3.6	6.8	158.36	299.13	21.00		
F6,3	5.50	23.76	3.2	5.5	134.69	231.50	25.00		
F8,1	8.11	51.66	20.6	26.4	398.78	511.06	12.50	439.64	550.12
F8,2	8.09	51.40	21.4	26.8	416.32	521.37	8.50		
F8,3	7.69	46.45	23.4	28.7	503.82	617.93	8.50		

The average yield strength values are used in theoretical calculations.

3.2.3. FRP

The unidirectional FRP is a non-corrosive and high alkali resistance fabric produce by VITRULAN company with behavior given in the following table 3-4 is used in this thesis.

Table 3-4 Summary of FRP Properties [16]

FRP type	E-Glass
Tensile Strength	772.95 MPa
Young's Modulus	21 GPa
Thickness	0.69mm
Fiber orientation	Uni-directional
FRP weight	168g/m ²

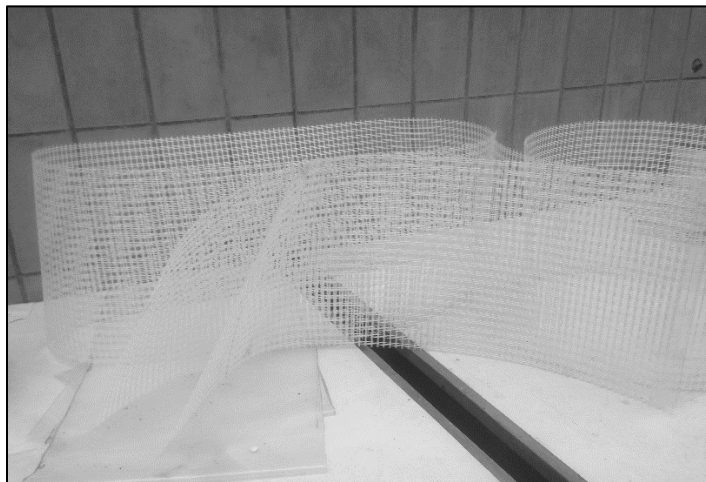


Figure 3-1 GFRP Used in the Experiment

Adhesive

An epoxy-based adhesive is used to bond the FRP with the concrete. The main properties of the adhesive are listed in the table 3-5 below.

Table 3-5 Summary of Adhesive Properties

Compressive Strength	50-60N/mm ²
Flexural strength	30-35N/mm ²
Tensile Strength	18-20N/mm ²
Bond strength to concrete	2.5-3N/mm ² (concrete failure)
Density	1.4kg/l

3.2.4. Prime

The prime is used to penetrate the surface of concrete providing an improved adhesive bond for the saturating resin or adhesive.

3.3. Test Specimen Preparation

The test specimens are mainly divided into two groups depending on their shape. The first is the circular specimen that has a 150mm diameter and 300mm height. They are set in 5 groups, these are first the control group which is plain concrete specimens, the second is concrete confined by transverse steel ties and the final three are one, two and three-layer FRP wrapped concrete with transverse steel ties. The second is rectangular specimen with a dimension of 150mm x 150mm x 300mm with a sub-classification of plain concrete specimens, concrete confined by transverse steel ties and the other two are two and three-layer FRP wrapped concrete with transverse steel ties. To study the effect of confinement only, in all cases, no longitudinal bars have been used. The reinforcement arrangement, the formwork and the casting of these specimens are shown in the figures below.

The transverse reinforcements were arranged with a center to center spacing of 67.5mm and were tied with 2.5mm wire to keep them in place. The clear cover of the concrete is 15mm. The concrete was mixed by a mechanical mixer and compacted using a vibrator.



Figure 3-2 Rebar Arrangement for Rectangular (Left) and Circular (Right) Specimens



(a)



(b)



(c)

Figure 3-3(a-c) Formworks and Rebar placing for Rectangular and Circular Specimens

Surface preparation was needed to bond the FRP with the concrete, so the specimens were washed, dried with air blow and coated with prime as shown in the figure 3-5 below.



Figure 3-4 Circular Specimens Before Surface Preparation



Figure 3-5 Circular Specimens After Surface Preparation

To keep the FRP debonding from the concrete quarter of the perimeter length were added as overlap.

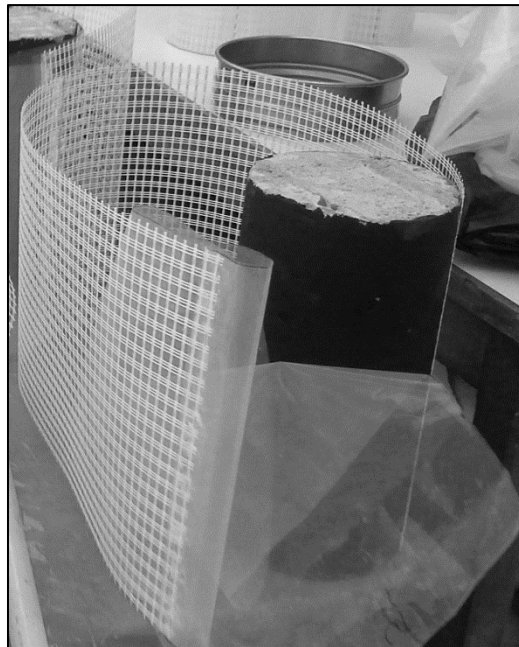


Figure 3-6 Wrapping of Circular Specimen With FRP

3.4. Test Setup and Experimental Procedure

After the test specimens were cured for 28 days the FRP layers were bonded using epoxy adhesive and allowed to cure up to 10 days. Then they were tested in the universal uniaxial testing machine which has a maximum loading capacity of 3000kN. To gain 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, also the load rate was changed to 0.25mpa/sec. Linear variable displacement transducer (LVDT) is used to measure the deflection of the specimens. The LVDT and load cell arrangement on the specimens are shown in the figure 3-7 below.

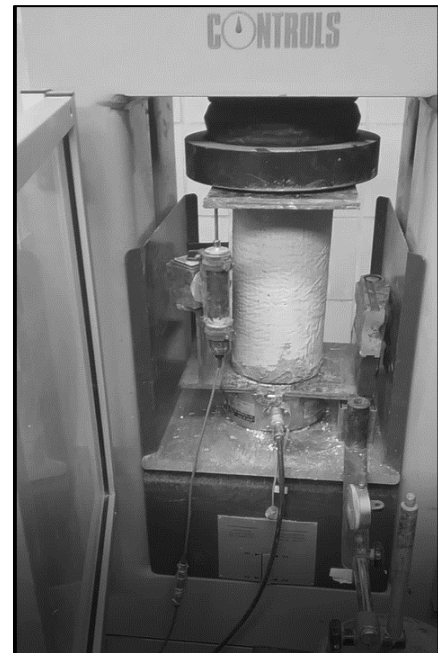


Figure 3-7 Experimental Setup for Rectangular(left) and Circular (right) Specimen

4. EXPERIMENTAL RESULTS AND DISCUSSION

4.1. Introduction

In this chapter, the test results of unconfined and confined specimens are presented. The behaviors observed during the experiments are discussed in detail. First, the results from the circular specimens are presented followed by a comparison between the circular unconfined concrete, circular concrete that is confined by steel ties and circular FRP wrapped concrete with steel tie confinement. Then the results from the rectangular section are described followed by the same comparison of rectangular unconfined concrete, rectangular concrete that is confined by steel ties and rectangular FRP wrapped concrete with steel tie confinement. Finally, a comparison between the circular specimen experimental result and the rectangular specimen experimental result are put in contrast and are briefly discussed.

Theoretical models from different researchers are used to estimate the analytic capacities of the FRP wrapped specimens and their results are compared with the results from the experimental programs.

4.2. Results of Circular Specimens

This section presents the results from the plain concrete, concrete with lateral steel ties and the FRP wrapped concrete confined with steel ties for circular shape specimens. The reading from the load cell which is recorded in the data logger is converted into stresses and the reading from the linear variable displacement transducers (LVDT) which is also recorded in the data logger is converted to strain by dividing it with the height of the specimen.

After the load cell data in the data logger shows the specimen has reached its peak the reading of load starts to drop, after some drop the test is brought to an end.

Here in every category three samples were taken and tested. The comparison between the samples is elaborated for each category.

4.2.1. Plain circular concrete

The plain circular concrete sample is taken as the control group for the class of circular specimens. The increment in the other circular sets is estimated by dividing their results with the plain circular ones.

Here the stress-strain curve of one of the plain concrete specimen is shown in the figure 4-1. The specimen reached a peak stress of 21.16MPa. the other two specimens have a maximum stress of 17.62 and 23.62Mpa so the average value of plain concrete circular specimen is 20.8MPa. the difference in the results of these three sample specimens due to the fact that the occurrence of local failure which is described as a failure at only the top or bottom part of the specimen. this phenomenon greatly affects the result of this specimen but since an average is taken the result somehow becomes satisfactory. The term CPC represents circular plain concrete in the figure 4-1 below.

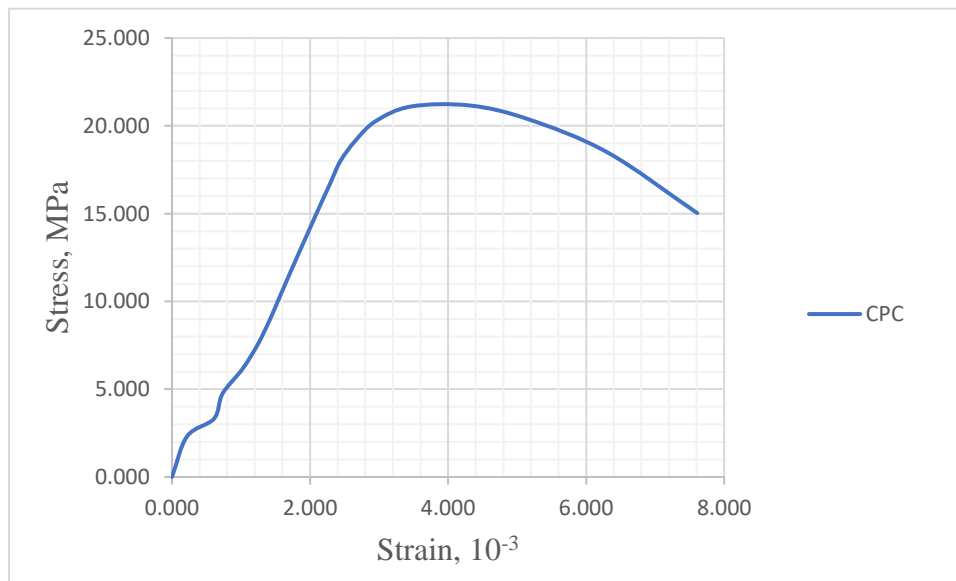


Figure 4-1 Stress-Strain Graph for Circular Plain Concrete Specimen C

The figure 4-2 below shows the failure of the plain circular specimen, a little local failure is observed but since it also propagated up to the center of the specimen it can be shown as a conventional failure for a plain concrete.



Figure 4-2 Typical Failure of Circular Plain Concrete Specimen

4.2.2. Circular concrete confined by steel ties

This specimen is different from the plain circular concrete one by the addition of lateral steel ties. The steel used for this circular specimen has a diameter of 6mm and its arranged in a hoop form. These circular steel hoops are connected by a 2.5mm wire and attached to the formwork so that there should not be any movement of the steel hoops and the concrete cover is kept constant throughout while they formwork is filled with concrete.

The use of this specimen in this thesis is to show the use of steel stirrup and their ability in increasing the axial carrying capacity of a column. The two main usage of steel ties are first to prevent the longitudinal steel from buckling and the other is to prevent the concrete from lateral expansion i.e. for the confinement of concrete. Now since the specimen used is very short the first usage is limited meaning the longitudinal bar does not buckle. Thus, by taking the longitudinal bar out we can clearly see the second usage of this hoop as they increase the axial capacity of the specimens.

In an observation of the test, the concrete specimen with steel ties showed an increase in maximum stress than the plain as expected and has given a much higher peak and ultimate strain values

because they have managed to sustain a higher load than the plain concrete specimens after they reached peak stress. The stress-strain curve for the three specimens is shown in figure 4-3 below. The notation CSC in the graph is for circular steel confined concrete and the letters A, B, and C denotes the sample type. The values of the peak stress of the three specimens are 23.92, 27.71 and 19.02MPa with an average of 23.55MPa.

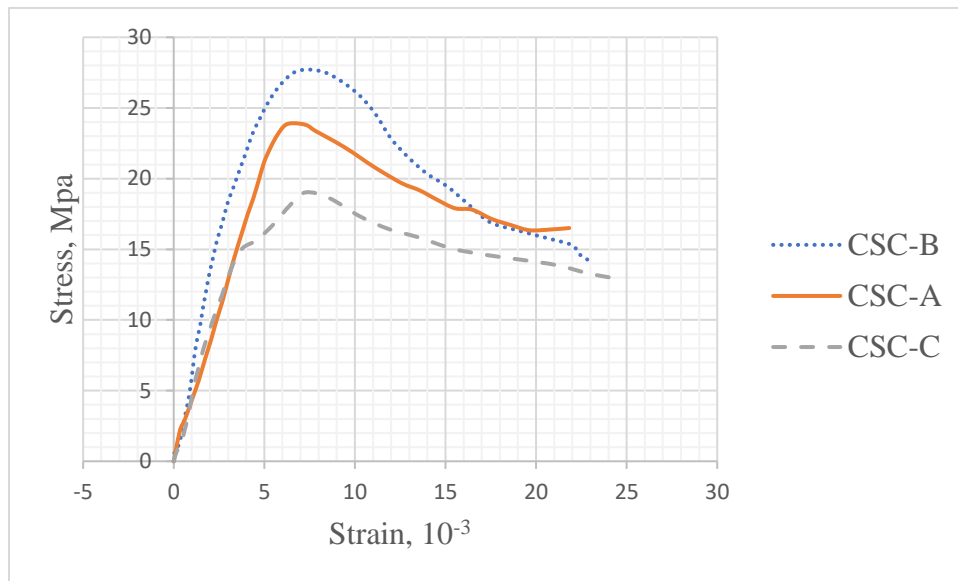


Figure 4-3 Stress-Strain Graph for Circular Concrete Confined with Lateral Steel

The figure 4-4 below shows one of the concrete confined by steel stirrups. The wires used played a good role in keeping the stirrups at the position. If you take a look at the stirrups they were able to keep the concrete from dilation thus increasing its axial carrying capacity. The concrete in the core looks intact which is a good sign of the failure not being sudden.



Figure 4-4 Typical Failure of Circular Reinforced Concrete Specimen A

4.2.3. FRP wrapped circular concrete with steel ties

These specimens are the main focus of this thesis. After the FRP is cured and the test set up arranged the FRP wrapped concrete with steel ties are set for the test. Here the upper face of the specimen is smoothed this can reduce the effect of local failure and as the number of layers increase they tend to make these weak spots strong and let the load transfers to the middle part. Thus, this multi-layer specimen tends to give us a consistent result than the rest.

The FRP wrapped circular samples showed all 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 specimens have 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 layer increase the failure of the specimen become more sudden. 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.

The maximum stress reached by one-layer specimen are 27.93, 31.83 and 23.29MPa with an average of 27.68MPa. For two-layer specimen are 32.96, 31.3 and 29.15MPa with an average of 27.68MPa. And For three-layer specimen are 38.17, 35.76 and 36.77MPa with an average of 36.9MPa.

The notation CFSC represents circular fiber wrapped steel confined concrete. While the number after that gives the number of layers of FRP that is applied on that specimen and the letter A, B or C after the number tells the specific specimen within the subcategory.

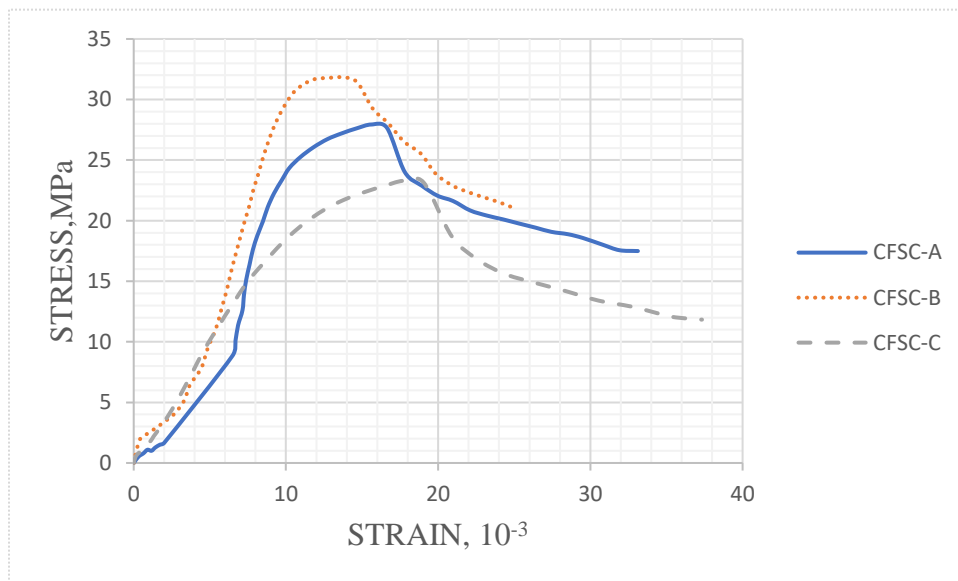


Figure 4-5 Stress-Strain Graph for Circular Concrete Wrapped with One Layer FRP and Confined with Lateral Steel

From the above figure 4-5 for one-layer specimens, we can easily see that after the specimens reach their peak stress they are accompanied by a sharp fall up to some load and they start to sustain a load and continue to deflect.

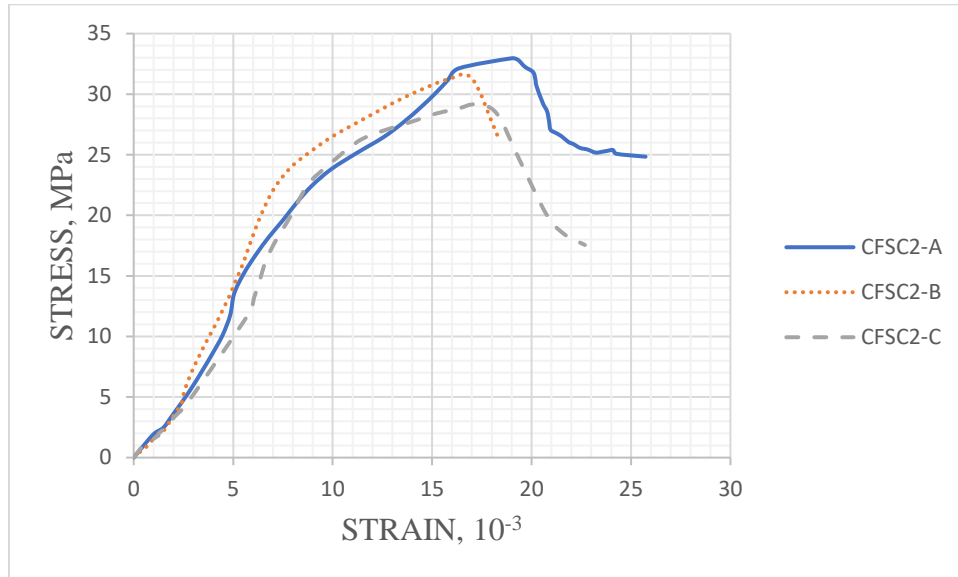


Figure 4-6 Stress-Strain Graph for Circular Concrete Wrapped with Two-Layer FRP and Confined with Lateral Steel

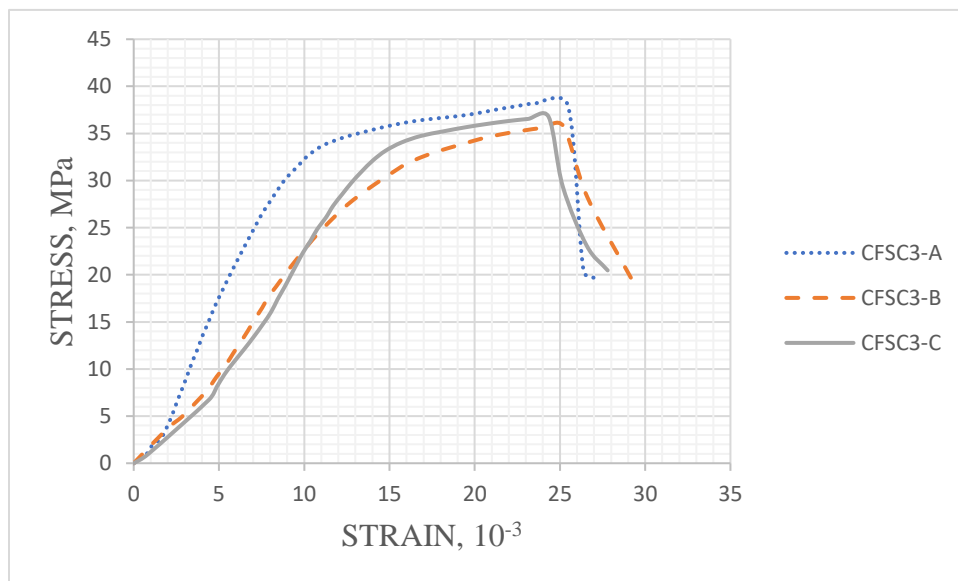


Figure 4-7 Stress-Strain Graph for Circular Concrete Wrapped with Three Layer FRP and Confined with Lateral Steel

The figure 4-8 below shows a typical failure of the one-layer specimen. For specimen concrete confined by FRP unlike the specimens that are only with lateral steel ties, after the specimen reaches its peak strength the cover of the concrete does not spall off but its kept intact by the externally wrapped FRP. When the load increases the expansion of the core concrete starts which

activates the confinement effect of the FRP wrapped confined concrete specimens. This is the reason why there is an increase in the axial capacity of this specimens.



Figure 4-8 Typical Failure for Circular Concrete Wrapped with One Layer FRP and Confined with Lateral Steel



Figure 4-9 Typical Failure for Circular Concrete Wrapped with Two-Layer FRP and Confined with Lateral Steel



Figure 4-10 Typical Failure for Circular Concrete Wrapped with Three Layer FRP and Confined with Lateral Steel

The previous figures show all of the specimen's fibers are ruptured. Most of the rupture occurred in the middle part of the specimens which shows that the FRP was preventing the concrete from dilation. The damage of the concrete was higher in the one-layer specimens while the three-layer specimen just show the rupture of the FRP.

4.2.4. Comparison between Circular Specimens Result

To show the effectiveness of FRP wrap the comparison between the specimens is performed. The three-layer specimen gave the higher result as expected with an increase of 77% from the control plain concrete. A summary of the comparison between the specimens is shown in the table 4-1 given below.

Table 4-1 Comparison Between Circular Specimens

Specimen Description	Maximum Stress (MPa)	Mean Value (MPa)	Ratio to Plain Specimen
CPC-A	17.62	20.8	1
CPC-B	21.16		
CPC-C	23.62		
CSC-A	23.92	23.55	1.13
CSC-B	27.71		
CSC-C	19.02		
CFSC1-A	27.93	27.68	1.33
CFSC1-B	23.29		
CFSC1-C	31.83		
CFSC2-A	32.96	31.14	1.5
CFSC2-B	31.3		
CFSC2-C	29.15		
CFSC3-A	38.17	36.9	1.77
CFSC3-B	35.76		
CFSC3-C	36.77		

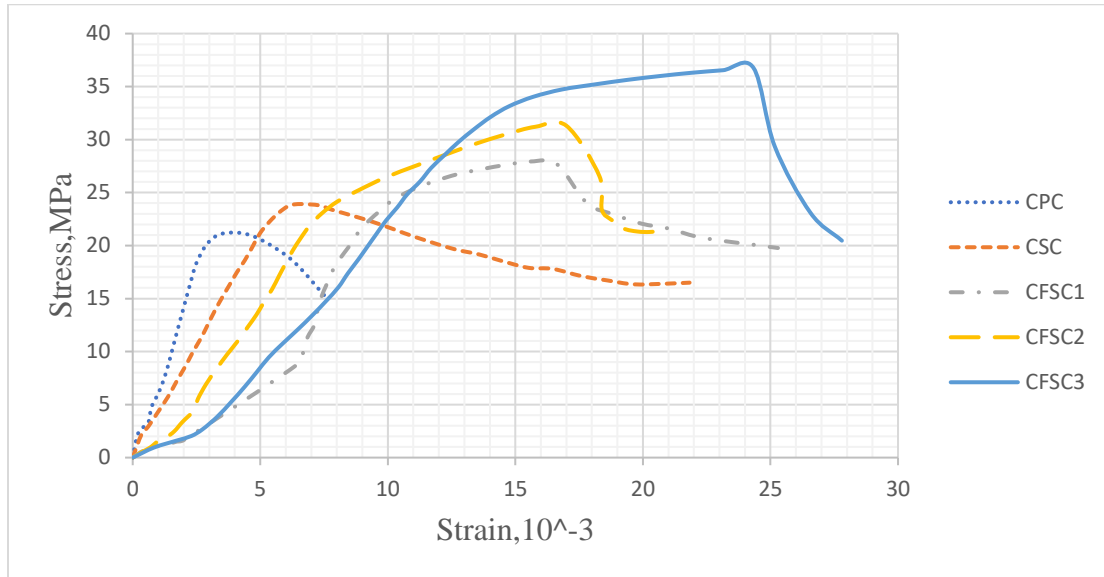


Figure 4-11 Stress-Strain Comparison Between Circular Specimens

4.3. Results of Rectangular Specimens

This Part shows the results from the plain concrete, concrete confined with steel ties and the FRP wrapped concrete confined with steel ties of rectangular specimens.

4.3.1. Plain rectangular concrete

The plain concrete specimens reached its peak stress at 17.36MPa. The stress-strain curve of the plain concrete specimen is shown in the figure 4-12 below.

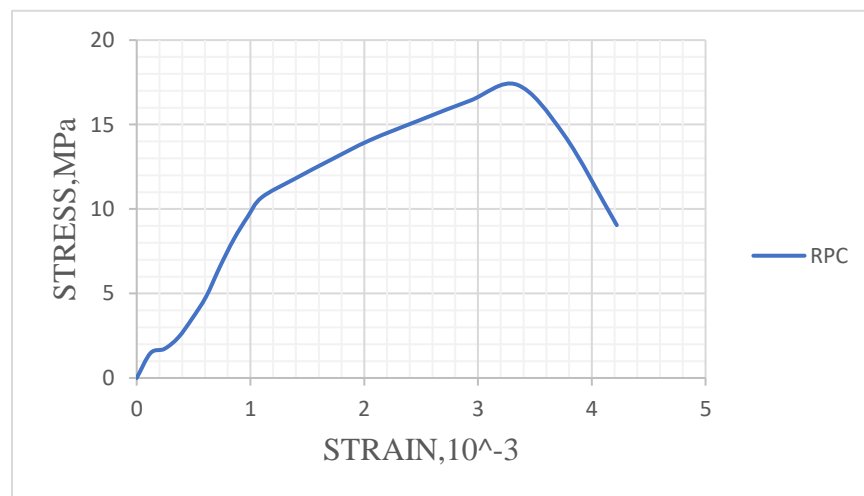


Figure 4-12 Stress-Strain Graph for Rectangular Plain Concrete Specimen



Figure 4-13 Typical Failure of Rectangular Plain Concrete Specimen

4.3.2. Rectangular concrete confined by steel ties

The steel confined concrete specimen as the circular one showed an increase in maximum stress than the plain and has given a much higher peak and ultimate strain values. The stress-strain curve for the two specimens is shown in the figure 4-14 below. The values of the peak stress of the two specimens are 21.63 and 20.43MPa with an average of 21.03MPa

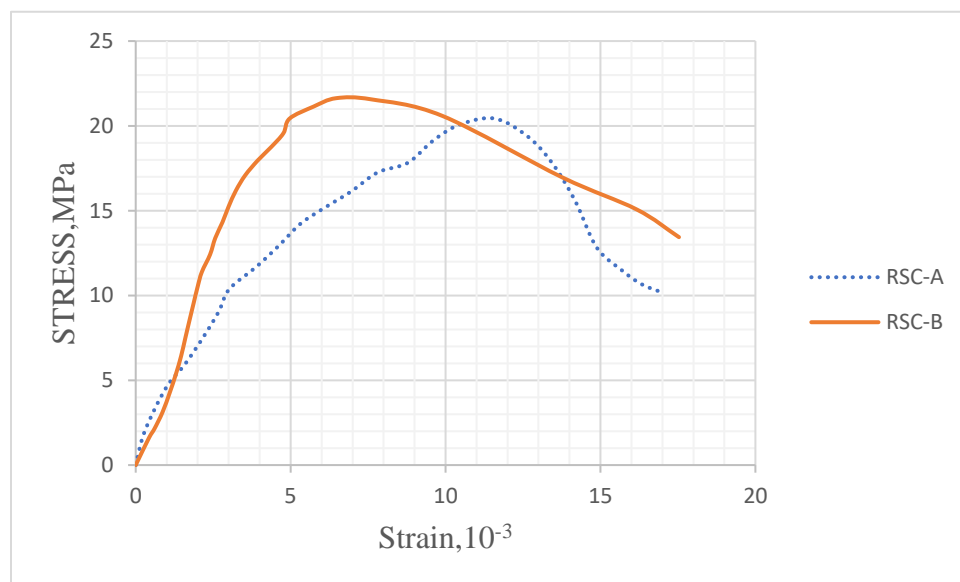


Figure 4-14 Stress-Strain Graph for Rectangular Concrete Confined with Lateral Steel



Figure 4-15 Typical Failure of Rectangular Reinforced Concrete Specimen

4.3.3. FRP wrapped rectangular concrete with steel ties

The FRP wrapped rectangular samples showed an increase in peak strength than the plain and the reinforced specimens and we can also say as the layer increased the peak stress increased. Like the circular ones 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 a small popping off the outer plaster epoxy.

The maximum stress reached by two-layer specimen is 21.51 and 23.78MPa with an average of 22.66MPa. And for three-layer specimen are 24.68 and 24.87MPa with an average of 24.78MPa.

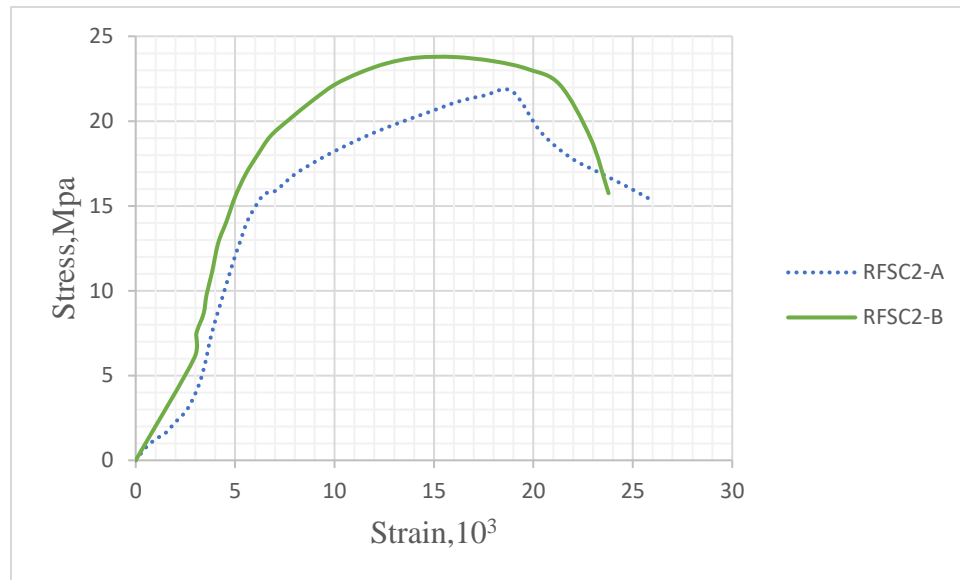


Figure 4-16 Stress-Strain Graph for Rectangular Concrete Wrapped with Two-Layer FRP and Confined with Lateral Steel

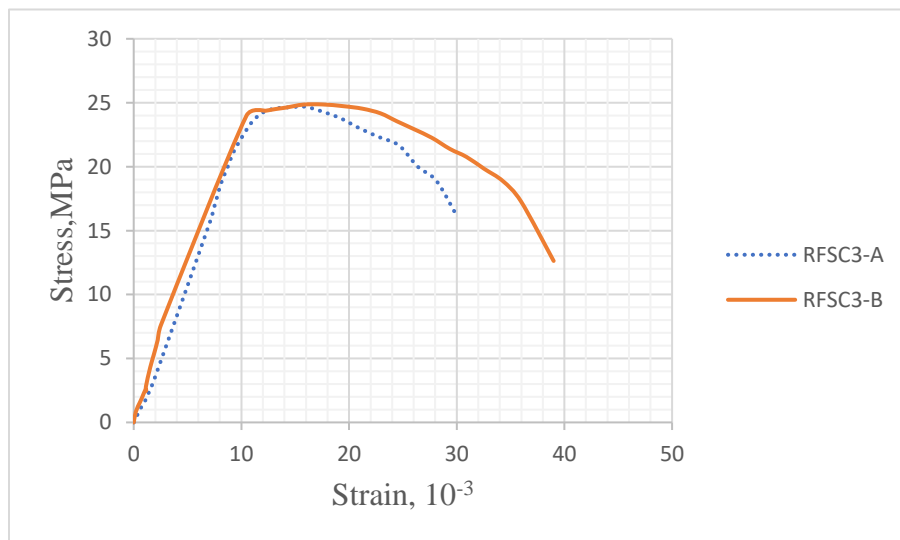


Figure 4-17 Stress-Strain Graph for Rectangular Concrete Wrapped with Three Layer FRP and Confined with Lateral Steel



Figure 4-18 Typical Failure for Rectangular Concrete Wrapped with Two-Layer FRP and Confined with Lateral Steel



Figure 4-19 Typical Failure for Rectangular Concrete Wrapped with Three Layer FRP and Confined with Lateral Steel

Figure 4-19 shows all the FRP wrapped specimens fail at the corner because of the stress developed at the corners. This stress decreases the capabilities of the FRP. Rounding the corners would decrease stress developed in this section thus making the FRP better and efficient.

4.3.4. Comparison between Rectangular Specimens Result

To show the effectiveness of FRP wrap the comparison between the specimens is performed. The three-layer specimen gave the higher result as expected with an increase of 77% from the control plain concrete. A summary of the comparison between the specimens is shown in the table 4-2 given below.

Table 4-2 Comparison Between Rectangular Specimen

Specimen Description	Maximum Stress (MPa)	Mean Value (MPa)	Ratio to Plain Specimen
RPC-C	17.36	17.36	-
RSC-A	21.63	21.03	1.21
RSC-B	20.43		
RFSC2-A	21.51	22.66	1.31
RFSC2-B	23.78		
RFSC3-A	24.68	24.78	1.43
RFSC3-B	24.87		

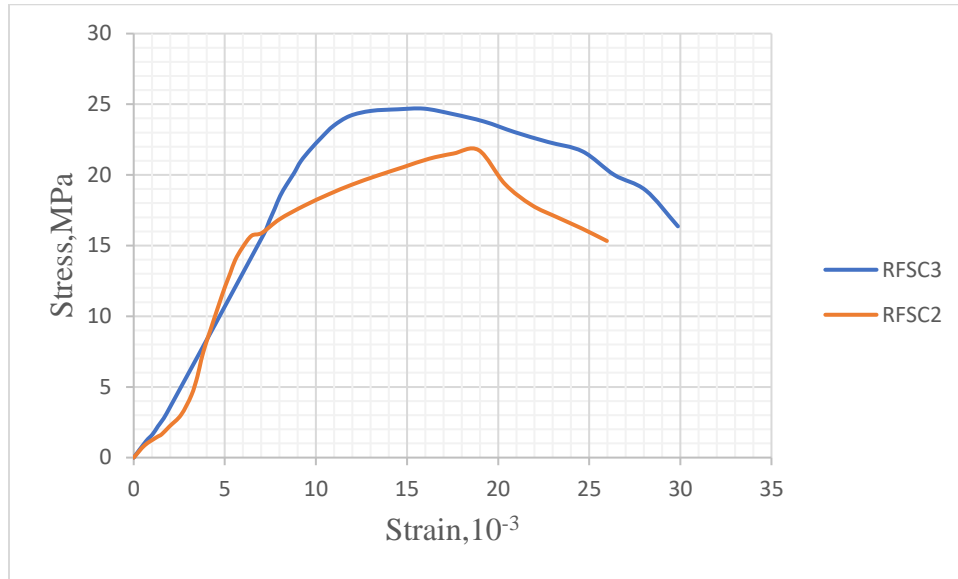


Figure 4-20 Stress-Strain Comparison Between Rectangular Specimens

4.4. Comparison between Circular and Rectangular Specimens Result

The effectiveness of FRP wrap depends on the shape of the column as we can see from the results. The circular specimen showed a much higher increment than the rectangular ones for example for the three-layer circular specimen the increment was 77% while for rectangular one it was found to be 43%.

Table 4-3 Comparison Between Circular and Rectangular Specimen

Number of FRP layers	Circular Specimen percentage increment to plain concrete (%)	Rectangular Specimen percentage increment to plain concrete (%)	Difference
2-Layers	50	31	19
3-Layers	77	43	34

4.5. Comparison of Test Results with Different Theoretical Models

4.5.1. Comparison of Theoretical and experimental results

The table 4-4 below summarizes the comparison between experimental and theoretical results for peak stress.

Table 4-4 Comparison Between Theoretical and Experimental Results

Specimen type	Experimental result	Lam & Teng model result	(Experimental)/ (Lam & Teng)	Pellegrino & Modena	(Experimental)/ (Pellegrino & Modena)
Circular 1-layer FRP	27.68	29.78	0.93	26.38	1.05
Circular 2-layer FRP	31.14	35.42	0.88	35.02	0.89
Circular 3- layer FRP	36.9	40.22	0.92	45.64	0.81
Rectangular 2-layer FRP	22.66	23.87	0.95	19.44	1.16
Rectangular 3-layer FRP	24.78	27.13	0.91	20.65	1.2
		Average	0.92		1.02

The two models can predict the confined concrete strength with a good accuracy. For Pellegrino & Modena model as the number of layers increase the accuracy also decreases. The models are better in predicting circular section than rectangular ones.

5. CONCLUSION AND RECOMMENDATION

5.1. Conclusion

Based on the experimental investigation, the following conclusions are drawn

- Using external FRP enhanced the properties of the concrete specimen. The confinement of column prevents the concrete from expanding and allows the concrete to absorb higher stress, resulting in a higher load carrying capacity.
- The peak stress capacities of the circular FRP wrapped concrete with steel ties improved 33% for one layer 50% for two layers and 77% for three layers of FRP than the plain concrete.
- The peak stress capacities of the rectangular FRP wrapped concrete with steel ties improved 31% for two layers and 43% for three layers of FRP than the plain concrete
- Increasing the number of layers of the fibers were found to have a significant effect, especially where 3 layers were applied. There were a better axial stress increment effect and better axial deflection.
- The Comparisons made between theoretical calculations and experimental results show that the model prepared by Lam &Teng and Pellegrino & Modena can be used to estimate the peak stress of externally wrapped FRP concrete with internal steel ties under pure uniform pressure.

5.2. Recommendation for further research

Taking from the output of the thesis and the scope furthers investigation on the following studies are suggested.

- A study on FRP confined columns with eccentric and cyclic loading.
- Further investigation on the relationship between internal hoop or spiral confinement with the external FRP confinement
- Extended experiment on the effectiveness of FRP wraps for a different type of fibers.
- Interaction diagrams for design of columns strengthen by FRP confinement.

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APPENDIX

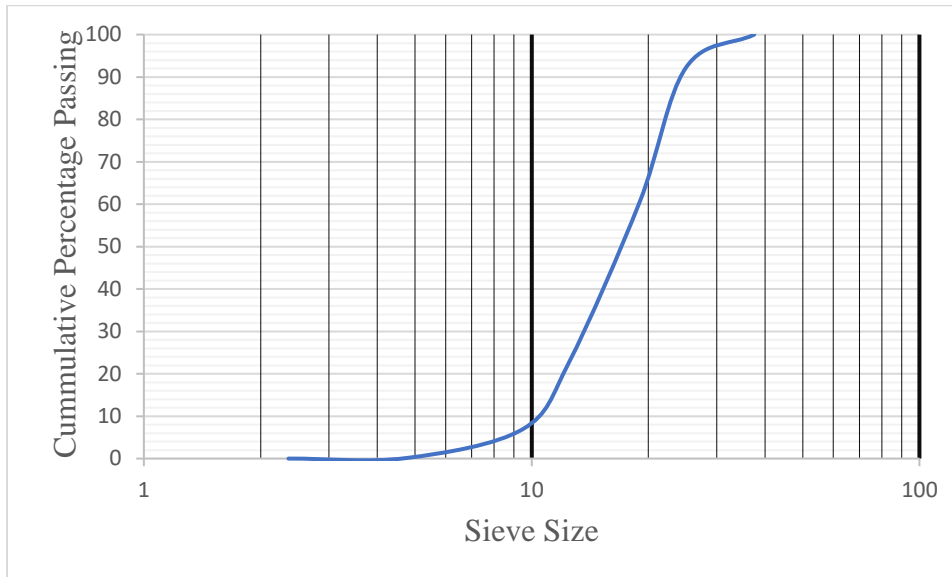
A. Sieve analysis of fine aggregate

Sieve Size (mm)	Weight of sieve (g)	Weight of sieve plus retained	Weight retained	Percentage retained (%)	Cumulative percentage retained (%)	Cumulative passing
9.5	460	460	0	0.00	0.00	100.00
4.75	427	443	16	3.22	3.22	96.78
2.36	387	432	45	9.05	12.27	87.73
1.18	354	505	151	30.38	42.66	57.34
0.6	323	540	217	43.66	86.32	13.68
0.3	301	354	53	10.66	96.98	3.02
0.15	283	292	9	1.81	98.79	1.21
PAN	734	740	6	1.21	0.00	100.00
			497		3.40	

B. Sieve analysis and Gradation curve of coarse aggregate

Sieve Size(mm)	Weight of Sieve(g)	Weight of Sieve + Retained(g)	Weight of Retained(g)	Percentage Retained(g)	Cumulative Coarser(g)	Cumulative Percentage Passing(g)
37.5	440.5	440.5	0	0	0	100
25	453.5	609.5	156	7.8	7.8	92.2
19	442	1075	633	31.65	39.45	60.55
12.5	450.5	1205.5	755	37.75	77.2	22.8
9.5	460	776.5	316.5	15.825	93.025	6.975
4.75	427.5	564.5	137	6.85	99.875	0.125
2.36	387.5	390	2.5	0.125	100	0
pan	254	254	0	0	100	0
		Total	2000			

Gradation curve of coarse aggregate



C. Description for coefficients for Carlo Pellegrino and Claudio Modena Model

ρ_f is the FRP strengthening ratio equal to:

$$\rho_f = \frac{4n_f t_f}{D} \text{ (circular columns)}$$

$$\rho_f = \frac{2n_f t_f (b+h)}{bh} \text{ (Rectangular columns)}$$

Being n_f and t_f the number of FRP layers and the thickness of the single FRP layer, respectively, and D , b , and h the geometric dimensions of the cross-section (diameter D for circular cross-sections, width b , and height h for rectangular cross-sections). k_f is the coefficient of efficiency of the confinement, and can be computed as the following product of coefficients:

$$k_f = k_\alpha k_v k_h$$

k_α is the coefficient that is used when fibers are spirally installed with an angle α with respect to the member cross-section and the coefficient of vertical efficiency k_v , takes into account, for

discontinuous wrapping, the reduction in the confinement effectiveness due to the diffusion of stresses between two subsequent wrappings.

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

This coefficient takes into account the “arch effect” near the corners of rectangular cross sections which reduces the effectively confined area to a fraction of the overall concrete cross section. This effect depends on the corner radius r .

The coefficient of efficiency k_s for the confining transverse steel is given by

$$k_s = k_{es}k_v$$

where k_{es} is coefficient of horizontal efficiency defined as

$$k_{es} = \frac{1 - \sum(w_{xi}^2 + w_{yi}^2)/6xy}{1 - \rho_{cc}}$$

being $k_{es}=1$ for circular cross-sections.

k_v is the coefficient of vertical efficiency defined as

$$k_v = \frac{\left(1 - \frac{s'}{2d_s}\right)^2}{1 - \rho_{cc}}$$

for circular columns confined with circular stirrups

$$k_v = \frac{\left(1 - \frac{s'}{2d_s}\right)}{1 - \rho_{cc}}$$

for circular columns confined with spirals

$$k_v = \frac{\left(1 - \frac{s'}{2x}\right)\left(1 - \frac{s'}{2y}\right)}{1 - \rho_{cc}}$$

for rectangular columns

In the above expressions, x and y =dimensions of the stirrups; w_{xi} and w_{yi} =distances between two longitudinal bars along the two main directions in the cross-section plain; ρ_{cc} =longitudinal steel ratio; d_s =diameter of the stirrups/spirals; and s' =net distance between two stirrups/spirals. More details on confinement of concrete columns with transverse steel can be found in Mander et al. (1988).

The reduction coefficient k_R takes into account that, for rectangular columns with $2r/b \geq 0.3$, confining pressure corresponding to peak stress is lower than that corresponding to ultimate failure. k_R is obtained as a function of $2r/b$ with the following expressions derived from a regression analysis:

$$k_R = 1 - 2.5(0.3 - 2r/b) \text{ for } 2r/b < 0.3$$

$$k_R = 1 \text{ for } 2r/b \geq 0.3$$

The following table is for determining coefficients A and α for equation 2-17.

	Circular Cross-Section		Rectangular Cross-Section	
	Without steel	With steel	Without steel	With steel
A	3.55	2.95	2.55	1.35
α	-0.15	-0.4	-0.25	-0.5

D. Detail calculation of confinement using Lam & Teng model (2003)

(1) Circular

Using formulas described in the literature review and material properties listed in the experimental program the capacity of the confined concrete and the ultimate strain are calculated below.

For one-layer specimen first, the rupture strain is calculated using a reduction factor of 0.586.

$$\varepsilon_{h,rupt} = k_e \varepsilon_{frp} = \mathbf{0.586 * 0.037 = 0.0217}$$

$$f_l = \frac{2E_{frp} \varepsilon_{jt}}{d} = 4.192$$

$$f'_{cc} = f'_{co} + 3.3 f_l^{0.7} = \mathbf{29.78}$$

$$\frac{\varepsilon_{cu}}{\varepsilon_{co}} = 1.75 + 12 \frac{f_l}{f'_{co}} \left(\frac{\varepsilon_{h,rupt}}{\varepsilon_{co}} \right)^{0.45} = 0.017642 = 17.642 * 10^{-3}$$

The two and three layers of lateral stress are calculated by only changing the number of layers, thus the results are 8.384 and 12.58MPa. Using this the peak stress for the confined concrete is calculated and the results are 35.42 and 40.22MPa for two and three-layers respectively. Finally, the ultimate stains are 0.031786 and 0.04594 for two and three layers respectively.

(2) Rectangular

For rectangular specimen lam and Teng propose a formula that includes the shape effect. When calculating the ratio of effective confinement area to that of the total concrete area without rounded corners it becomes 1/3. The lateral pressure and the peak stress of confined concrete for two layers are given as:

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

$$f_l = \frac{2E_{FRP} t \varepsilon}{D} = 5.92$$

$$f'_{cc} = 23.87$$

The ultimate strain is calculated in the same way as it's calculated for circular and the result is 0.02742. For three layers using the same procedures the lateral pressure, the peak stress and the ultimate strain are 8.88MPa, 27.17 and 0.03939, respectively.

E. Detail calculation of confinement using Carlo Pellegrino and Claudio Modena model

(A) Circular

Carlo Pellegrino and et al. Models consider the lateral pressure by both the FRP and the steel stirrup. After computing each lateral pressure, it combines them to get the peak stress that the specimen can achieve. For one-layer FRP wrapped confined concrete the lateral pressure induced by the FRP, the lateral pressure induced by steel stirrup, the peak stress and the ultimate axial strain are calculated as shown below.

$$\text{FRP: } - f_{lf} = 1/2 k_f \rho_f E_f \varepsilon_f^{eff}$$

$$\rho_f = \frac{4n_f t_f}{D} = 0.0184$$

$$k_f = 1$$

$$\varepsilon_f^{eff} = k_e \varepsilon_{fu} = 0.5 * 0.037 = 0.0185$$

$$f_{lf} = 3.574$$

$$\text{Steel: } - f_{lf} = 1/2 k_s \rho_{st} f_{yst}$$

$$k_s = k_v = \frac{\left(1 - \frac{st}{2d_s}\right)^2}{1 - \rho_{cc}} = 0.5166$$

$$\rho_{st} = 6.98 * 10^{-3}$$

$$f_{ls} = 0.28$$

(1) effective confinement pressure at failure

$$P_u = f_{lf} + f_{ls} \frac{A_{cc}}{A_g} = 3.574 + (0.28 * 0.64) = 3.753$$

(2) peak stress

$$k_1 = k_A = A \left(\frac{P_u}{f_{co}} \right)^{-\alpha} = 2.95 * (0.18)^{0.4} = 1.487$$

$$\frac{f_{cc}}{f_{co}} = 1 + k_1 \frac{P_u}{f_{co}} = 1.268$$

$$f_{cc} = 26.38$$

(3) ultimate axial strain

$$\frac{\varepsilon_{cc}}{\varepsilon_{co}} = 2 + B \left(\frac{P_u}{f_{co}} \right) = 2 + 28 * 0.18 = 7.04$$

$$\varepsilon_{cc} = 0.01408 = 14.08 * 10^{-3}$$

⇒ Two layers

$$\text{FRP: - } f_{lf} = 1/2 k_f \rho_f E_f \varepsilon_f^{eff}$$

$$\rho_f = \frac{4n_f t_f}{D} = 0.0368$$

$$k_f = 1$$

$$\varepsilon_f^{eff} = k_e \varepsilon_{fu} = 0.5 * 0.037 = 0.0185$$

$$f_{lf} = 7.148$$

$$\text{Steel: - } f_{lf} = 1/2 k_s \rho_{st} f_{yst}$$

$$k_s = k_v = \frac{\left(\frac{1-s'}{2d_s} \right)^2}{1-\rho_{cc}} = 0.5166$$

$$\rho_{st} = 6.98 * 10^{-3}$$

$$f_{lf} = 0.28$$

(1) effective confinement pressure at failure

$$P_u = f_{lf} + f_{ls} \frac{A_{cc}}{A_g} = 7.148 + (0.28 * 0.64) = 7.327$$

(2) peak stress

$$k_1 = k_A = A \left(\frac{P_u}{f_{co}} \right)^{-\alpha} = 2.95 * (0.352)^{0.4} = 1.943$$

$$\frac{f_{cc}}{f_{co}} = 1 + k_1 \frac{P_u}{f_{co}} = 1.684$$

$$f_{cc} = 35.02$$

(3) ultimate axial strain

$$\frac{\varepsilon_{cc}}{\varepsilon_{co}} = 2 + B \left(\frac{P_u}{f_{co}} \right) = 2 + 28 * 0.352 = 11.856$$

$$\varepsilon_{cc} = 0.0237 = 23.71 * 10^{-3}$$

⇒ Three layers

$$\text{FRP: - } f_{lf} = 1/2 k_f \rho_f E_f \varepsilon_f^{eff}$$

$$\rho_f = \frac{4n_f t_f}{D} = 0.0552$$

$$k_f = 1$$

$$\varepsilon_f^{eff} = k_e \varepsilon_{fu} = 0.5 * 0.037 = 0.0185$$

$$f_{lf} = 10.722$$

$$\text{Steel: - } f_{lf} = 1/2 k_s \rho_{st} f_{yst}$$

$$k_s = k_v = \frac{\left(1 - \frac{s'}{2d_s}\right)^2}{1 - \rho_{cc}} = 0.5166$$

$$\rho_{st} = 6.98 * 10^{-3}$$

$$f_{lf} = 0.28$$

(1) effective confinement pressure at failure

$$P_u = f_{lf} + f_{ls} \frac{A_{cc}}{A_g} = 3.574 + (0.28 * 0.64) = 10.9$$

(2) peak stress

$$k_1 = k_A = A \left(\frac{P_u}{f_{co}}\right)^{-\alpha} = 2.95 * (0.524)^{0.4} = 2.278$$

$$\frac{f_{cc}}{f_{co}} = 1 + k_1 \frac{P_u}{f_{co}} = 2.194$$

$$f_{cc} = 45.635$$

(3) ultimate axial strain

$$\frac{\varepsilon_{cc}}{\varepsilon_{co}} = 2 + B \left(\frac{P_u}{f_{co}}\right) = 2 + 28 * 0.524 = 16.672$$

$$\varepsilon_{cc} = 0.03334 = 33.34 * 10^{-3}$$

(B) Rectangular

For rectangular specimens, the difference from the circular is not the formula that expresses the confined concrete but the reduction in the lateral pressure by FRP confinement and the coefficient k_1 for the reason described earlier is due to the corner stresses. For two layers FRP wrapped confined rectangular specimen the lateral pressure due to the FRP, the lateral pressure due to the steel stirrups, the peak stress and the ultimate strain are shown in the calculation below.

$$\text{FRP: } - f_{lf} = 1/2 k_f \rho_f E_f \varepsilon_f^{eff}$$

$$f_{lf} = 2.382$$

$$\text{Steel: } - f_{lf} = 1/2 k_s \rho_{st} f_{yst}$$

The calculations for the values of ρ_{st} and k_s are described in the appendix

$$f_{ls} = 1.64$$

(1) effective confinement pressure at failure

$$P_u = f_{lf} + f_{ls} \frac{A_{cc}}{A_g} = 2.382 + (1.64 * 0.64) = 3.43$$

(2) peak stress

$$k_1 = k_A = A \left(\frac{P_u}{f_{co}} \right)^{-\alpha} = 1.35 * (0.2)^{0.5} = 0.6$$

$$\frac{f_{cc}}{f_{co}} = 1 + k_1 \frac{P_u}{f_{co}} = 1.12$$

$$f_{cc} = 19.44$$

(3) ultimate axial strain

$$\frac{\varepsilon_{cc}}{\varepsilon_{co}} = 2 + B \left(\frac{P_u}{f_{co}} \right) = 2 + 28 * 0.2 = 7.6$$

$$\varepsilon_{cc} = 0.0152 = 15.2 * 10^{-3}$$

For three layers FRP wrapped confined concrete the results of peak stress and ultimate axial strain are 20.65 and 0.0191 respectively.

⇒ Rectangular three layers

$$\text{FRP: } - f_{lf} = 1/2 k_f \rho_f E_f \varepsilon_f^{eff}$$

$$\rho_f = \frac{2n_f t_f (b + h)}{bh} = 0.0552$$

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

$$\varepsilon_f^{eff} = k_e \varepsilon_{fu} = 0.5 * 0.037 = 0.0185$$

$$f_{lf} = 3.573$$

$$\text{Steel: } - f_{lf} = \frac{1}{2} k_s \rho_{st} f_{yst}$$

$$k_s = k_v = \frac{(1-\frac{s'}{2x})(1-\frac{s'}{2y})}{1-\rho_{cc}} = 0.6$$

$$\rho_{st} = 12.41 * 10^{-3}$$

$$f_{lf} = 1.64$$

(1) effective confinement pressure at failure

$$P_u = f_{lf} + f_{ls} \frac{A_{cc}}{A_g} = 3.573 + (1.64 * 0.64) = 4.62$$

(2) peak stress

$$k_1 = k_A = A \left(\frac{P_u}{f_{co}} \right)^{-\alpha} = 1.35 * (0.27)^{0.5} = 0.7$$

$$\frac{f_{cc}}{f_{co}} = 1 + k_1 \frac{P_u}{f_{co}} = 1.19$$

$$f_{cc} = 20.65$$

(3) ultimate axial strain

$$\frac{\epsilon_{cc}}{\epsilon_{co}} = 2 + B \left(\frac{P_u}{f_{co}} \right) = 2 + 28 * 0.27 = 9.56$$

$$\epsilon_{cc} = 0.0191 = 19.12 * 10^{-3}$$