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SHAPE MODIFICATION OF SQUARE COLUMN SECTIONS TO IMPROVE THE EFFECTIVENESS OF FRP CONFINEMENT

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MASTER'S THESIS

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Dedicated to

My mother and the memory of my father.

Hussein AL-TAMEEM

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LIST OF SYMBOLS AND ABBREVIATIONS

f'_{cc}	: Ultimate axial stress of the confined concrete column
f'_{co}	: Peak stress of the unconfined concrete column
ε_{co}	: Axial strain at the peak stress of the unconfined concrete
ε_{cc}	: Ultimate axial strain of the confined specimen in case of sufficient confinement
ε_{cu}	: Ultimate axial strain of the confined specimen in case of insufficient confinement
f_c	: Compressive strength
k_ε	: Strain efficiency factor
$\varepsilon_{h,rup}$	: Actual rapture strain
ε_f	: Ultimate tensile strain of the GFRP from the coupon test
P	: Load
σ_r	: Lateral confining pressure
σ_r	: Compressive stress
E_{frp}	: Modulus of elasticity
$f_{l,a}$	: Confining pressure
k_1	: Confinement effectiveness coefficient
k_s	: Shape factor
S'	: Clear spacing
k_v	: Vertical confinement effectiveness coefficient

ACI : American concrete institute

ASTM : American society for testing and materials

C : Core

CC : Circularized core

cm : Centimetre

CFRP : Carbon fibre reinforced polymer

CFFT : Concrete-filed fibre tube

CRC : Circularized core with round corners

D : Dimeter

2D : Two dimensions

3D : Three dimensions

EI : Epoxy paint

F : Full wrapping

FRC : Fibre reinforced concrete

FRP : Fibre reinforced polymer

GFRP : Glass fibre reinforced polymer

GPA : Gigapascal

KN : Kilonewton

L : Length

LVDT : Linear variable differential transformers

mm : Millimetre

MPa : Megapascal

P : Partial wrapping

PVC : Polyvinyl chloride

RC : Reinforced concrete

Rc : Core with round corners

SCC : Self-compacted concrete

SMA : Shape memory alloy

t : Thickness

VG : Vermiculite/gypsum

R : Radius

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ÖZET

FRP SARGILAMANIN ETKINLIĞININ ARTTIRILMASI AMACIYLA KARE KESITLI KOLONLARIN BIÇIMSEL MODIFIKASYONU

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Amaç: Bu tez çalışması kare kesitli beton kolonlarda lifli polimer sargılamanın etkinliğinin arttırılabilmesi amacıyla önerilen yeni bir biçimsel modifikasyon yönteminin irdelenmesi amacıyla yürütülmüştür.

Materyal ve Yöntem: Çalışma kapsamında ölçekli kare kesitli beton kolonlar ve biçimsel modifikasyon için gerekli beton parçalar üretilmiştir. Beton kolonların bir kısmı sivri köşelidir, bir kısmında ise köşeler yuvarlatılmıştır. Sivri köşeli numunelerde uygulanan biçimsel modifikasyon daha önceki çalışmalarda önerilen yöntemdir. Yuvarlatılmış köşeye sahip kolonlarda uygulanan biçimsel modifikasyon ise bu tez çalışmasında önerilen yöntemdir. Ayrıca köşeleri yuvarlatılmış numunelerden bazılarına biçimsel modifikasyon uygulanmamıştır. Biçimsel modifikasyon uygulanmış ve uygulanmamış numunelerin çoğu tek kat cam lifli polimer (GFRP) vasıtasıyla sargılanmıştır. Sargılamada tam ve parçalı olmak üzere iki yöntem izlenmiştir. Güçlendirmenin etkinliğini ortaya koyabilmek amacıyla sargılama ve biçimsel modifikasyon uygulanmamış numuneler de hazırlanmıştır. Tüm numuneler monotonik eksenel yük altında test edilmiştir.

Bulgular: Beton basınç cihazı kullanılarak toplamda 24 numune test edilmiştir. Test sonuçları sargılanmış betonda eksenel basınç dayanımı ve birim deformasyon kapasitesinin arttırılmasında önerilen biçimsel modifikasyonun başarısını ortaya koymuştur. Dahası, önerilen biçimsel modifikasyon yönteminde lifli polimer üzerinde ölçülen nihai çekme birim deformasyon değeri kupon çekme deneylerinde aynı malzeme için elde edilen değerlere yaklaşmıştır. Tam ve parçalı olmak üzere her iki sargılama yöntemi de numunelerin eksenel basınç dayanımı ve birim deformasyon kapasitesini arttırmıştır. Her ne kadar parçalı sargılamada elde edilen dayanım ve birim deformasyon artışı tam sargılamaya kıyasla daha az olsa da daha ekonomiktir.

Sonuç: Bu çalışmayla GFRP'nin sargılamadaki etkinliğinin biçimsel modifikasyon yoluyla ciddi oranda arttırılabileceği anlaşılmıştır. Önerilen biçimsel modifikasyon, sargı malzemesinin etkinliğini arttırmada dikkat çekici bir yöntem olduğunu ortaya koymuştur. Artan eksenel dayanım, birim deformasyon kapasitesi ve sargı malzemesi kopma dayanımı yanında, önerilen güçlendirme yöntemiyle kullanılan sargı malzeme miktarı, daha önceki çalışmalarda önerilen yöntemlere kıyasla %15 oranında azaltılmıştır; ayrıca kesit boyutundaki artışlar da daha az olmuştur. Dolayısıyla, bu çalışmadaki biçimsel modifikasyon yöntemi kare kesitli beton kolonların lifli polimerlerle sargılanmasında önerilmektedir.

Anahtar Kelimeler: Beton, FRP, Daireselleştirme, Biçimsel Modifikasyon, Güçlendirme, Sargılama, Kare Kolon, Parçalı Sargılama, Tam Sargılama.

ABSTRACT

SHAPE MODIFICATION OF SQUARE COLUMN SECTIONS TO IMPROVE THE EFFECTIVENESS OF FRP CONFINEMENT

AL-TAMEEMI H. Aydin Adnan Menderes University, Graduate School of Natural and Applied Science, Civil Engineering Program, Master's Thesis, Aydin, 2021.

Objective: This research was carried out in order to investigate the efficiency of a new shape modification method for square concrete column confined by fibre reinforced polymer.

Material and methods: The research was carried out by preparing a scaled square plain concrete columns and concrete segments. The columns were either with sharp edges or rounded edges. Columns with sharp edges were used to implement a previous shape modification method. While columns with rounded edges were used to conduct the proposed shape modification method. Columns with just rounded edges without modification were also prepared. All the modified and non-modified column were wrapped with a single layer of GFRP. Two wrapping techniques were conducted fully wrapping and partial wrapping. Specimens without any confinement were also prepared to show the effect of strengthening. All the prepared specimens were tested under monotonic axial loading.

Results: A total of 24 specimens were tested by a compression test machine. The test results indicated the success of the proposed shape modification method to enhance the axial stress and strain of the confined specimens. Moreover, the recorded ultimate tensile strain of GFRP confined modified specimens by the proposed shape modification method, was close to the measured ultimate tensile strain of the coupon test. Both wrapping techniques enhanced the axial stress and strain of the strengthened specimens. Even though the enhancement in the axial stress and strain of the confined specimens by partial wrapping was lower than the full wrapping, but it can be more economic.

Conclusion: It was understood in this study that the efficiency of the GFRP can be significantly enhanced by modified the shape of the square concrete column. The proposed shape modification method was proved to be an attractive method in enhancing the effectiveness of the confinement material. Besides the enhancement in the axial stress, axial strain and rupture strain, the proposed shape modification method succeeded to save about 15% of the amount of the confinement material compared with the previous shape modification method. The cross-section shape of the modified columns by the proposed method was decreased by 20 mm. Therefore, the proposed method can be highly recommended for strengthening the square concrete column with FRP-composite.

Keywords: Concrete**,** FRP, Circularization, Shape modification, Strengthening, Confinement, Square column, Partial wrapping, Full wrapping.

1. INTRODUCTION

1.1. Background

In general, concrete structures are designed to withstand all kinds of forces. Many reasons make the structures' safety questionable, such as changing the structures usage, construction errors, environmental effects, and natural disasters. Thus, the existing structures require an assessment to check their capacity with regard to defined demand. In most cases, assessment results show the incapability of the existing structures to withstand the expected forces. There are two solutions; either to destruct and re-build the structure or to strengthen it. In many cases, the destruction of the structures is not desirable for many reasons such as the cost and the time of the destruction and reconstruction. Moreover, some special structures like bridges and tunnels magnify the problem. Where the consequences of the destruction of the infrastructure may not be acceptable because it affects daily life. Therefore, strengthening the structures may be a better solution in certain cases.

The structure may require either a member strengthening or system rehabilitation (i.e. addition of shear walls, etc.). The member strengthening means upgrading the mechanical behaviour of the concrete member to withstand all expected forces without failure. The suggested strengthening system takes into account all the parameters such as service life and sustainability, etc. where it is not logical to strengthen an old structure with high cost. But it may be a better solution for the historical buildings.

The strengthening process is not straightforward and it requires a high experience to estimate the consequences of the work. In nowadays, computer software is used widely for this purpose.

Many methods have been suggested to strengthen the columns. However, three methods are considered as the most popular methods in strengthening of these concrete members. Each of those methods has advantages and disadvantages.

The reinforced concrete/mortar jacketing is one of these three methods. This technique is widely used to rehabilitate the columns (Raza et al., 2019). In general, the RC jacketing of the concrete core enhances the axial load-carrying capacity, flexural strength, and ductility. This method starts by surrounding the concrete core with the reinforcement, then placing the formwork and pouring the concrete/mortar inside. The reinforcement is tied with the core by anchoring rebars or high strength bolts (Raza et al., 2019). This method is easy to handle where there is no need for skilled workers and the materials are available. In contrast, jacketing the concrete core leads to an increase in the cross-sectional area of the member, increases the dead load, and decreases the service space in the strengthened structure (Gholampour et al., 2019). Moreover, durability problems may take place because of the additional stresses that may result in cracking and debonding of the RC jacket (Gholampour et al., 2019). Recently, there was a concern to develop this technique by using high-performance materials or fibres with concrete mixing. Those additional materials may result in an improvement in ductility. Because of the nature of the concrete, the ductility is not improved significantly by the conventional materials (Gholampour et al., 2019).

Steel jacketing is the second method that is used to strengthen the concrete members. This technique is implemented by placing steel angles at the corners of the rectangular/square core and linking the steel angle with steel battens by welding or bolting and the gap between the steel and the concrete core can be filled by mortar or epoxy (Raza et al., 2019; Tarabia and Albakry, 2014). This technique also improves the axial load-carrying capacity, flexural strength, and ductility. Although, the increase in the cross-sectional dimensions is less than the concrete jacketing technique, steel jacketing is costly, not easy to handle and corrosion, fire resistance issues are questionable (Raza et al., 2019; Tarabia and Albakry, 2014). A steel tube may be used, for the confinement of circular members. It may also be used for the rectangular/square concrete columns but it results in a significant increase in the cross-section area. The steel tube is placed around the concrete core. Then the tube is welded and the gap between the core and the tube can be filled by mortar or other material (Li et al., 2019). Parameters such as the steel thickness and the infill-material can significantly affect the behaviour of the confined member (Tarabia and Albakry, 2014; Li et al., 2019).

Fibre-reinforced polymer (FRP) jacketing is the last method that has become very popular in the last two decades. FRP-jacket is used for improving the axial load-carrying capacity, shear resistance, and ductility. In the FRP jacketing, the core concrete is wrapped by the FRP composite sheets. This wrapping is provided by a wet-lay-up technique where epoxy is used as the adhesive (Raza et al., 2019). This technique is considered as an efficient confinement method thanks to the superior features of the FRP-composites such as high corrosion resistance, high strength to weight ratio, resistance for the chemical attack, and the limited creep strain (Gholampour et al., 2019; Raza et al., 2019; Youssf et al., 2017). However, FRP-composite is an expensive material and has low fire resistance and shows poor properties in a wet environment (Raza et al., 2019; Youssf et al., 2017). The FRP-composite is available in different types such as carbon fibre, glass fibre, basalt fibre, and aramid fibre. The effectiveness of FRP-composite depends on many parameters and each parameter can significantly change its efficiency.

1.2. Research Significance

Fibre-reinforced polymer composite proved its efficiency in strengthening of the existing concrete columns and as have been mentioned above, many parameters can significantly change the efficiency of the FRP-composite. Studies have been conducted to evaluate the efficiency of the FRP-confined circular concrete columns, and the results proved the high enhancement in the axial load-carrying capacity and the ductility (Mirmiran et al., 1998; Micelli and Modarelli, 2013; Vincent and Ozbakkaloglu, 2013; Saljoughian and Mostofinejad, 2015). However, the efficiency of the FRP-composite becomes significantly less when applied to the rectangular/square concrete column (Mirmiran et al., 1998; Micelli and Modarelli, 2013).

The low efficiency attributes to the non-uniformity of the confinement, the sharp corners, and the flat sides (L. Wang et al., 2008; Mirmiran et al., 1998; Micelli and Modarelli, 2013). Sharp corners may lead to a premature failure as a result of the concentration of the stresses at the corners. Therefore, many studies have been conducted to increase the efficiency of FRP confinement in square/rectangular sections. Rounding the corners of the rectangular/square concrete columns proved its effect on increasing the efficiency of the FRP-composite which improves further with increasing the corner radius (Al-Salloum, 2007; L. Wang et al., 2008; Micelli and Modarelli, 2013). On the other hand, increasing the corner radius is limited by the presence of the reinforcement. Also, it requires effort and time. As a consequence, some researchers investigated the ability to change the cross-sectional shape from rectangular/square to circular cross-section by a technique called circularization (Hadi et al., 2013; Yan and Pantelides, 2010).

The experimental results proved the success of the process. The circularization technique can be conducted by many ways such as, surrounding the concrete core by formwork and pouring the concrete inside, attaching concrete pieces on the surface of the concrete core or it can be implemented by preparing FRP-tube around the concrete core and pouring the concrete/mortar inside (Hadi et al., 2013, 2017; Yan and Pantelides, 2010; Youssf et al., 2017;

Zeng et al., 2017). Although the circularization technique significantly improves the load-carrying capacity and the ductility of the rectangular/square concrete column, the increase in the cross-section size and dead load should be taken into account (Hadi et al., 2013; Yan and Pantelides, 2010).

In this study, a new circularization technique was designed to improve the confinement effectiveness with a less increase in the cross-sectional dimensions. The technique starts with rounding of the corners first and then attaching pre-cast concrete pieces around the concrete core. The effect of the sharp corners is eliminated by rounding the corners and the flat sides are modified by the pre-cast concrete pieces with a curvilinear shape. According to the best knowledge of the author of this thesis, such a circularization method has never been studied until this date.

Moreover, the study includes a comparison between the proposed circularization technique and the one suggested by the previous studies. The method of rounding the corners (i.e., without circularization) is also included in this comparison to constitute a basis.

Finally, depending on the results of the experiments, a numerical model is used to predict the axial response of confined concrete. The results of both the experimental work and the numerical model are compared.

The research significance can be summarized as below:

- Experimentally evaluate the efficiency of the new circularization technique
- Experimentally and numerically assess the key parameters of the stress-strain behaviour of the FRP-confined concrete column.

1.3. Research Objective and Scope

The study presents experimental work and theoretical study of the FRP-confined plain concrete columns. The circularized-specimens by the proposed shape modification technique are compared with the circularized-specimens of the previous shape modification technique and the specimens with rounded-corners which are confined by glass FRP (GFRP) composites.

The research objectives can be summarized as below:

- Conduct experimental work to assess the new shape modification technique and compare it with the previous one.

- Compare the strengthening efficiency of the GFRP-composite confined concrete specimens modified with different techniques.

- Conduct a theoretical study to predict the key parameters of the axial behaviour of the confined-specimens. The results of the theoretical and experimental study are compared.

1.4. Thesis Organization

This thesis contains six chapters. The first chapter is the introduction which is already presented above. The literature review about the strengthening of the concrete columns is summarized in Chapter 2. In Chapter 3, the material and methods to conduct the circularization technique is presented. The test results and the discussion are conducted in Chapter 4 and 5 respectively. A theoretical investigation is presented in Chapter 6 to predict the certain parameters of the axial stress-strain response. Finally, conclusions are summarized and further scientific recommendations are provided in Chapter 7.

2. LITERATURE REVIEW

2.1. General Introduction

In this chapter, the previous studies that have a direct relationship with the strengthening of the concrete column are presented. For ease, the chapter is divided into six parts. The first part includes the experimental investigation of the concrete columns strengthened by concrete jacket and steel cage or tube. In the second part experimental investigations of concrete columns strengthened by fibre reinforced polymers are summarized.

The experimental investigations of the shape modification of rectangular/square concrete columns strengthened by fibre reinforced polymers are reviewed in the third part. In fourth part, the strengthening of the concrete columns by other materials is discussed. Some theoretical investigations of FRP-confined concrete columns are reviewed in the last part.

2.2. Strengthening the Concrete Column by Concrete Jacket and Steel Cage or Tube

The oldest techniques that were used widely in the strengthening of the concrete columns are concrete jacket and steel cage or tube. The simplicity of these techniques was the reason of its popularity. In the next paragraphs some studies related to these techniques are presented.

Tarabia and Albakry (2014) conducted an experimental study of using steel cage to strengthen the RC columns. The parameters of the study were the steel angles size, the spacing between the steel battens, the connection between the steel angles and the steelhead, and the type of the material which was injected between the column surface and the steel battens. 10 specimens were prepared and divided into two groups depending on the mentioned parameters. The failure mode of the unconfined specimens was by buckling of the longitudinal steel bars and crushing of the concrete while the confined specimens failed by buckling of the vertical steel angles Furthermore the rupture of the welding of the steel battens were recognized in some of the specimens. The technique showed a great improvement in the axial behaviour of the columns and each parameter affects differently. Increasing the steel angles. size plays an important role in improving the axial behaviour of the specimens. Increasing the spacing between the steel battens led to decreases in the effectiveness of the steel cage. Furthermore, the type of injection material may slightly affect the results where the use of cement can be recommended considering the economy. Generally, steel cage doubled the load-carrying capacity and improved the ultimate axial strain by 50%.

Gholampour et al. (2019) experimentally examined strengthening of the concrete columns by using fibre reinforced concrete jackets (FRC). The parameters of the study were the type of the cementation composites, polyethylene fibres content, and reinforcement ratio. The engineering cementation composites with three different ratios of fibres and ultra-high-performance cementation composite with one fibre ratio were utilized to prepare the specimens. Furthermore, the experiments include either one or three steel stirrups to check the effectiveness of increasing the reinforcement ratio. The axial monotonic load was applied to all the prepared-specimens. The discussion of the results starts with the failure mode, where the specimens confined with concrete cover without fibres or reinforcement failed suddenly and explosively. Furthermore, the failure mode of the specimens with just fibre or reinforcement does not differ but less explosively. However, the specimens with fibre and reinforcement resulted in a ductile failure. FRC jacket significantly enhanced the axial load capacity and, ultimate axial and lateral strain. In contrast, the enhancement ratio decreases with an increase in both the fibres and reinforcement content. It was proved that using low reinforcement ratio and fibres content can be recommended to increase both the ductility and the strength of the concrete column.

Li et al. (2019) evaluated experimentally the behaviour of the slender RC columns retrofitted with a concrete-infilled circular steel tube. Nine RC specimens were prepared and the self-compacted concrete (SCC) was used to fill the gap between the steel tube and the concrete core. The parameters of the study were the slenderness (L/D), the steel tube thickness (D/t), and SCC strength. The specimens were tested under monotonic axial load. The results of the experimental study showed the effect of each parameter on the load-carrying capacity, stiffness, and ductility. In general, the strengthening technique significantly improved the behaviour of the columns, and the parameters showed a different effect on the behaviour where increasing (L/D) and (D/t) decreases the load-carrying capacity, stiffness, and the ductility. While increasing the SCC strength leads to an improvement in the load-carrying capacity and stiffness but it reduced the ductility.

2.3. Strengthening the Concrete Column by Fibre Reinforced Polymer

Retrofitting circular and rectangular/square concrete columns by FRP-composites have been studied comprehensively by many researchers. The investigations focused on the parameters that may affect the efficiency of FRP-confined concrete columns such as cross-section shape, corner radii, fibre angle orientation, number of FRP- composite layers, the method of wrapping, the eccentric load, cross-sectional sizes, the preloading ratio for the existing columns, the concrete strength, the fire endurance and the post-tension for the FRP layers.

Mirmiran et al. (1998) studied certain parameters for the concrete column and the confinement method that may have an influence on the effectiveness of the FRP-confinement. The main parameters were the cross-sectional shape, the height of the columns, the bond between the column and the FRP-shell. Two different cross-section shapes were tested, namely circular and square. Four columns with different heights and constant diameter were manufactured to show the effect of the specimen height. Three different ways of wrapping were utilized, bonded specimen as single-wrap and multi-layered, unbonded specimen as single-wrap and multi-layered, and mechanical bond by using shear connectors ribs. The results of the study showed that the FRP-composite was more effective with the circular column than the square column. Besides, increasing the shell thickness was more effective too with a circular cross-section. The height of the specimens showed insignificant to no effect on the FRP confinement. The maximum eccentricity and the reduction of load carrying capacity remain within the permissible limits which recommended by ACI code. No remarkable effect on the FRP effectiveness has appeared by utilizing either FRP-tube or wet-layup techniques for the strengthening purpose. Furthermore, conducting different approach to wrap the plies as single-layer or multi-layers did not lead to a change in the load-carrying capacity or the ductility. However, the mechanical bond enhanced the effectiveness of the FRP-composite.

It was experimentally was proved that the FRP-composites' strength cannot be fully utilized when it is used for the column confinement. The specimens usually fail before the strain of the FRP confining jacket reach its ultimate tensile strain capacity. Therefore, Mortazavi et al. (2003) experimentally investigated pre-tensioning of FRP-composite to increase the enhancement in the load-carrying capacity and the ductility. The study included glass and carbon fibre with different ratios of the expansive agent. The expensive agent was mixed with the cement grout to provide expansive grout. The technique was implemented by a pre-formed

FRP tube. The FRP-tube was placed around the concrete core then the expansive grout was poured inside. It was proved firstly that the stiffness of the wrapping material, the ratio of the expensive agent, and the volume of the expensive grout affects the expensive pressure. The results of the study indicated that the load-carrying capacity and the ductility were notably increased by using expansive grout. The failure mode was explosive in each case of the wrapping. The failure mode of the glass fibre was completely different than the failure mode of the carbon fibre. The pre-tensioning technique succeeded but increasing the cross-sectional area and the cost of the expansive agent should be taken into account.

The´riault et al. (2004) examined the effects of the column size and the slenderness on the FRP-confined circular concrete column. The parameters of the study included two FRP types, carbon and glass fibre, different slenderness ratio and size. The specimens were arranged as small, medium, and large specimens. Monotonic axial load was applied and the results showed that there is no significant effect of the column size or slenderness on FRP-confined circular concrete column with medium and large size. On the other hand, the results of the small column (= 50mm diameter) were proved to be different and the researchers pointed to the gain that results from small specimens is less dependable, unlike the gain that results from medium and large specimens.

It was proved that the FRP-confined concrete column shows poor properties with the presence of fire, thus, the ACI committee pointed that the FRP wraps will be completely lost during fire (Bisby et al., 2005). Therefore, Bisby et al. (2005) evaluated the effect of a new method on the fire endurance of the CFRP-confined RC column. Two full scale reinforced concrete columns were prepared and the fire protection system included two components. The first component is modified cementitious vermiculite/gypsum plaster (VG), the other component is an intumescent epoxy paint (EI). Firstly, VG was sprayed and then EI was applied. To ensure mechanical anchorage between the CFRP surface and the VG, galvanized steel plastering lath was used with two different thicknesses. The proposed fire protection system behaved well and it was intact until the failure. The columns suddenly failed after 5.5 hours of exposure to the fire. Furthermore, the failure mode was buckling/crushing by spalling the concrete cover and fire protection system violently.

The sharp edges and the flat sides stand behind the low enhancement of the ductility and strength of the rectangular/square concrete columns confined by FRP-composite. Therefore, Al-Salloum (2007) studied the effect of the sharp corners on the confinement effectiveness of the FRP-confined plain square concrete columns. The parameters of the study were the corner radii and cross-sectional shape. Two different cross-sections were utilized during the experimental work, namely square and circular cross-sections. Four values of corner radius were conducted that were 5, 25, 38 and 50 mm. A monotonic axial load was applied. As a result of the study, it may be concluded that rounding the sharp corners enhanced the ultimate compressive strength and strain. Also, increasing the corner radius led to more improvement in strength and ductility. FRP-composite was more efficient with circular cross-section than others, which was attributed to the uniformity of the confinement. However, the failure mode in the case of the circular cross-section was more explosive than the square cross-section and increasing the radius results in more explosive failure mode. In the end, a modified analytical study was proposed for the FRP-confined square columns and it showed a good agreement with the experimental results.

L. Wang et al. (2008) studied the effect of the concrete strength with the corner radii. The corner radius was increased gradually until reaching the circular cross-section shape. The parameters of the study were the corner radius, the number of the FRP plies, and the concrete strength grade. Five different corner radii were conducted, such as 15, 30, 45, 60, and 75mm. The numbers of the layers were 1 and 2 respectively. Two concrete strength grades (C30 and C50) were used to check the efficiency of the FRP-confined normal and high strength concrete. The results of the study indicated that insufficient confinement can be obtained due to the sharp corners of the concrete columns. On the other hand, the ductility remarkably increased by the FRP confinement. Moreover, increasing the corner radius with constant confinement thickness led to increasing strength. Also, increasing the confinement thickness with a constant corner radius increased the strength of the specimens too. In the case of C30, the ductility increased with a small corner radius. However, there is no enhancement in the ductility with increasing the confinement thickness even it may reduce it. In the case of C50, enlarging the corner radius led to an increase in the ductility. However, increasing the confinement thickness showed more increment in the ductility with smaller column radii (<40mm). Furthermore, the study concluded that FRP-composite is more effective with the normal concrete strength than the high strength concrete column for the same confinement thickness.

The eccentric load is considered as an important factor that may affect confinement effectiveness of the FRP-composite. As a result, Wu and Jiang (2013) investigated experimentally and analytically the effect of the load eccentricity on the behaviour of the plain concrete column confined by FRP. The parameters of the study included two different FRP stiffness and eccentric loading ranging between 0-50 mm. 36 circular concrete specimens have been prepared and a special metal head was used to apply the load with different eccentricates. 1 and 2 plies FRP was used as external confinement of the specimens. The failure mode of the confined specimens was by rupturing of the FRP, however, the specimens with high eccentricity failed less violently and less FRP ruptured. The load-carrying capacity of the specimens was significantly affected by the increasing eccentricity where the ultimate load dropped to the half with 50mm eccentricity. The effect of the eccentric load was insignificantly affected by the FRP stiffness. The researcher pointed out that the stress-strain model that had been developed for the concentric loading cannot be used for the eccentric loading. Therefore, a new model was proposed.

Micelli and Modarelli (2013) comprehensively studied various parameters that may affect the behaviour of the FRP-confined concrete column. The main parameters were concrete strength, cross-sectional shape, cross-section type, type of the FRP composite, number of FRP layers, and the corner radius. Two different concrete grades were used as 28 and 38 MPa. Two different cross-section shapes were designed, square and circular cross-section. Two different cross-section types were tested, solid and hollow specimens. Two different FRP composites were utilized as CFRP and GFRP with different thickness (i.e., 1, 2, 3, 4 and 5 layers). Two different corner radii were conducted, 10 and 25 mm. The 10 mm radius demonstrates an error in the specimen preparation. 128 specimens have been prepared and uniaxial load has been applied. The researchers pointed out that the cross-section shape plays a clear role in improving the effectiveness of the FRP-composite where circular cross-section showed much better improvement than others. Moreover, in the case of the square column, increasing the aspect ratio led to a decrease in the effectiveness of the strengthening. As expected, the cross-section type caused a clear effect on the strengthening, where the solid cross-section showed better improvement than the hollow cross-section regardless of the cross-sectional shape. The type of the FRP-composite did not show a significant difference, considering the same stiffness for the CFRP and GFRP. Increasing the FRP-composite thickness does not show a notable effect on the slope of the stress-strain curve after the transition zone, however, some differences can be observed regarding the hollow specimens. As previously proved, the corner radius has an important role in the behaviour of the FRP-composite. Increasing the concrete strength led to a decrease in FRP-composite effectiveness. In conclusion, the experimental results have been compared with the different design models and good agreement was obtained for the load-carrying capacity and less for the ultimate strain.

As have been proved above that FRP-composite can significantly enhance the concrete column behaviour when the fibres are oriented along the hoop direction. Therefore, Vincent and Ozbakkaloglu (2013) experimentally evaluated the effect of the confinement method, fibres orientation angle, and end conditions of the specimens on the efficiency of the FRP-confinement of circular concrete columns. Two different ways of confinement have been utilized by using a concrete-filled fibre tube (CFFT) and FRP-wrapped externally. Besides, 5 different orientation angles have been conducted, such as 45, 60, 75, 88, and 90 degrees with the respect to the vertical axis. Moreover, two different ways of axial load application were implemented by inclusion or exclusion a steel disk. The researchers pointed out that the efficiency of the FRP-confined concrete column was enhanced by increasing the orientation angle with the respect to the longitudinal axis. When the orientation angle continually increased, enhancement in the ductility was observed but the load-carrying capacity did not change. And a very low enhancement can be achieved with orientation angle of 45 degrees. The confinement method has a slight effect on the efficiency of the FRP, however, using the FRP-wrapping method resulted in slightly less axial stress with more axial strain compared with the CFFT method. The specimen end condition has insignificant to no influence on the efficiency of the FRP. For instance, a specimen tested by using a steel plate has f_{cc}/f_{co}= 2.15 while a specimen tested without a steel plate has f_{cc}/f_{co}= 2.23.

The FRP-composite is considered as an expensive material. Thus, the fully wrapping technique may not be considered as economical. Therefore, Saljoughian and Mostofinejad (2015) experimentally evaluated the strengthening of the square concrete columns by using partial wrapping and a corner strip-batten technique for FRP-confinement under concentric and eccentric loading. In this technique, less amount of FRP-composite could be used compared to the fully wrapping technique. The test parameters were partial wrapping, corner strip-batten, corner strip-batten with longitudinal stripes, and corner strip-batten with longitudinal strips and groves. Axial loading was applied to the specimens with the eccentricities of 0, 30, 60, 90, 120 mm. The researchers concluded that the use of corner strip-batten showed better enhancement in terms of the compressive strength when compared with the traditional partial wrapping under the concentric loading. However, the more FRP was used in the proposed technique. On the other hand, the effectiveness of the FRP wrapping was significantly decreased by applying eccentric loading. The longitudinal strip did not have a remarkable effect on the compressive strength of the column under concentric loading. In contrast, the results of compressive strength under eccentric loading showed a significant increase. Moreover, the groves on the column sides enhanced the performance of the FRP composite, hence the compressive strength of the column was increased in each loading condition. Using the corner strip-batten technique resulted in a low-stress concentration at the sharp edges of the column specimen. And consequently, the rupture location of the FRP strips was changed from the corner to the middle.

Pham et al. (2015) investigated the applicability of partial technique on the circular concrete column. The parameters of the study were the type of the FRP-composite and the wrapping technique. Three different wrapping techniques were implemented: fully, intermittent, and non-uniformly wrapping. High strength concrete column was utilized to prepare the specimens. The results of the study can be summarized in the following points. The failure mode of fully and nonuniformly wrapped specimens was by rupturing of the FRP at the mid-height of the specimen with an angle of 45 degrees. In contrast, the specimens which were partially wrapped, the failure mode started with cracks on the concrete between the FRP strips, then the concrete cover crushed, and finally the specimens failed explosively. The intermittent wrapping technique in the case of the GFRP composite provided lower compressive strength but higher axial strain compared with the fully wrapping technique. However, the nonuniformly wrapping technique led to higher compressive strength and axial strain compared with the other techniques. Moreover, the intermittent wrapping technique in the case of CFRP resulted in lower compressive strength. It can be concluded that the nonuniform wrapping showed better results, taking into account the same FRP volume was utilized in each technique. A good agreement between the analytical and the experimental results were obtained.

The concrete columns could be with different sizes; therefore, cross-sectional sizes may have an effect. As a consequence, D. Wang et al. (2016) experimentally and analytically evaluated the effect of the cross-sectional size on the stress-strain behaviour of the square concrete columns confined by CFRP. The parameters of the study were the cross-sectional size effect and the presence/absence of the reinforcement. The specimens were prepared carefully to ensure the direct effect of the cross-sectional size where the same height to width ratio and the corner radius to width ratio were obtained. The results pointed out that the cross-sectional size has no significant effect on the stress-strain behaviour of the specimens with a small and medium-size (less than 350 mm). However, the effect of the cross-sectional size was clear for the specimens with larger cross-section sizes (more than 350mm). Increasing the cross-sectional size led to a decrease in the effective confinement of the CFRP. Although the reinforcement enhances the compressive strength by providing extra confining pressure, premature failure could be present because of the buckling of the longitudinal reinforcement.

Meanwhile, there was no clear influence of increasing the cross-sectional size on the failure mode. Increasing the cross-sectional size results decrease in the rupture strain. Moreover, the rupture strain at the corner was smaller than the rupture strain in the middle region. Depending on the outcome, the researchers recommended using the rupture strain at the column corners as the effective lateral rupture strain.

Pre-loaded columns and the effect of the pre-loading ratio can be questionable too. Therefore, Pan et al. (2017) studied experimentally the influence of the preloading on the stress-strain curve of the concrete column strengthened by CFRP. Two different cross-section types, namely square and circular cross-sections have been prepared. The parameters of the study were preloading ratio, concrete strength, and the number of the CFRP layers. The results of the study designate that the increase in the preload ratio led to a decrease in the ultimate stress and strain of each circular and square concrete column confined by CFRP. The increase in the number of the CFRP layers resulted in decreasing the peak stress and strain of the preloaded circular concrete column confined by CFRP. However, the peak strain of the square concrete column looks irrelevant. The concrete strength has insignificant to no effect on the peak stress and strain of the preloaded concrete column confined by CFRP. A new design-oriented model has been proposed utilizing the test results.

2.4. Shape Modification of the Rectangular Concrete Column Strengthened by Fibre Reinforced Polymer

The previous studies show that the FRP-composite is much more effective when applied on the circular cross-sections in comparison to the rectangular/square sections. Therefore, many studies have been conducted that try to change the cross-sectional shape of the rectangular/square cross-section to a circular or elliptical cross-section. Different ways were implemented to change the cross-sectional shape of the rectangular/square to circular columns under a technique called circularization.

Yan and Pantelides (2010) circularized the rectangular and square concrete columns by using FRP-shell and expansive cement concrete. The parameters of the study included cross-sectional shape, FRP-composite type, and FRP-composite thickness. Two different concrete column cross-sectional shapes were studied, square and rectangular. The shape modification techniques were applied by utilizing non-shrink cement concrete and expansive cement concrete. Two different FRP composite types were implemented, carbon fibre reinforced polymer (CFRP) and glass fibre reinforced polymer (GFRP). The numbers of FRP layers were 2 and 6 layers. C15 normal concrete strength grade was utilized to prepare the specimens. The researchers pointed that the circularization technique succeeded and utilizing expansive cement concrete in the shape modification technique outperformed the non-shrink cement concrete and achieved higher compressive strength and ultimate axial strain. Furthermore, using expansive cement concrete with prefabricated FRP-shell may decrease the cost of the construction. In the end, the shape modification technique can be recommended but the cost and the increase in the cross-sectional area should also be taken into account.

The implementation of the circularization technique as explained in (Yan and Pantelides, 2010), may require relocating all the stuff outside. Therefore, Hadi et al. (2013) investigated the applicability of shape modification technique by attaching prefabricated concrete pieces on the column surface. The wrapping materials were CFRP and steel straps, various load conditions were applied as concentric and eccentric loading. And two types of tests were conducted, flexural and compressive strength test. In addition to the circularization technique, rounding the corner was also implemented. The results of the work showed that utilizing the circularization technique significantly outperformed the enhancement by rounding the corners. Steel straps improved the load-carrying capacity of the column but no confinement enhancement has been observed. The eccentric loading extremely decreased the effective confinement of the FRP-composite. On the other hand, its effect was lower in the case of wrapping the specimens by steel straps. Under the flexural test, the confined specimens took long time before reaching the maximum load value and that attributed to its high ductility. No debonding was found between the square core and the concrete segments. In the end, the researcher concluded that utilizing the circularization technique succeeded to improve the behaviour of the RC square column confined by FRP and it can be recommended as an effective way to strengthen the columns of the buildings and bridges.

Partial wrapping succeeded in improving the confined column behaviour (Saljoughian and Mostofinejad, 2015; Pham et al., 2015). However, its efficiency should also be evaluated for the circularized columns. Thus, Zeng et al. (2017) studied experimentally the possibility of implementing the partial wrapping on the circularized-column. The test parameters were the vertical spacing between the FRP strips, the thickness of the FRP layer, and the strength of the peripheral concrete that was used for circularization. The circularization technique was implemented by pouring the concrete around the square core. Axial loading has been applied on the column specimen and the researchers summarized that the circularization technique significantly enhanced the compressive strength of the specimens. Increasing the FRP thickness resulted in an enhancement in the ultimate compressive strength and strain. The partial technique proved its efficiency not just only by enhancing the compressive strength and strain but also achieved saving in the amount of the FRP composite. However, increasing the vertical spacing between the FRP strips led to premature failure by crushing the concrete between the FRP strips. The high strength concrete of the peripheral concrete resulted in a decrease in the confinement stiffness ratio by increasing the unconfined concrete strength. The hoop strain has no relationship with the shape modification, the vertical spacing of the FRP strips, or the thickness of the FRP layers.

Environmentally, using recycled materials could be recommended. As a consequence, Youssf et al. (2017) investigated applicability of the circularization technique by using crumb rubber concrete experimentally. The parameters were the shape modification approach, the type of the concrete, and the thickness of the FRP-composite. Three different methods of modification technique were used: refining the corners, rounding the corners by concrete angle, and circularizing the columns by concrete segments. Moreover, crumb rubber concrete was used in the modification procedure with different contents and particle sizes. The results indicate that the circularization technique results in a better enhancement in the column behaviour than the others. The use of the crumb rubber concrete can be recommended in case of using a circularization technique instead of the conventional concrete. However, the particle sizes have no significant difference in the behaviour of the column under the axial loading. The thickness of the FRP composite plays an important role in increasing the compressive strength and axial strain. On the other hand, increasing the thickness of the FRP composite led to an increase in the stiffness, as a consequence the hoop strain is decreased. Compared with the study of (Zeng et al., 2017) no debonding has been observed between the core and the concrete segments.

The hollow section column was proved to have different behaviour than the solid section (Micelli and Modarelli, 2013). Thus, Hadi et al. (2017) examined experimentally the effect of the circularization technique on the hollow reinforced concrete column confined by FRP-composite. 20 hollow RC specimens were prepared by using normal concrete. The parameters of the study included rounding the corner, circularization technique, effect of the extra 1-layer of FRP attached horizontally and effect of the extra 1-layer of FRP attached vertically before the circularization. Two different loading conditions were applied as concentric and eccentric loading. The results showed a significant enhancement in the behaviour of the columns by utilizing the circularization technique. Furthermore, the extra FRP layer attached horizontally improved the compressive strength and the ductility of the column under the concentric loading. On the other hand, the vertical FRP strips enhanced the compressive strength of the column under the eccentric loading. However, the enhancement was not significant.

2.5. Strengthening the Concrete Column by Other Materials

In addition to the strengthening techniques that have been explained above, there was also a concern to use non-conventional techniques to improve the axial behaviour of the concrete columns. In the following paragraphs two other techniques that have been used to strengthen the concrete columns are reviewed.

Moghaddam et al. (2007) investigated experimentally and numerically the behaviour of the concrete column confined by using metal strips. The study included two different types of confinement, active confinement, and passive confinement. The active confinement was applied by using post-tensioning metal strips. The parameters of the study included cross-sectional shape, width, and thickness of the metal strips, the spacing between the metal strips, and the number of the plies. The specimens were cast and wrapped by a special method. The failure modes of the specimens were cone, shear, cone-shear, and cone-columnar. The researchers pointed out that the active confinement enhanced the strength and ductility of the specimens more than the passive confinement regardless of the cross-section shape. The behaviour of the cylinder specimens was better than the prismatic specimens Also, chamfered-corners provided better results than the sharp-corners of the prismatic specimens. Increasing the spacing between the two adjacent strips led to decreases in the strength and strain of the strengthened specimens. However, increasing the number of the plies and the width enhanced the strength and strain of the confined specimens. The numerical study represented the behaviour of the specimens accurately but underestimated the effect of the metal strips.

Choi et al. (2008) evaluated experimentally the effect of different types of shape memory alloy wires (SMA) on the behaviour of the cylinder plain concrete column. Two different phases of SMA wires were utilized martensitic and austenitic in the work. The procedure of the martensitic wrapping started by elongated the wires, then wrapping it around the specimens. In the next stage, it was heated by a jacket till 200º C. The austenitic wires were elongated manually during the wrapping period. The ends of the wires were fixed by anchors. Two different pitches, 2 and 4 mm were conducted for wrapping the wires. Six specimens were prepared, four for martensitic and two for austenitic phases. The axial compressive test was applied and the results showed that the compressive strength increased slightly while the ultimate failure strain was significantly enhanced. The pitches do not affect the effectiveness of the SMA and each wire type showed similar enhancement. The improvement in the behaviour depends on the recovery stress and the stress depends on the pre-strain of the wires.

2.6. Theoretical Investigation of Concrete Column Strengthened by Fibre Reinforced Polymer

Strengthening the concrete columns by FRP-composite requires accurate models to predict the ultimate compressive strength and strain.

Lam and Teng (2003a) presented a design-oriented model for concrete columns uniformly confined by the fibre-reinforced polymer. The researchers tried to provide a simple and accurate model. The simplicity of the model allows us to use it directly in the design. In the model, the actual rupture strain of the FRP was considered instead of the ultimate tensile strain from the coupon test. Also, the confinement efficiency of the FRP was found by dividing the actual rupture strain from the test by the ultimate tensile strain from the coupon test. The model was examined by a large database and good agreement was observed.

The experimental studies showed remarkable differences between the results of the ultimate strain and stress of the circular and rectangular/square concrete columns confined by FRP-composite. Therefore, Lam and Teng (2003b) proposed an extension to the design-oriented stress-strain model of uniformly confined concrete column to predict the ultimate compressive stress and strain for concrete column non-uniformly confined by FRP composite. Two shape factors were proposed to be added in the main formula to predict the enhancement in the axial stress and strain for the square and rectangular concrete column confined by FRP. The shape factors enabled to account of the effective confinement area of the concrete column. To prove the efficiency of the proposed model, it was necessary to check it with a test database. Therefore, the outcome of 58 specimens was compared with the proposed model. A great correlation has been obtained.

Teng et al. (2007), proposed a new stress-strain model for FRP strengthened concrete column. The proposed model had been used firstly by Mander et al. (1988) for steel confined concrete. However, the results of the formula for estimating the ultimate axial stress of the confined concrete column by FRP does not agree with the experimental findings. Therefore, a new equation was suggested to estimate the ultimate axial stress. The proposed equation to calculate the ultimate axial stress is similar to what has been proposed by Lam and Teng, (2003a, 2003b). Nevertheless, here it is used for another purpose. The proposed model was validated with a large database and good agreement was gained.

2.7. Summary of Literature Review

The content of this chapter can be summarized in the following paragraphs depending on the studies presented above.

Using concrete jacketing is considered as an effective way to enhance the load-carrying capacity. On the other hand, the ductility does not improve significantly by using only a concrete jacket without reinforcement and fibres (Gholampour et al., 2019).

The steel cage successes to improve the behaviour of the concrete column by taking into account the parameters that may have an effect on its efficiency such us, steel angle size and the spacing between the battens (Tarabia and Albakry, 2014).

The confinement of the concrete columns by steel tube can significantly improve the load-carrying capacity and ductility. However, increase in the slenderness and D/t ratio may reduce the efficiency of the steel tube. In contrast, using high strength concrete may increase the efficiency of the technique (Li et al., 2019).

The cross-sectional shape plays an important role in the effectiveness of the FRP-confined concrete column, where circular cross-section shows better enhancement than square cross-section (Mirmiran et al., 1998; Micelli and Modarelli, 2013). Moreover, the effect of the specimen height is in agreement within the permissible limits of ACI prevision for the tied columns (Mirmiran et al., 1998). The results indicate that there is a slight effect of the bonding between the FRP-composite and the column surface on the confinement efficiency. However, the mechanical bond by means of shear connector ribs made of a special polyester paste proves its efficiency in the enhancement of the behaviour of the FRP-confined the concrete columns (Mirmiran et al., 1998).

The ductility of the concrete column with the sharp corner can be enhanced by the FRP confinement but no increase in the compressive strength should be expected (Al-Salloum, 2007). Increasing the corner radius significantly improves the confinement effectiveness of the FRP-composite which leads to increases in the ductility and the compressive strength (Al-

Salloum, 2007; Hadi et al., 2013; L. Wang et al., 2008; Micelli and Modarelli, 2013; Zeng et al., 2017). FRP-composite is more effective with normal strength concrete than high strength concrete considering the same confinement thickness (L. Wang et al., 2008; Micelli and Modarelli, 2013). The partial wrapping could be used rather than fully wrapping from the economical point of view. Also, the corner strip-batten technique can be an alternative way for partial wrapping (Pham et al., 2015; Saljoughian and Mostofinejad, 2015). It is evident that the orientation angle significantly affects the effectiveness of the FRP-confined concrete columns and the confinement method has a slight effect on the FRP-composite efficiency. Moreover, the end conditions of the specimens have an insignificant effect on the test results (Vincent and Ozbakkaloglu, 2013). The eccentric load has a negative effect on the efficiency of the FRP-confined concrete column (Hadi et al., 2013, 2017; Saljoughian and Mostofinejad, 2015; Wu and Jiang, 2013). Also, it is not logical using the same models of the concentric load to predict the results of the eccentric load. Therefore, a new model was proposed in (Wu and Jiang, 2013).

Increasing the aspect ratio of the square concrete column affects the FRP-composite effectiveness negatively. Therefore, the FRP-composite is less effective with a rectangular column compared to the circular and square sections (Micelli and Modarelli, 2013). Moreover, FRP-composite effectiveness becomes lower with hollow sections (Micelli and Modarelli, 2013). Increase in the number of FRP-composite plies lead to more improvement in the strength and ductility of the column, but no effect on the slope of the stress-strain curve above the f_{co} was observed (L. Wang et al., 2008; Micelli and Modarelli, 2013; Zeng et al., 2017). The cross-sectional size of the square concrete column less than 350 mm does not show an effect on the stress-strain curve of the FRP-confined square concrete column (D. Wang et al., 2016). Furthermore, the existence of transverse steel reinforcement may improve the confinement effectiveness. But also, the buckling of the longitudinal steel bars may cause premature failure (D. Wang et al., 2016). On the other hand, the gain from the results of the circular concrete columns having small cross-sectional sizes (=50 mm) is less dependable (The´riault et al., 2004). Besides, the slenderness has insignificant to no effect on the FRP-confined concrete column (Mirmiran et al., 1998; The´riault et al., 2004).

The pre-tensioned technique for the FRP-composite successes to increase the gain in the load-carrying capacity and the ductility (Mortazavi et al., 2003). The pre-loading is considered to be an important factor, for instance, the enhancement decreases proportionally with increasing the preloading ratio. Furthermore, at a certain preloading ratio, the enhancement decreases with increasing the FRP thickness comparing with the un-loaded specimens (Pan et al., 2017). Using VG with EI as a fire protection system enhanced the fire endurance of the CFRP-confined concrete column until 5.5 hours (Bisby et al., 2005).

The circularization technique enhanced the effectiveness of the FRP-confined concrete column (Hadi et al., 2013; 2017, Yan and Pantelides, 2010; Youssf et al., 2017; Zeng et al., 2017). The partial wrapping succeeded with the circularization technique not just in improving the axial behaviour of the concrete but also in saving the amount of FRP (Zeng et al., 2017). Using the crumb rubber concrete succeeded to be an alternative material to implement the shape modification technique (Youssf et al., 2017). The shape modification technique was provided to be an effective method with the hollow cross-section as well (Hadi et al., 2017). FRP-composite enhanced the behaviour of the column in the case of flexural test especially when the fibre orientation angle is parallel to the longitudinal axis (Hadi et al., 2013, 2017). All the mentioned ways to apply the shape modification technique was proved to be successful but increasing the cross-section size and the dead load still questionable.

Using the pre-tensioned metal strips in strengthening the concrete column succeeded to enhance the load-carrying capacity and ductility. Moreover, parameters such as the spacing between the strips, the width of the strips, and the number of the plies may affect the behaviour of the concrete column (Moghaddam et al., 2007). The shape memory alloy wires (SMA) technique enhances the ductility of the concrete column. In contrast, the improvement in the compressive strength is insignificant (Choi et al., 2008).

The proposed design oriented-models by Lam and Teng (2003a, 2003b) succeeded to provide an accurate prediction of the ultimate axial stress and strain for the FRP confined column. However, the stress-strain behaviour of the confined column can be generated following the suggested model by Teng et al. (2007).

3. MATERIAL AND METHODS

3.1. General Introduction

The proposed shape modification technique for the FRP confinement of square columns was evaluated experimentally. The experimental program was conducted at the laboratory of the Civil Engineering Department, Aydin Adnan Menderes University. All the works such as preparing the formwork, casting the concrete, curing and testing the concrete specimens and segments were carried out at the laboratory. The required materials were supplied locally and used at the laboratory. The following sections of the chapter provide all the details of the experimental program.

3.2. Design of the Specimens

Twenty-one square plain concrete specimens were prepared. The dimensions of the specimens were 109 x 109 mm with 300 mm high. Normal strength concrete was used to prepare all the required specimens with compressive strength of 21 MPa.

The uni-directional glass fibre reinforced polymer (GFRP) was the confining material that was used to strengthen the concrete specimens. The mechanical properties of the GFRP are mentioned later on.

3.3. Test Configuration

The concrete specimens were arranged in four groups. Three identical specimens were prepared for each parameter. The first group (C) includes the unconfined square specimens. The second group (RC) represents the usual way of strengthening the concrete specimens by rounding the corners and wrapping the GFRP sheet. The third group (CC) presents the shape modification method applied in the previous studies by attaching concrete segments on the surfaces of the unconfined specimens and wrapping the GFRP sheet around them.

The last group (CRC) includes the proposed shape modification method by rounding the corners and attaching concrete segments on the flat surfaces of the concrete specimens and wrapping the GFRP sheet. All the concrete specimens were wrapped with a single layer of

GFRP. Furthermore, two different ways of wrapping were conducted, fully wrapping is indicated by the letter (F), and partial wrapping is indicated by the letter (P). In the partial wrapping, the GFRP ring has a constant width of 35 mm while the clear spacing between each two adjacent GFRP rings was 18 mm for method-1 and approximately 31 mm for method-2. In other words, six GFRP rings were used in method-1 and five GFRP rings were utilized in method-2 with constant GFRP width of 35 mm (Figure 3.1). It is worth mentioning that the radius of the corners was measured from the centre of the specimen (Figure 3.1). Table 3.1 includes all the required details of the concrete specimens and the wrapping methods.

Table 3.1. The test matrix

Group	Number of Specimens	External Modification	Confinement Scenarios	GFRP Width	Clear Spacing
C	3	None	None	-	-
RCF	3	Round Corners	Full Wrapping	300	-
RCP1	3	Round Corners	Partial Wrapping	35	18
CCF	3	Circularization	Full Wrapping	300	-
CRCF	3	Round Corners, Circularization	Full Wrapping	300	-
CRCP1	3	Round Corners, Circularization	Partial Wrapping	35	18
CRCP2	3	Round Corners, Circularization	Partial Wrapping	35	31

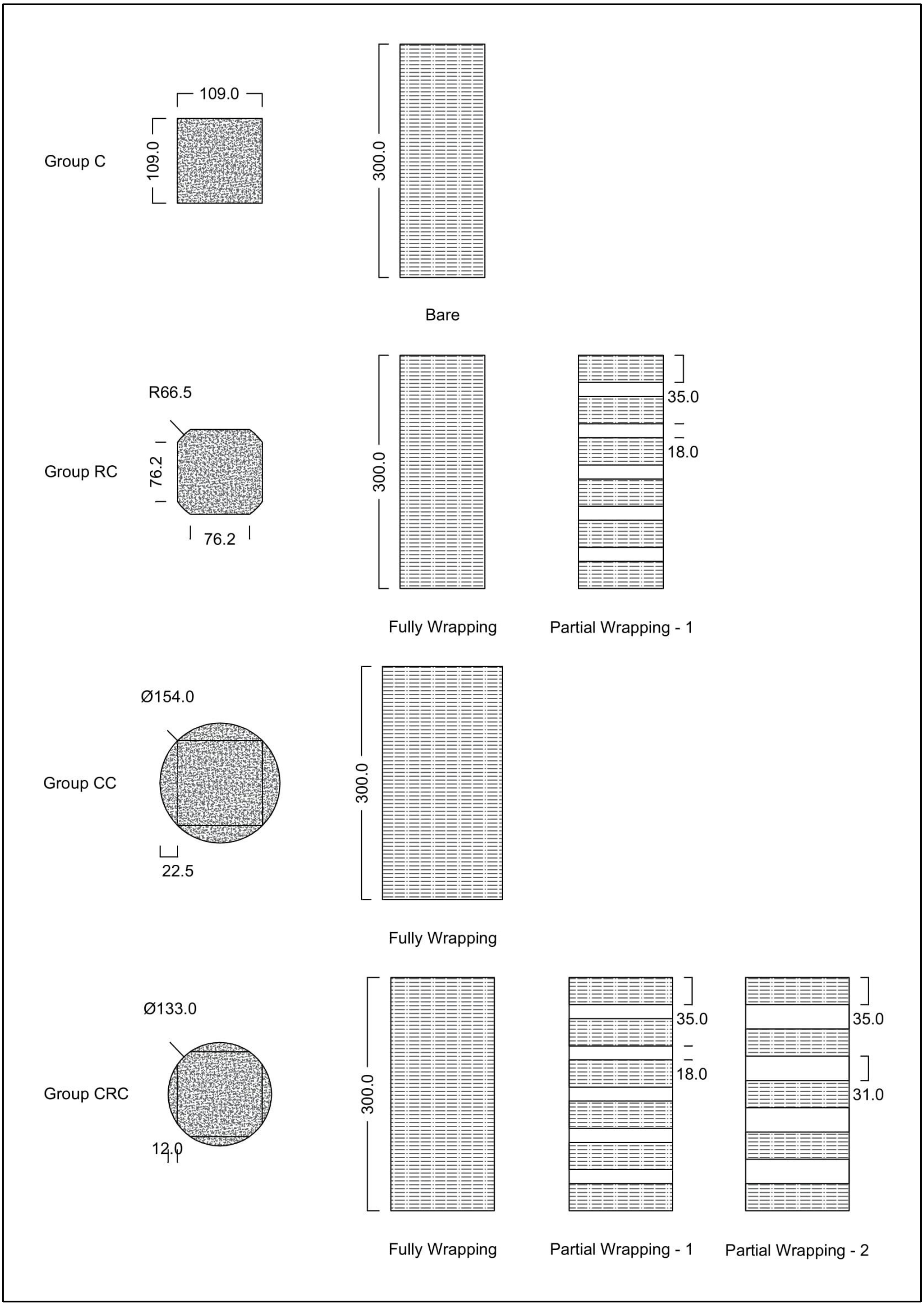


Figure 3.1. The wrapping methods of the specimens (All units in mm).

3.4. Formwork Setup

Plywood formwork was prepared for the experimental work. The formwork has two main parts, one of them for the square cores and another part for the concrete segments that will be used finally to circularize the square cores. At first, 2D and 3D drawings were prepared by a computer software to prevent any mistakes that may occur during the preparation process of the formwork. Figure 3.2 and 3 shows all the details of the formwork. The PVC pieces shown in Figures 3.2.a and b were used to constitute the concrete segments that were utilized for the circularization of specimens without and with rounded corners (i.e. in the test groups CC and CRC), respectively. The wooden plates were used to prepare the formwork and it was supplied from a local company. The plates were cut by a jigsaw to the required pieces and then all the pieces were attached to each other by screws.

The PVC pieces illustrated in Figure 3.2.c were used for rounding the corners. The PVC pipes were cut to the required shape by using the jigsaw to form these pieces. The PVC pieces were attached then at the corners of the formwork by using adhesive (Figure 3.4).

To prepare the concrete segments, PVC pipes were utilized as well. The pipes were cut to the required parts. In the case of the large segments, wooden plate pieces were used to hold it inside the formwork. For the small segments, screws were used to hold it inside.

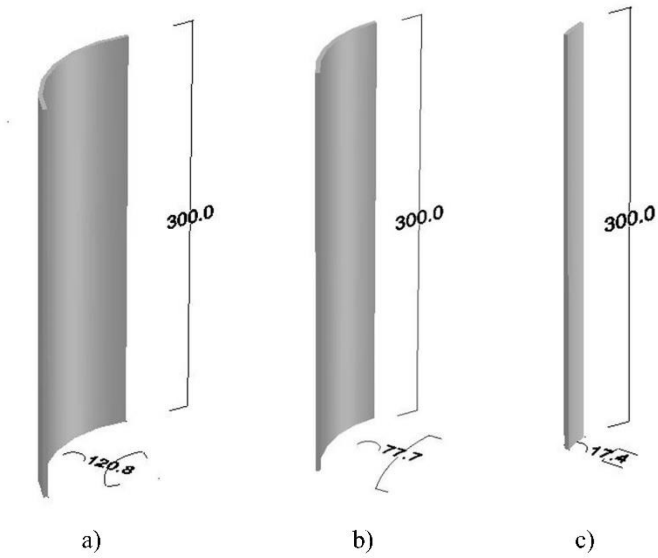


Figure 3.2. 3D drawing of the all the PVC pieces to produce, a) large segment, b) small segment and c) rounded corners, (All units in mm)

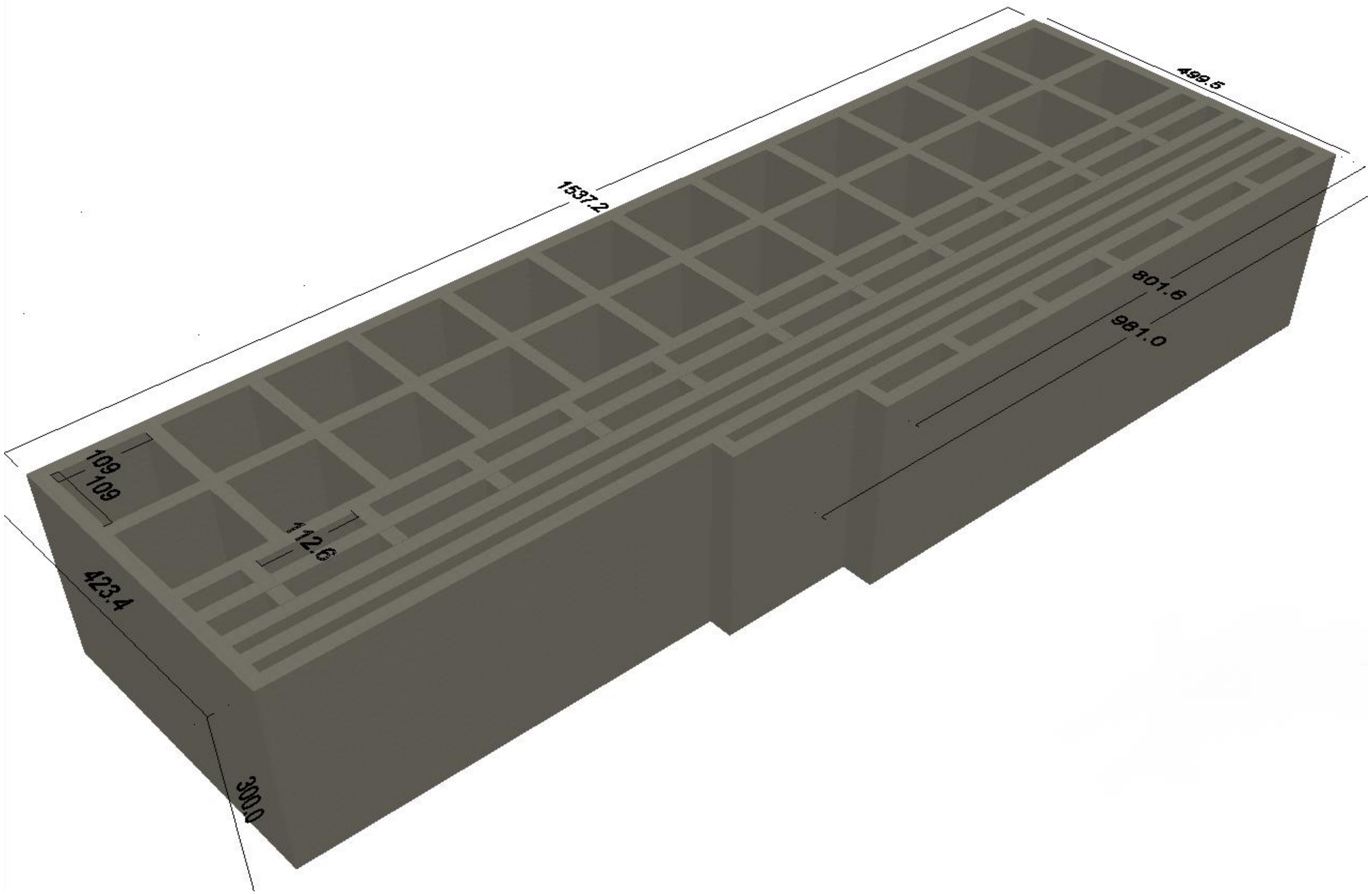


Figure 3.3. 3D drawing of the formwork (All units in mm)

3.5. Preparation of the Specimens

After finishing the preparation process of the formwork, it was cleaned well from any dust. The oil then was applied to the inner surfaces of the formwork to make the removal process easier (Picture 3.1).

3.5.1. Concrete Mix Materials

Two different concrete mixes were prepared for the work. The first mix (namely C-1) to prepare the concrete cores. And the other one for concrete segments. The ordinary Portland cement was used in both mixes. Crushed gravel with a nominal maximum size of 5mm was used for C-1 as a coarse aggregate and crushed stone was used as a fine aggregate. However, the crushed stone was used only as aggregate for the second mix (namely C-2) because of the small sizes of the concrete segments. Furthermore, a chemical admixture was used in the second mix to increase the workability of the concrete mix. Table 3.2 shows the weight proportions of the concrete mix of each concrete batch.

Table 3.2. The weight proportions of the concrete mixes

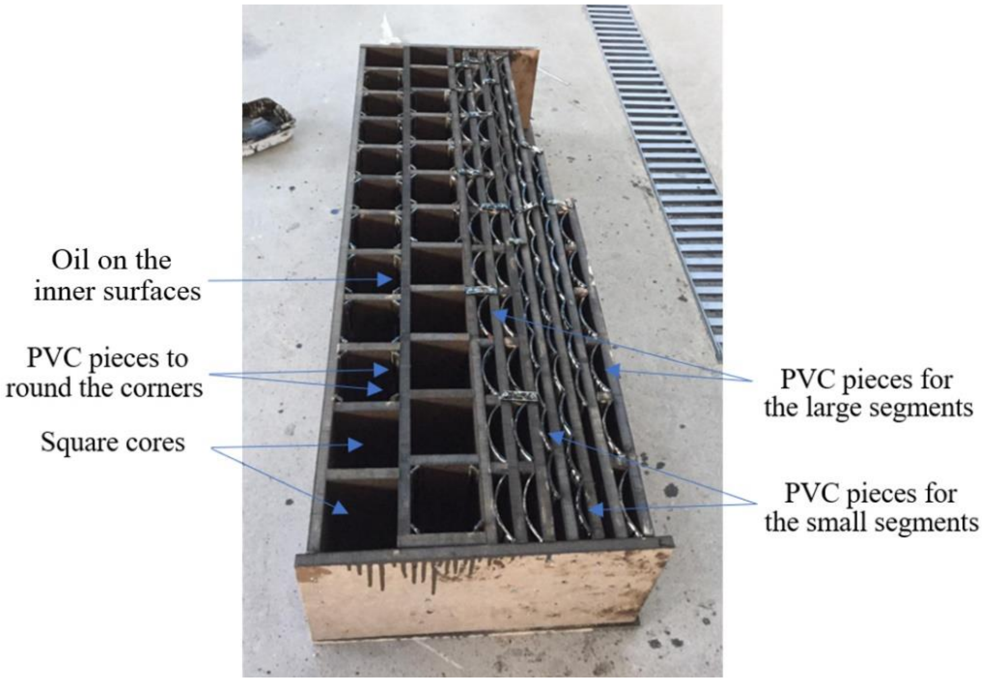
Mix	***fc*, MPa**	**Cement, (%)**	**Fine aggregate, (%)**	**Coarse aggregate, (%)**	**Water, (%)**	**Admixture, (%)**
C-1	21	12	19	58	11	-
C-2	25	16	75	-	9	0.4

3.5.2. Concrete Pouring Process

The pouring process of the concrete was conducted in two steps. At first, low strength concrete with compressive strength 13 MPa was prepared for the concrete cores to represent a weak column that require strengthening. However, the concrete with a compressive strength of 17 MPa was prepared for the concrete segments. The mixing design was prepared carefully, and 3 cylinders were cast for each concrete batch to test the compressive strength after 28 days. The concrete was cast in three layers for each specimen where each layer was compacted very well to prevent any voids inside the concrete. Bar clamps were used to guarantee the stability of the formwork (Picture 3.2). The small segments were prepared by following another technique because of their small size. The formworks of these small segments were positioned horizontally for this purpose. Picture 3.3 and 4 shows this process that was conducted to prepare the small segments.

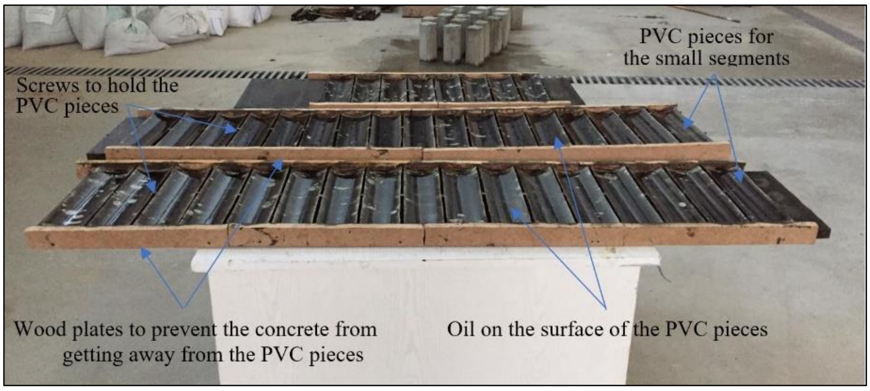
3.5.3. Concrete Curing Process

After one week, the formwork was removed. The concrete segments were placed into pool water and cured in the room temperature for 28 days. However, water was sprayed onto the concrete cores regularly without placing them inside a pool water to ensure low strength concrete. The concrete cores were cured in the room temperature for 28 days.



Picture 3.1. The formwork after finishing the preparation process and applying the oil inside.

Picture 3.2. The formwork after casting the concrete



Picture 3.3. The formwork of the small segments before and after pouring the concrete

Picture 3.4. The formwork of the small segments before and after pouring the concrete.

3.5.4. Shape Modification Process

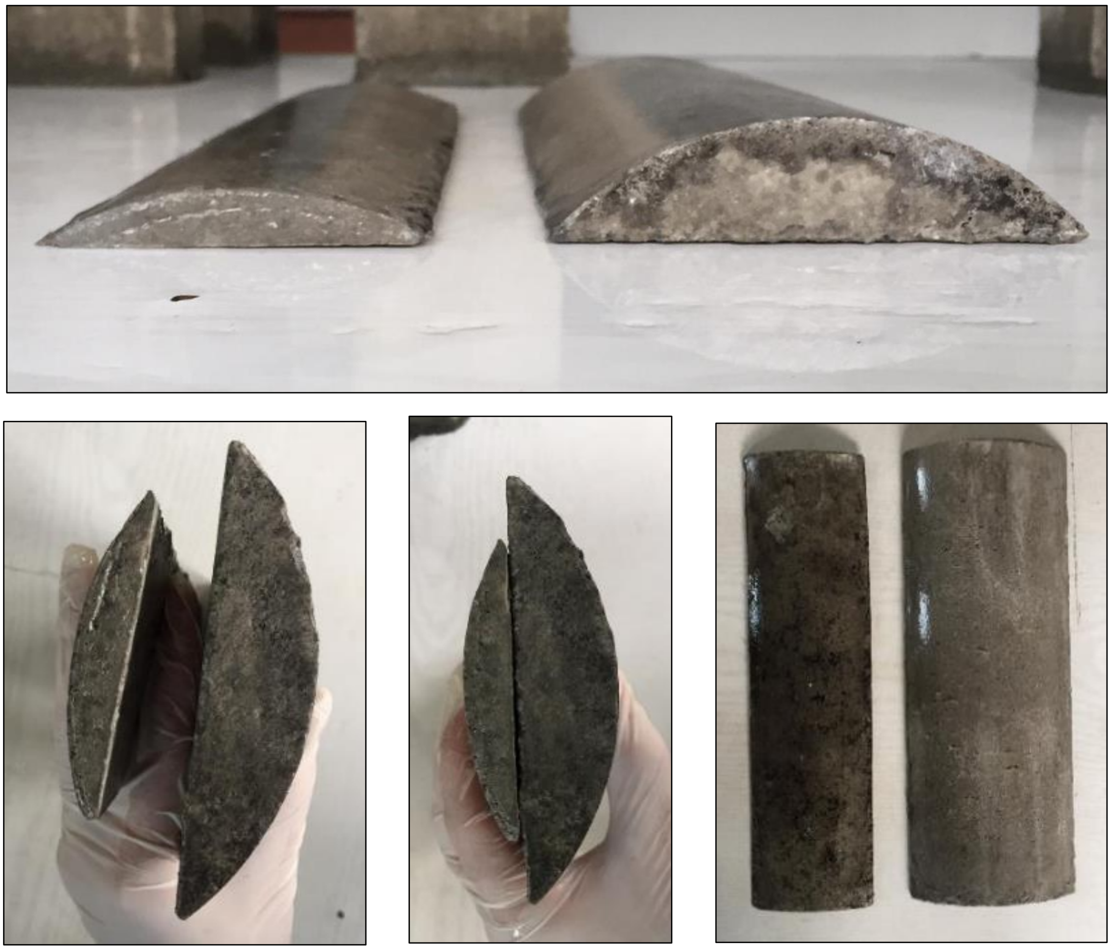
After 28 days, the concrete segments were taken out of the pool water (Pictures 3.5 and 6). The segments were then cleaned well to ensure a smooth surface. The concrete cores were located on the appropriate place and all the flat sides of the cores were cleaned very well from the dust.

Before starting the shape modification technique, the specimens in each group were capped at both ends with high strength mortar. The aim here is to ensure the load distribution evenly (Picture 3.7).

The two- component epoxy was used as adhesive material to bond the concrete segments on the flat sides of the concrete cores. Three specimens were left without any modifications as was planned.

At the first, the primer was applied on the surface of the specimens and the concrete segments, as was recommended in the manufacturer's sheet to fill in air voids and provide high bond strength (Picture 3.8). Both the ends and the corners of the specimens were covered to keep them clean after the end of the shape modification technique (Picture 3.9). After one day, the two- component epoxy was mixed well relying on the instructions of the manufacturer. Then the component was applied on the surface of the flat sides of the specimens and the flat sides of the concrete segments as well by using a brush. The segments were then attached on the flat sides of the specimens and zip ties were used to hold the concrete segments around the specimens properly (Pictures 3.10 and 11). All the specimens were then left for one week before wrapping the FRP-composite.

Picture 3.5. Concrete segments after taking them out of the water pool

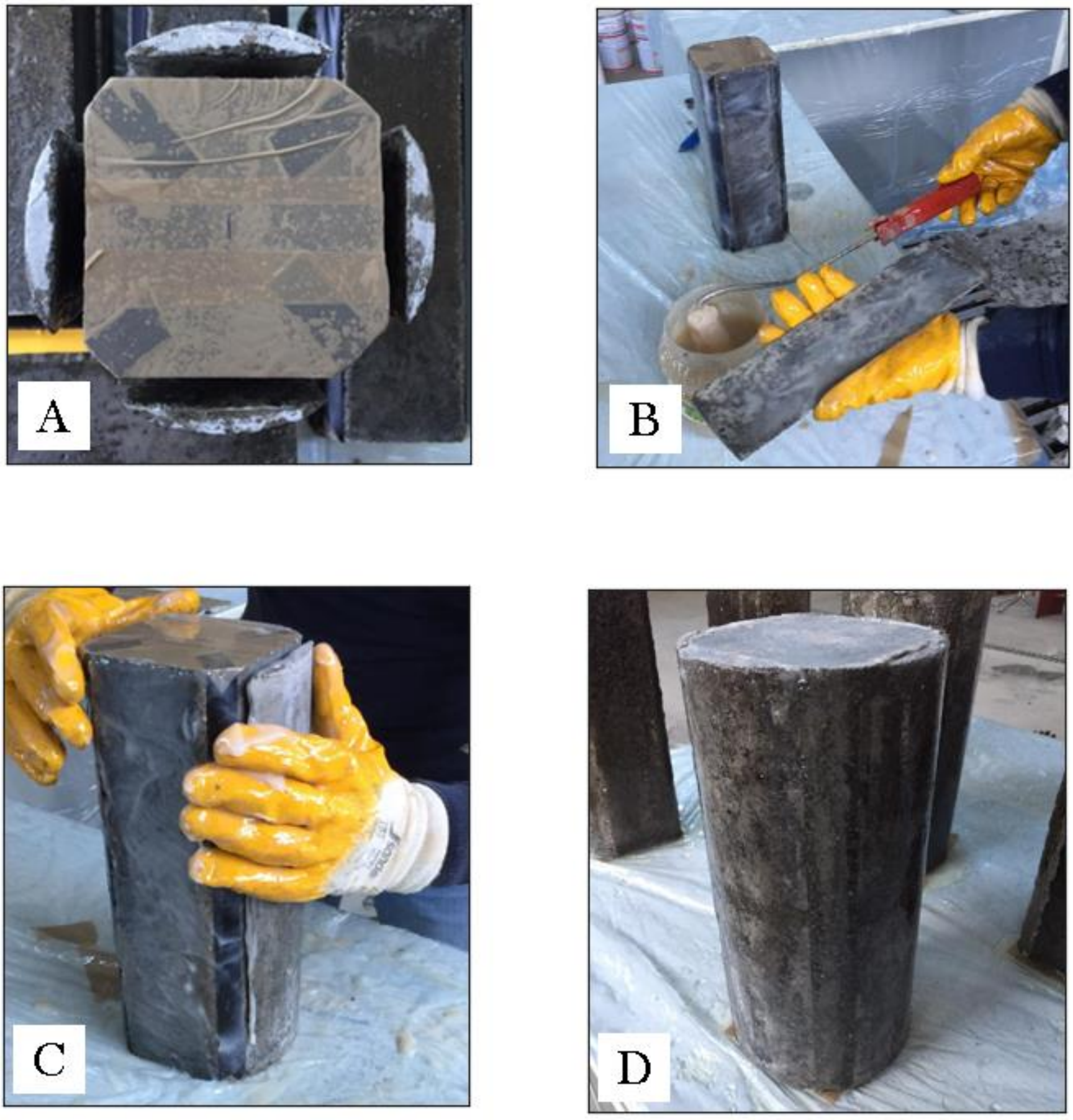


Picture 3.6. Size difference between the concrete segment of the proposed shape modification method and the previous shape modification method

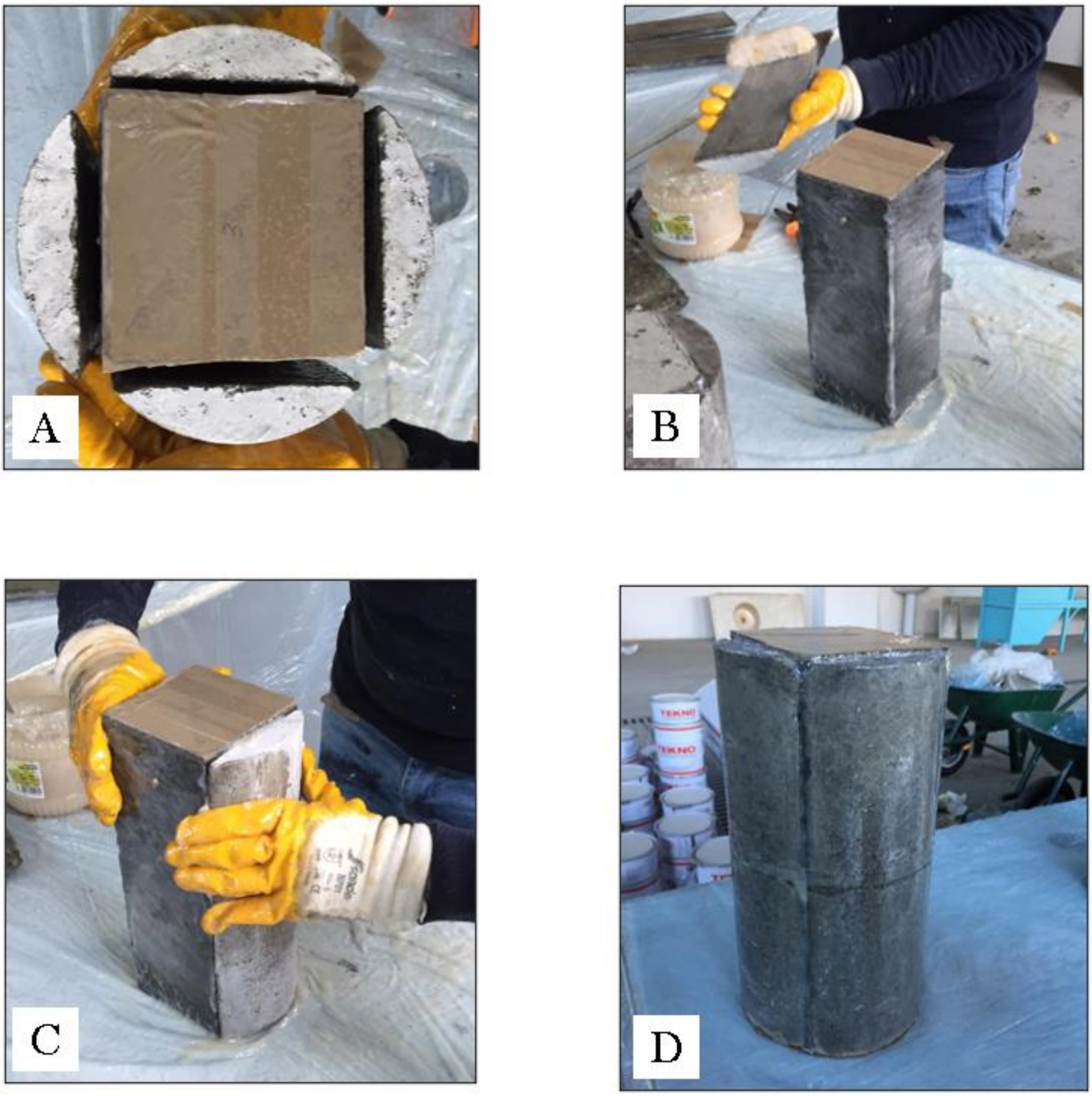
Picture 3.7. Concrete specimens after capping the ends

Picture 3.8. Concrete specimens after applying the primer on the flat surfaces

Picture 3.9. Concrete specimens after covering the ends and the corners



Picture 3.10. Steps of implementing the shape modification technique for the rounded-corners of the core, a) top view for the core and the concrete segments, b) applying the epoxy on the surface of the specimen and the concrete segment, c) attaching the specimens on the surface of the core, and d) the final shape of the specimen.



Picture 3.11. Steps of implementing the shape modification technique for the unrounded-corners of the core, a) top view for the core and the concrete segments, b) applying the epoxy on the surface of the specimen and the concrete segment, c) attaching the specimens on the surface of the core, and d) the final shape of the specimen.

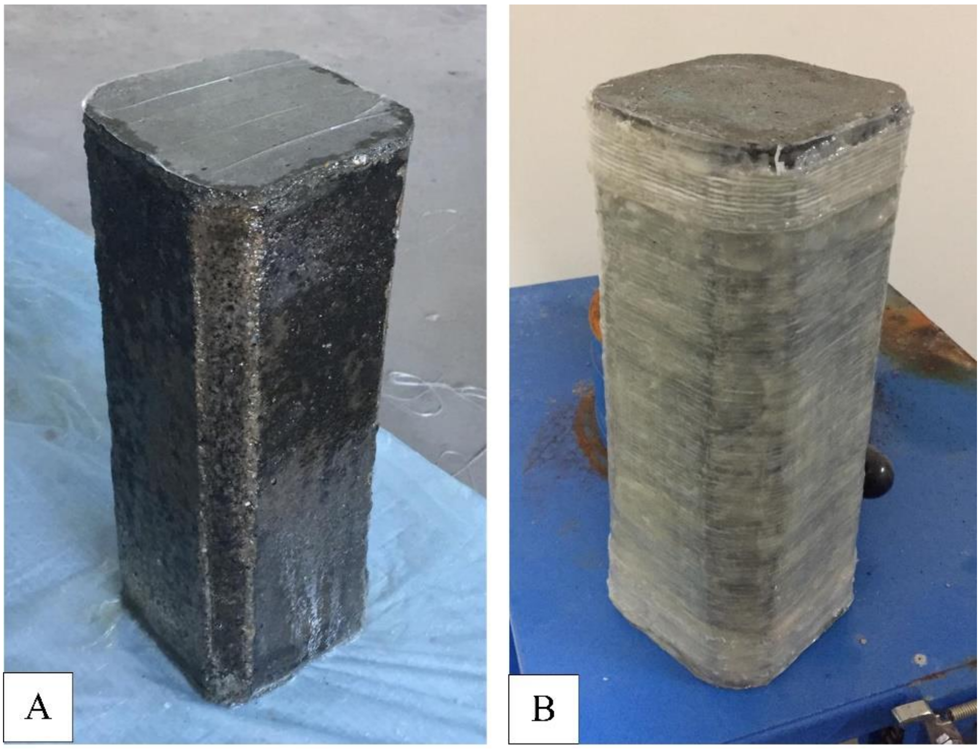
3.5.5. Wrapping the External Confinement

The specimens in the group C were left without any modification or confinement to represent the unconfined concrete columns. The specimens in the group RC, CC, and CRC were wrapped by a single layer of GFRP with different wrapping techniques (i.e. fully or partial wrapping).

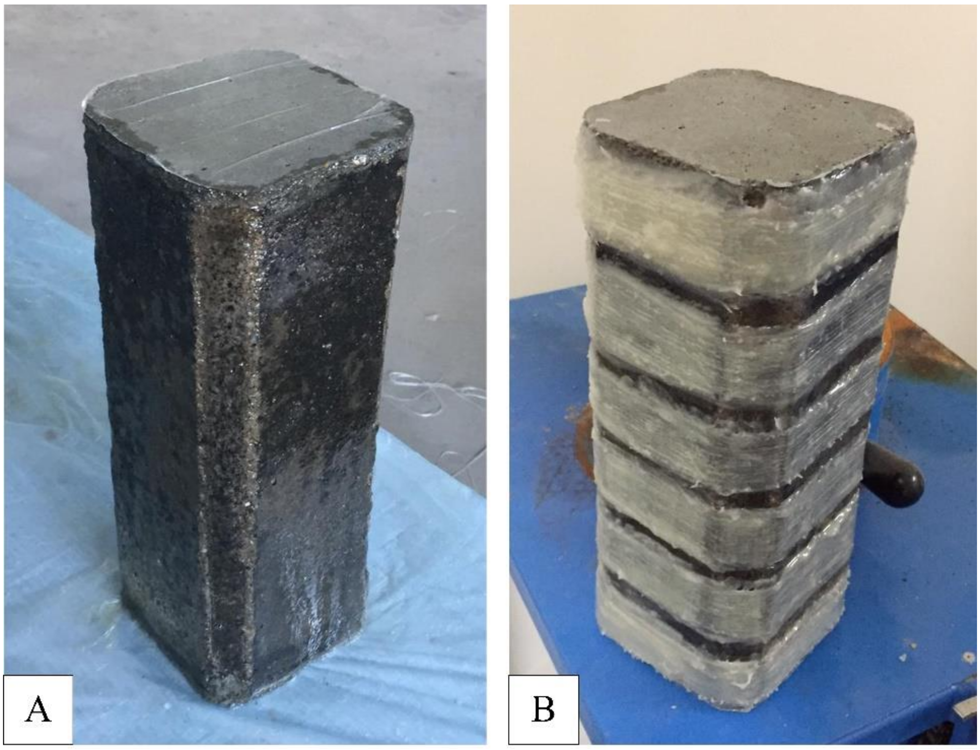
The uni-directional GFRP with a width of 300 mm and thickness of 0.2 mm was used as a confinement material. The wet-layup method was conducted to confine the concrete specimens. Before starting the confinement process, the GFRP sheets and rings were prepared and located in the appropriate place (Picture 3.12). After that, the epoxy primer was applied on the side surfaces of the specimens. In the following day, the epoxy was applied on the surface of both the specimens and the GFRP sheets or rings by using a brush.

The shell was then wrapped around the specimens carefully. An overlapping equal to 30% of the circumferences of the specimen was implemented to ensure a sufficient bonding and to avoid premature failure (Mirmiran et al., 1998; Youssf et al., 2017). To prevent unexpected damage at the ends of the specimens, extra 25 mm GFRP rings were wrapped at the ends of the specimens (Pham et al., 2015; Zeng et al., 2017). Additional epoxy was applied on the GFRP sheet and all the voids were eliminated by the roller (Pictures 3.13-18). All the specimens were left for two weeks to dry enough before the test, as it was recommended by the supplier.

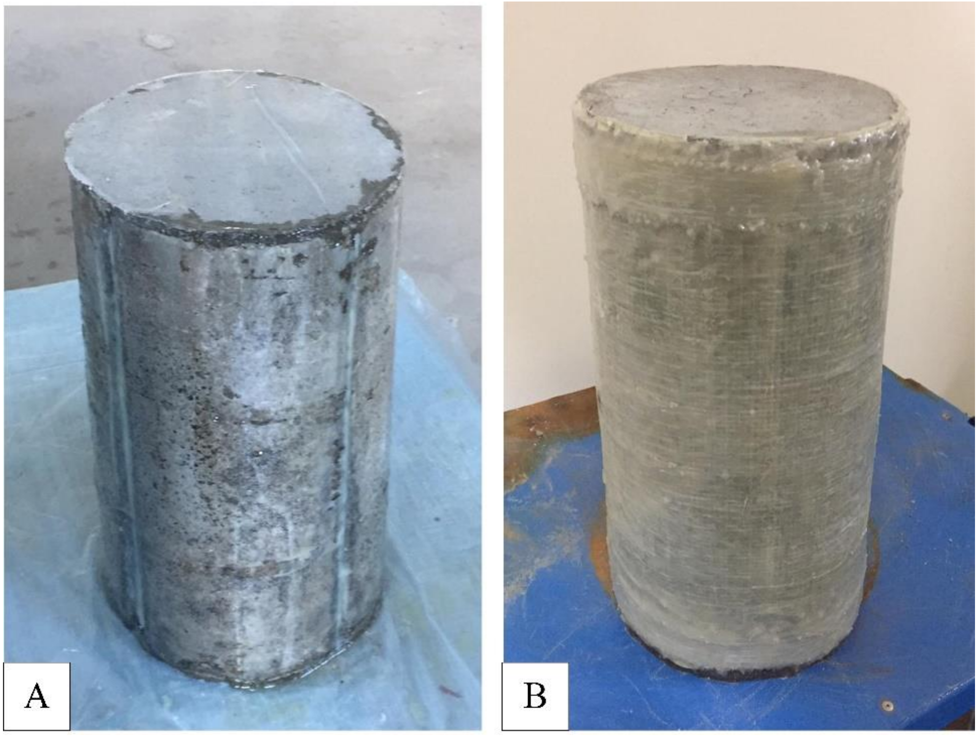
Picture 3.12. GFRP sheets and rings after the cutting process.



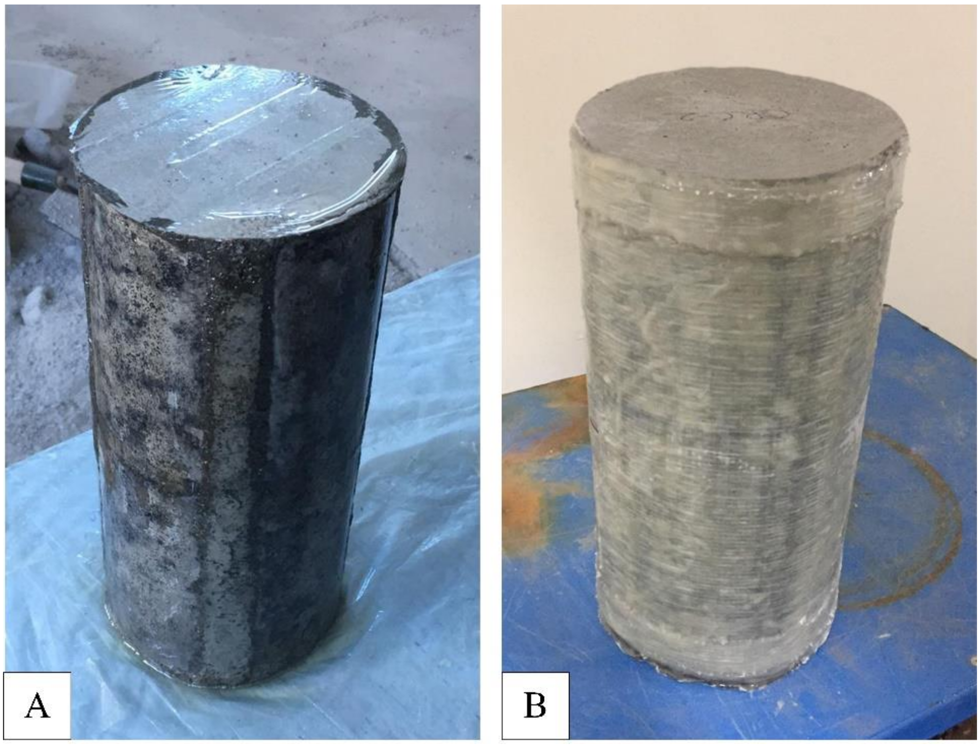
Picture 3.13. RCF group, a) applying the epoxy primer, and b) wrapping the GFRP sheet.



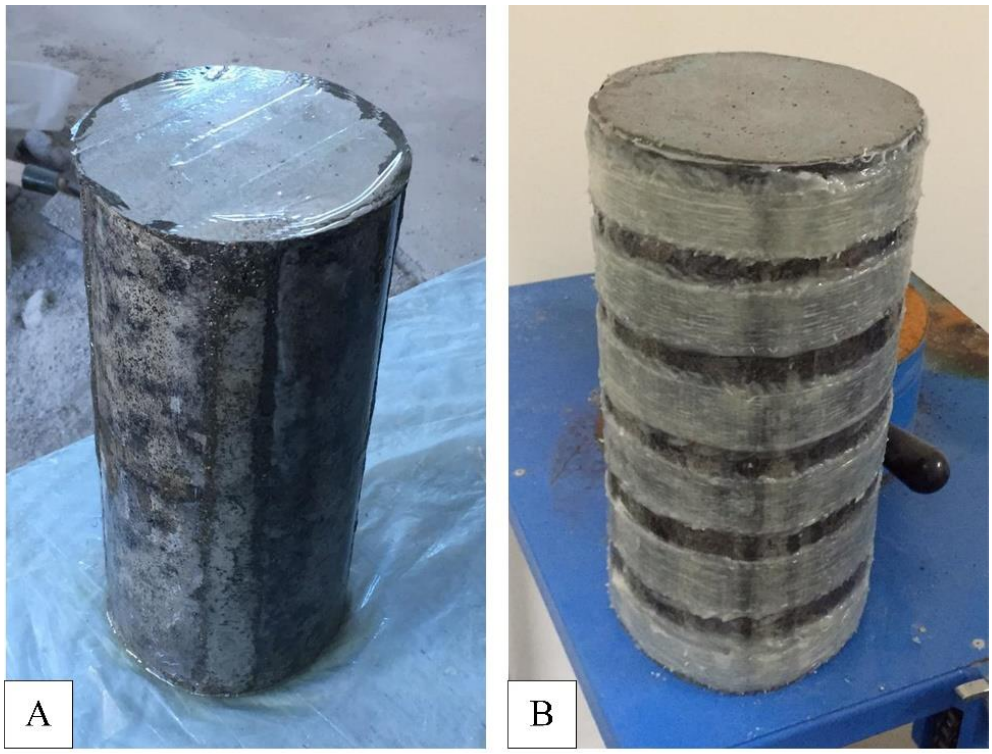
Picture 3.14. RCP1 group, a) applying the epoxy primer, and b) wrapping the GFRP rings.



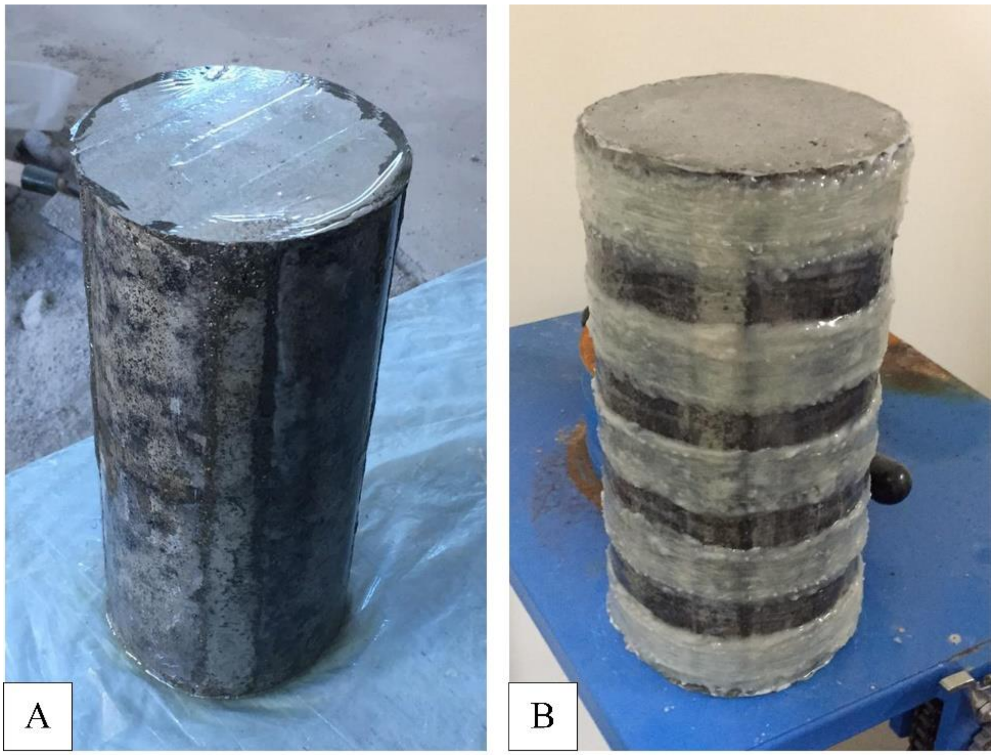
Picture 3.15. CCF group, a) applying the epoxy primer, and b) wrapping the GFRP sheet.



Picture 3.16. CRCF group, a) applying the epoxy primer, and b) wrapping the GFRP sheet



Picture 3.17. CRCP1 group, a) applying the epoxy primer, and b) wrapping the GFRP rings.



Picture 3.18. CRCP2 group, a) applying the epoxy primer, and b) wrapping the GFRP rings

3.6. Preliminary Test

The preliminary tests have been conducted to determine the mechanical properties of each material that was used in this study.

3.6.1. Concrete

According to (ASTM C469), three concrete cylinders for each concrete batch have been tested to determine the compressive strength of the concrete after 28 days. For this purpose, a total of 6 cylinders with 150 mm diameter and 300 mm height were prepared in this study (Picture 3.19). The axial tests of the cylinders yielded the average concrete compressive strength of 21 MPa and 25 MPa for the C-1 and C-2 mix, respectively.

Picture 3.19. Concrete cylinders to test the compressive strength after 28 days.

3.6.2. FRP-composite

The mechanical properties of the GFRP were obtained by the coupon test according to (ASTM D3039). Four flat coupons with a single layer of GFRP were prepared. The coupons with a width of 15 mm and a height of 250 mm were prepared. The nominal thickness of the layer was 0.2 mm. The ends of the coupons were placed in between two steel tabs with a length of 50 mm at each end. The steel tabs and GFRP sheets were bonded by using epoxy. These steel tabs were placed in between the grips of the tensile testing machine. The tensile coupon tests were conducted at the Middle East Technical University, Ankara. The test results have been summarized in (Table 3.3) and (Figure 3.4) shows the stress-strain curves obtained as a result of the coupon tests.

Table 3.3. Mechanical properties of the CFRP from the coupon test.

Coupon No	Tensile Strength, MPa	Average Tensile Strength, MPa	Tensile Strain, %	Average Tensile Strain, %	Elastic Modulus, GPA	Average Elastic Modulus, GPA
Coupon 1	934.4		1.97		50	
Coupon 2	1020.8	982.625	2.23	1.995	54	50.25
Coupon 3	1244.4		2.12		51.5	
Coupon 4	730.9		1.66		45.5	

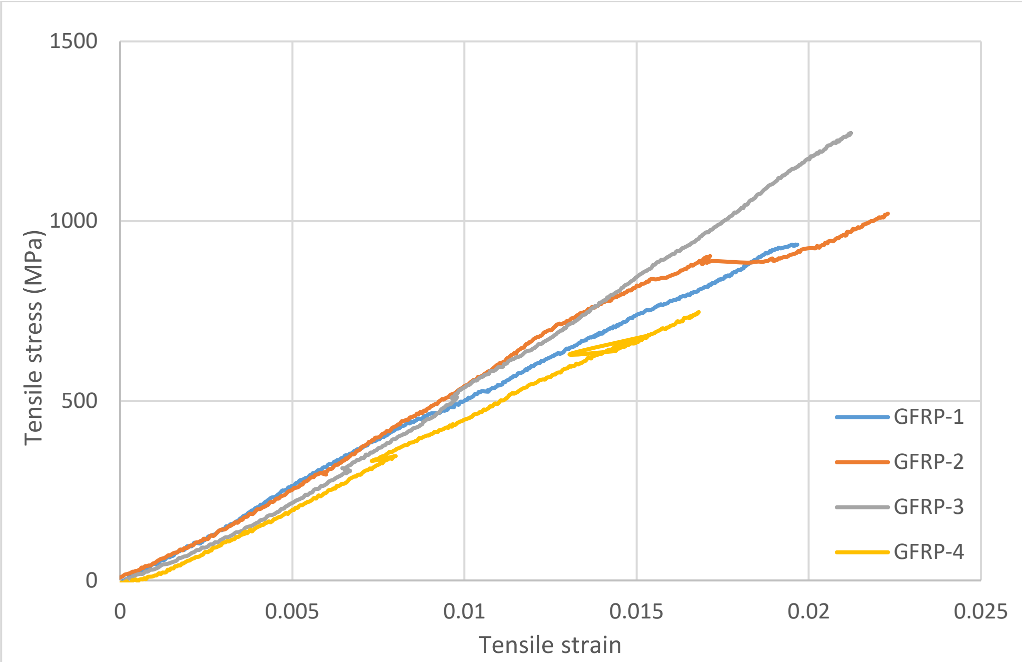


Figure 3.4. Stress-strain curve of the coupon test results.

3.7. Experimental Setup Instrumentation

The compression tests were conducted using a uniaxial test machine with a capacity of 3000 KN. However, a load cell was utilized to obtain the applied load data in synchronisation with the other measurements. The capacity of the load cell that is 600 KN determined the ultimate load capacity of the test setup. All the specimens were tested under a monotonic axial concentric load. Two linear variable differential transformers (LVDT's) were utilized to determine the axial displacement of the specimens under the axial load. The LVDTs were held on the appropriate place by magnetic base. Strain gauges were used to measure the strain along the hoop direction at different positions. For each confined specimen four strain gauges were attached at the mid-height. Two strain gauges were mounted at the centre of the sides face and the remaining two strain gauges were attached at the centre of corners (Figure 3.5). It is believed that the strain at the corners usually differs than the centre of the side face (L. Wang et al., 2008, D. Wang et al., 2016). Figure 3.5 shows more details about the strain gauges location.

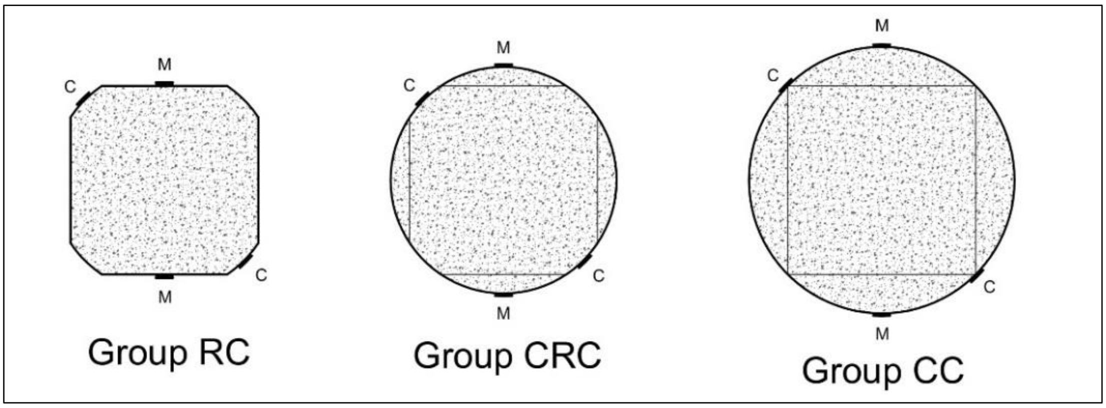


Figure 3.5. Locations of the strain gauges for each confined group, where C and M refer to the strain gauges at the centre of the corners and centre of the side face respectively.

3.8. Test Process

The specimens were located in the test machine one by one carefully. It was ensured that the specimens are under the centerline of the loading plate. The measurement of the LVDTs and the strain gauges were recorded by an automatic data acquisition system. It was ensured that the difference between the reading of the two LVDTs must not be more than 10%, otherwise, the test should be stopped. The difference in the reading of the LVDT refers to either an error in the calibration of the LVDTs or shiffting the spacimen away from the center of the loading plate. The compression tests were conducted by applying a constant stress (0.25 MPa/s) based loading according to (ASTM C39). All the results of the tests were recorded as will be discussed in the next chapter. Picture 3.20. shows more details about the test set-up that was used to conduct the work.

Picture 3.20. Test set-up

4. RESULTS

4.1. General Introduction

The obtained results from the experimental program are assessed here. The aim of this chapter is to study the behaviour of the specimens in each group under the axial monotonic loading. The failure mechanism of the confined and the unconfined specimens is discussed to show the effect of the FRP-composite and the effect of each technique on the confinement mechanism.

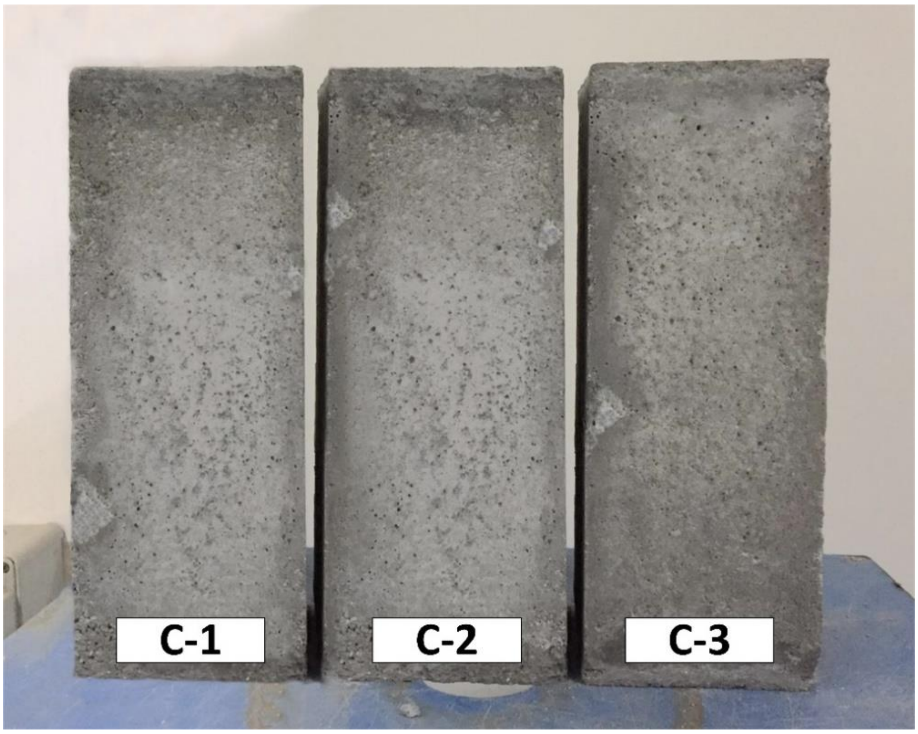
4.2. Failure Mode

The specimens in the group (C) failed immediately after reaching the maximum capacity. The failure mode was brittle and crushing the concrete on the sides was observed as shown in Picture 4.1.

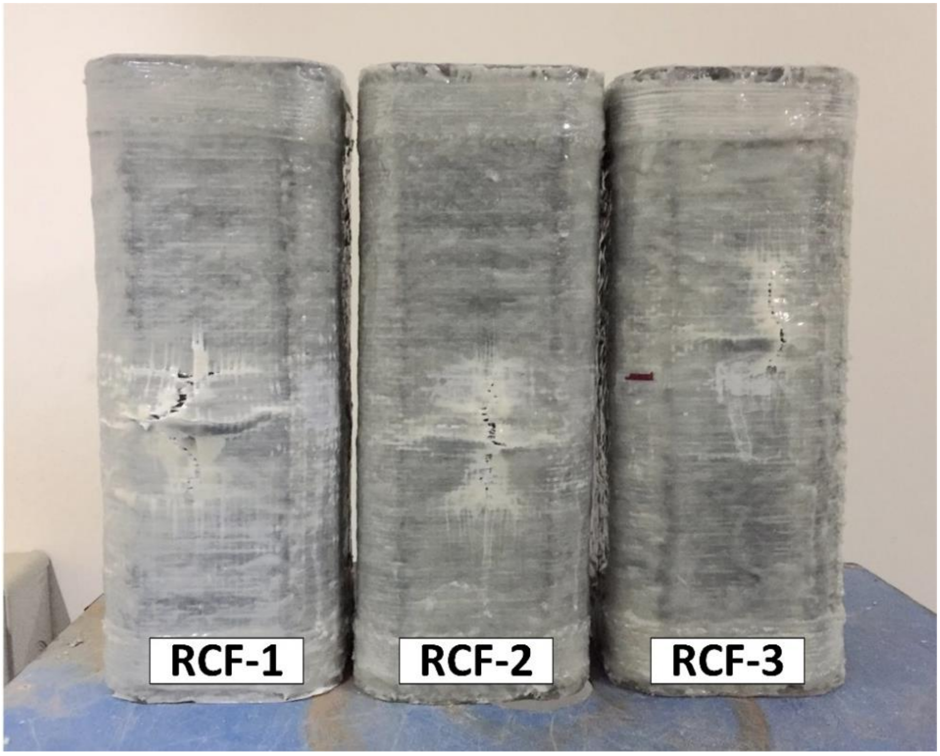
Meanwhile, the specimens in the group (RCF) failed by rupturing of the GFRP at the mid-height of the flat side (Picture 4.2). However, for the specimens in the test group RCP1, the failure was occurred by rupturing of the GFRP rings close to the corners (Picture 4.3). The reason of observing the failure near the corners may be related with the fact that the confinement is active at the four corners and the sharp edge between the corners and the flat sides has a negative effect on the GFRP-composite. The same failure mode was observed for similar specimens in the literature (Zeng et al., 2017). Moreover, in two specimens the GFRP rings ruptured away from the mid-height and crushing the concrete between the two adjacent rings was recognized, which corresponds with the observation of previous study (Zeng et al., 2017).

In the test group CCF and CRCF, two specimens of each group failed by rupturing of the GFRP shell near the mid-height. The failure mode was not explosive and popping voices were heard before the failure. Nevertheless, one specimen of each group failed more explosively and crushing the concrete could be clearly observed (Pictures 4.4 and 5)

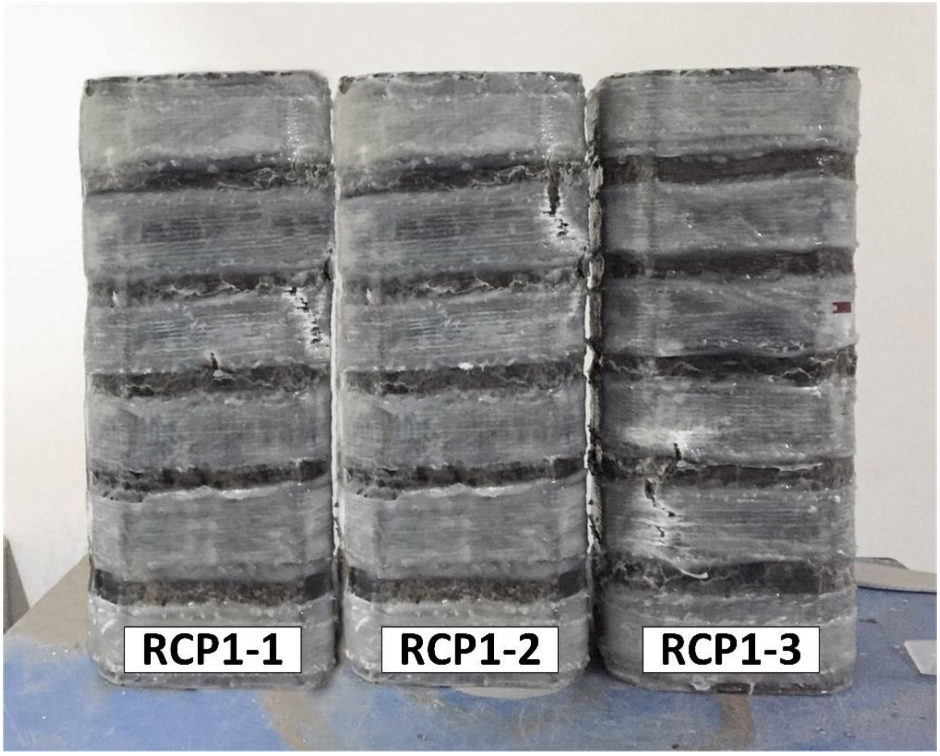
The specimens in the group CRCP1 failed by rupturing the GFRP rings as well. The rupture position was away from mid-height of the specimens. The failure started by crushing the concrete between the GFRP rings following by rupturing the GFRP strips. However, the failure mode of two specimens was more sudden and two rings completely separated away from the surface of the specimens. Moreover, crushing the concrete was clear (Picture 4.6). Meanwhile, the specimens in the group (CFRP2) failed by crushing the concrete between the two adjacent rings and no full rupture on GFRP rings was observed (Picture 4.7). It is worth to mention that many sounds precede the rupturing of the GFRP and cracking the concrete inside was heard before the rupture in some specimens. Furthermore, no debonding took place between the cores and the concrete segments of circularized specimens which refers to the perfect bond between them.



Picture 4.1. Failure mode of the unconfined specimens

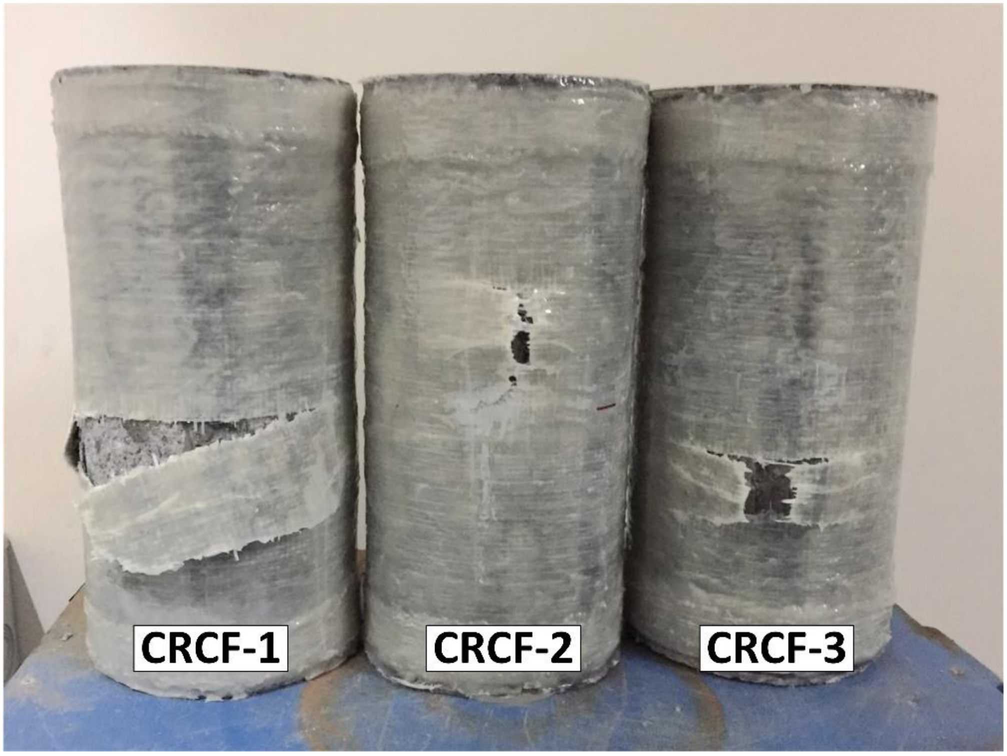


Picture 4.2. Failure mode of the specimens of RCF group



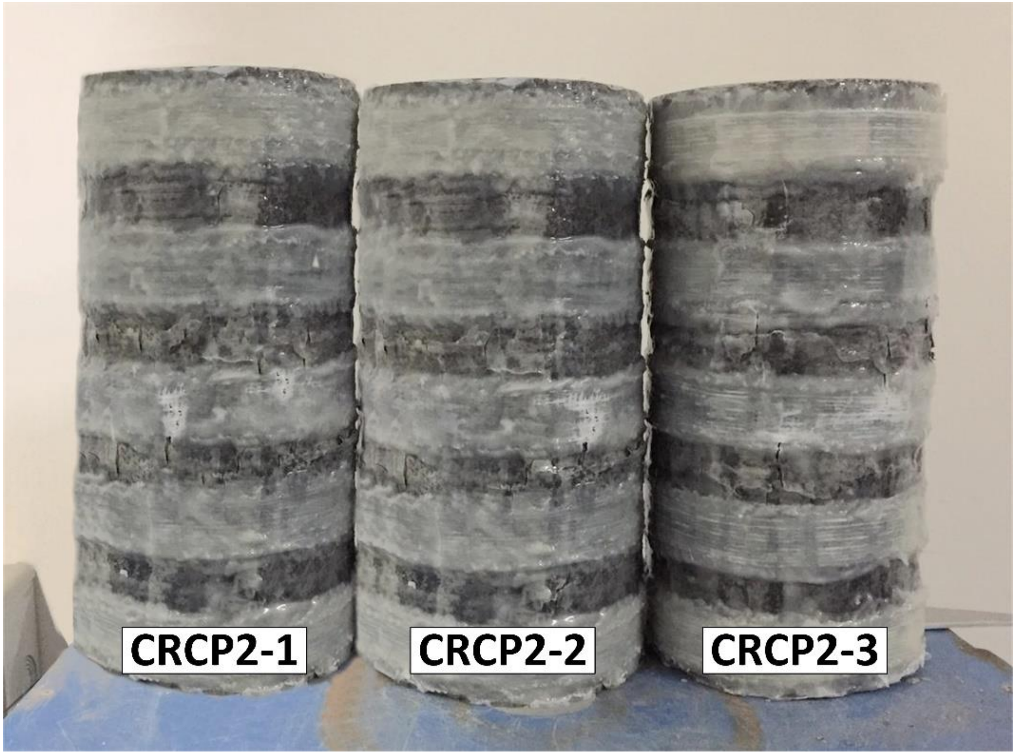
Picture 4.3. Failure mode of the specimens of RCP1 group

Picture 4.4. Failure mode of the specimens of CCF group



Picture 4.5. Failure mode of the specimens of CRCF group

Picture 4.6. Failure mode of the specimens of CRCP1 group



Picture 4.7. Failure mode of the specimens of CRCP2 group

4.3. Test Results

The axial stress can be found easily by dividing the load carrying capacity by the cross-sectional area. While the axial strain is calculated by dividing the average of the displacements which were recorded by the two LVDTs by the height of the specimen. Table 4.1, presents the test results of experimental work. The strength-enhancement (f'_{cc}/f'_{co}) and strain-enhancement ratios ($\varepsilon_{cu}/\varepsilon_{co}$) are also presented in the table. The strain efficiency factor can be found by using Eqn. 1.

$$k_{\varepsilon} = \frac{\varepsilon_{\mathrm{h,rup}\ (\mathrm{M\ or\ C})}}{\varepsilon_{f}} \tag{1}$$

Where k_{ε} is the strain efficiency factor, $\varepsilon_{h,rup,M}$ or $\varepsilon_{h,rupt,C}$ are the actual rupture strain along the hoop direction at the centre of the side face or the centre of the corner, respectively. And ε_f is the ultimate tensile strain of the GFRP from the coupon test.

As shown in Table 4.1, the specimens in the group CRCF have the highest axial strength and ultimate strain capacity which is followed by the specimens in the CCF and RCF groups. It should be noted that the rupture strain at the corners and sides are very close in the case of CRCF test group which designate a more uniform hoop strain distribution. Besides, the rupture strain almost attained the rupture strain obtained by the tensile coupon tests (Table 4.1). This is believed to lead to a more effective utilization of the GFRP as a confinement material in this group. In the RCF test group, the rupture strain values at the corners and sides are not as close as it was observed in CRCF group. This may designate a stress concentration that caused earlier rupture of the GFRP jacket. The circularization applied in the CCF group seems not to provide any improvement related to this non-uniform strain distribution issue (Table 4.1).

The decreased spacing of the GFRP rings in group CRCP1 lead to a slight improvement in the strength- and strain-enhancement ratios compared to group CRCP2. The improvement in the axial behaviour that could be obtained by the partial confinement applied in the case of circularized specimens of CRCP1 group was close to that of test group RCF where a full confinement was applied without circularization. And this was higher compared to the group RCP1 where partial confinement was applied without circularization. It should also be noted that the axial strength- and strain-enhancement ratios attained in the CRCP2 test group was higher than those obtained in the RCP1 group although less amount of GFRP rings was used with a larger spacing. This refers to the success of the shape modification technique to improve the efficiency of the GFRP shell.

As expected, the actual rupture strain at the corners was almost less than the flat sides, even though the rupture occurred near the corners. This may be related with the fact that the flat sides have concrete dilation more than the corners as also (D. Wang et al., 2016).

The partial wrapping technique provided less enhancement in the axial strength and ultimate strain capacity compared to the companion fully confined specimens, but it is more economical.

Table 4.1. Test results

Specimen	f'_{cc}[1] or f'_{co}[2] **(MPa)**	**Average** $f'_{c(c\ or\ o)}$ **(MPa)**	$\frac{f'_{cc}}{f'_{co}}$	ε_{cu}[3] or ε_{co}[4]	**Average** $\varepsilon_{c(c\ or\ o)}$	$\frac{\varepsilon_{cc}}{\varepsilon_{co}}$	$\varepsilon_{h,rup.M}$	**Average** $\varepsilon_{h,rup.M}$	$\varepsilon_{h,rup.C}$	**Average** $\varepsilon_{h,rup.C}$	$\frac{\varepsilon_{h,rup.M}}{\varepsilon_f}$	$\frac{\varepsilon_{h,rup.C}}{\varepsilon_f}$
C-1	22.76	21.52	1	0.0029	0.0028	1	-	-	-	-	-	-
C-2	20.37			0.0026								
C-3	21.42			0.0028								
RCF-1	27.07	26.7	1.24	0.016	0.0143	5.11	0.0104	0.0129	0.0105	0.0101	0.647	0.506
RCF-2	26.41			0.013			0.0155		0.0089			
RCF-3	26.61			0.014			0.0129		0.0107			
RCP1-1	23.47	23.14	1.07	0.0122	0.0116	4.14	0.0132	0.0093	0.0132	0.0102	0.47	0.51
RCP1-2	22.81			0.0114			0.0053		0.0058			
RCP1-3	23.14			0.0112			0.0093		0.0095			
CCF-1	29.22	29.8	1.38	0.016	0.0172	6.14	0.0123	0.0156	0.0115	0.013	0.78	0.65
CCF-2	29.87			0.017			0.018		0.0123			
CCF-3	30.32			0.0185			0.0165		0.0153			

CRCF-1	31.18			0.019			0.0181		0.0187			
CRCF-2	31.29	31.09	1.45	0.0164	0.0174	6.2	0.019	0.0181	0.0179	0.0183	0.91	0.92
CRCF-3	30.69			0.0167			0.0171		0.0183			
CRCP1-1	26.47			0.0122			0.017		0.013			
CRCP1-2	27.93	27.03	1.26	0.0132	0.0126	4.5	0.013	0.0147	0.0111	0.011	0.74	0.55
CRCP1-3	26.7			0.0124			0.0142		0.0088			
CRCP2-1	25.24			0.0127			0.0154		0.0127			
CRCP2-2	25.2	25.24	1.17	0.0117	0.0119	4.25	0.0168	0.0161	0.0152	0.014	0.81	0.7
CRCP2-3	25.23			0.0115			0.0161		0.014			

[1]: f'_{cc} is the ultimate stress of the confined specimens. [2]: f'_{co} is the peak stress of the unconfined concrete specimens, 3: ε_{cu} is ultimate axial strain of the confined specimens and 4: ε_{co} is the strain at the peak stress of the unconfined specimens.

4.4. Stress-Strain Curves

The behaviour of the specimens can be discussed clearly relying on the stress-strain curves. The stress-strain curves of the FRP confined concrete may be divided into two portions according to Lam and Teng, (2003a). The first portion starts from the zero to the peak stress of the unconfined specimen and the second portion begins approximately from the peak stress of the unconfined specimen to the ultimate stress of the confined specimen. When the slope of the second portion is ascending, this is assumed to indicate a sufficient confinement (Figure 4.1a). Whereas a confinement which cannot provide enough lateral pressure to result in an ascending second portion is defined as insufficient (Figure 4.1b). The two portions meet at a point called transition point (Figure 4.1).

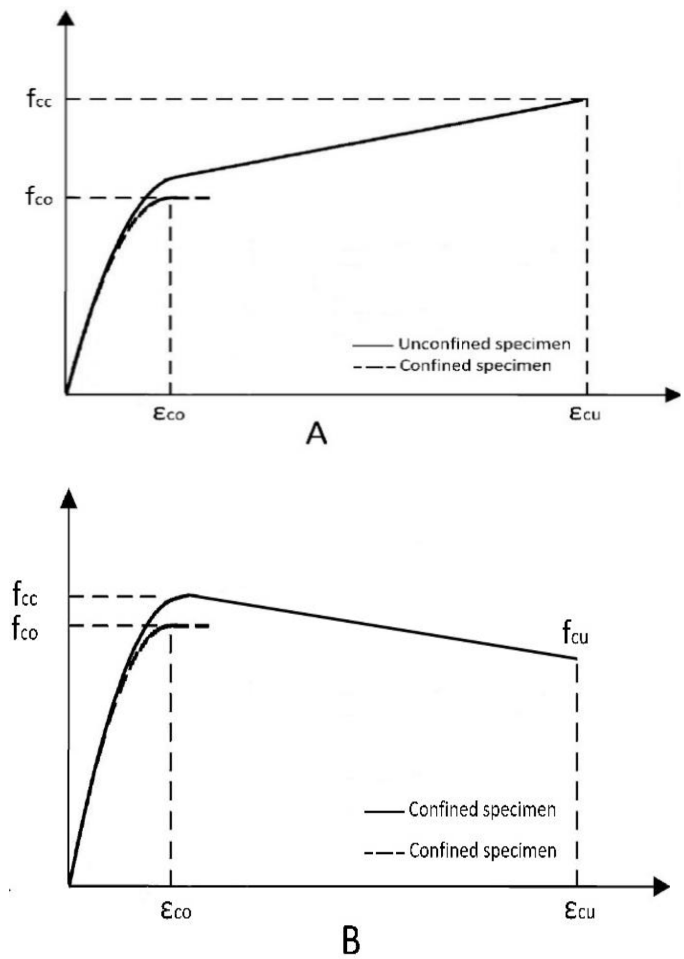


Figure 4.1. Stress-strain curves of confined and unconfined specimens, a) sufficient confinement, b) insufficient confinement

Both the axial strain and the lateral strain are plotted versus the axial stress in (Figures 4.2-8). The left part of the curve presents the axial stress against the average reading of the four strain gauges. While the right part shows the axial stress versus the average recording of LVDTs divided by the specimen height. It was ensured that recorded values by LVDTs started when the load plate started touching the top of the specimens. All the specimens showed the same behaviour during the first portion of the curve. However, after the peak stress of the unconfined specimens, the behaviour of each group varies from each other.

The unconfined concrete specimens of the test group C exhibited well-known brittle concrete response under compressive loading (Figure 4.2). A gradually ascending second portion was observed up to the failure in the axial compressive stress-strain diagrams of the specimens in the RCF, CCF and CRCF groups, after reaching the peak stress of the unconfined specimens (Figures 4.3, 5 and 6). This refers to sufficient confinement that could be provided by the GFRP shell. Nevertheless, the slope of the second portion in the stress-strain curve of the CRCF group was higher compared to the other groups, which led to higher strength-enhancement in this group

After the transition point in the RCP1 and CRCP2 groups, the second portion of the curves appeared to be descending instead of ascending (Figures 4.4 and 8). However, the maximum stresses of the CRCP2 group were higher than the maximum stresses of RCP1 group even though the total amount of GFRP rings was less. Moreover, the ductility continued in increasing until the failure. Meanwhile, the CRCP1 group with lower spacing of GFRP rings showed ascending behaviour after the transition point until the failure (Figure 4.7). That refers to an enhancement of the effectiveness of the GFRP after implementing the shape modification technique. It is worth mentioning that an increase in the rigidity was observed by conducting the partial wrapping method.

The discussion which will be presented in the Chapter 5 is carried out regarding the average test results of three identical specimens in each group. Therefore, the average axial stress-strain curves for the fully and partially wrapping are provided in Figure 4.9 and 4.10, respectively. For the comparison purposes, all of the average curves are also presented in Figure 4.11 together.

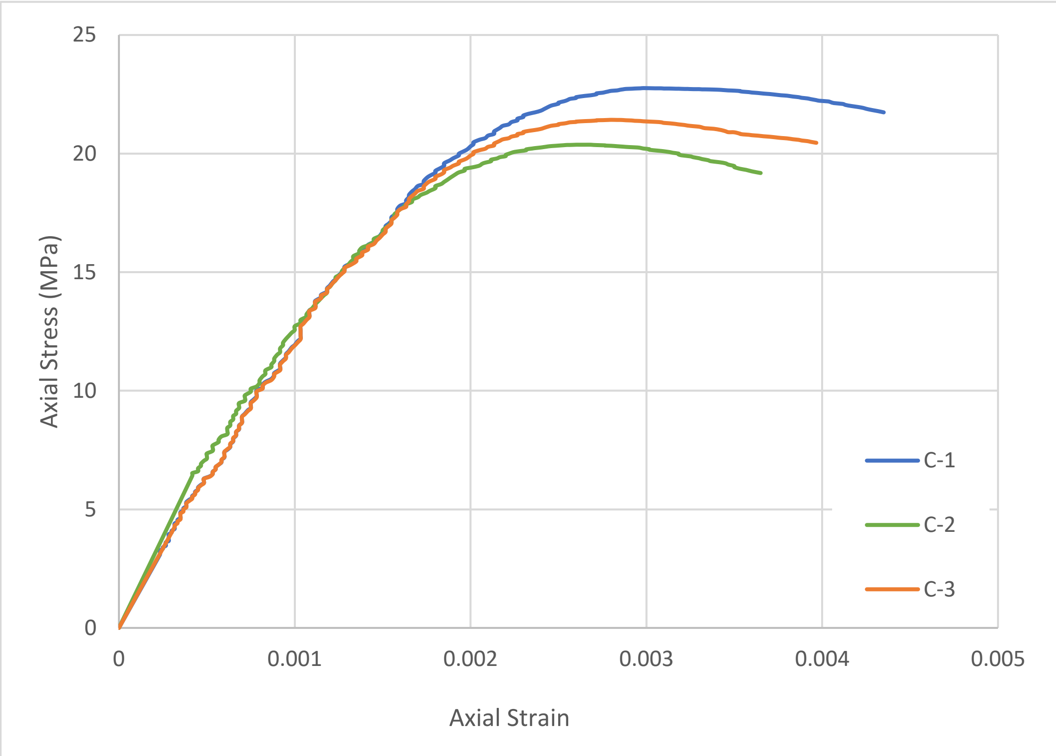


Figure 4.2. Stress-strain curves of the unconfined specimens

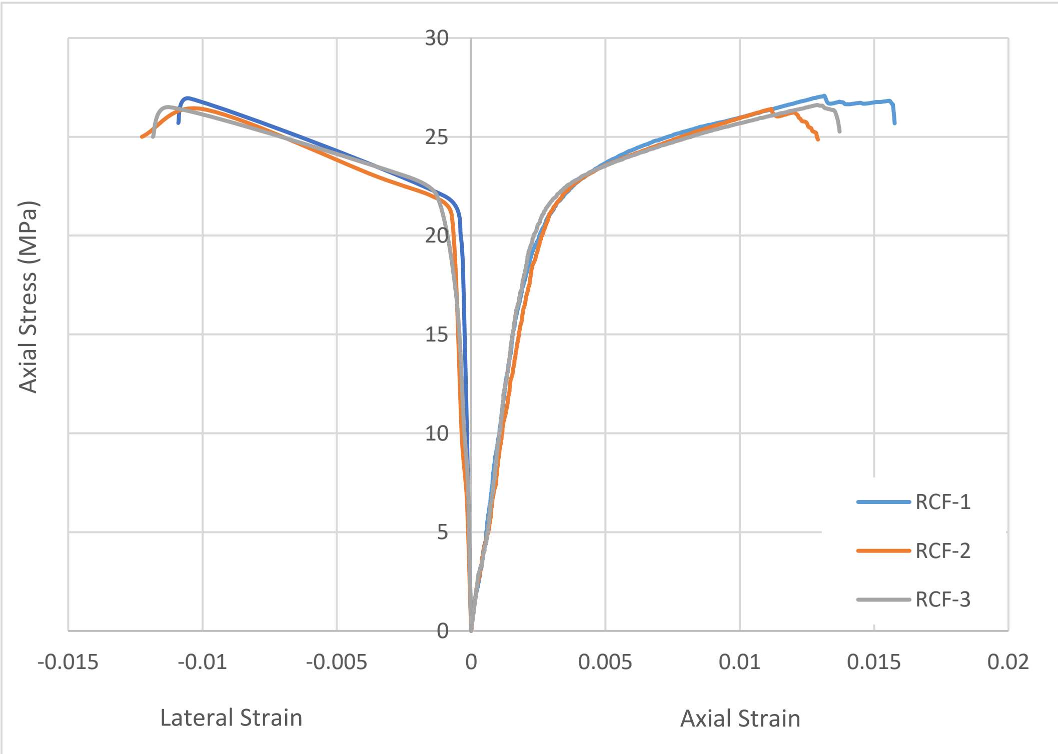


Figure 4.3. Stress-strain curves of the specimens in the RCF group

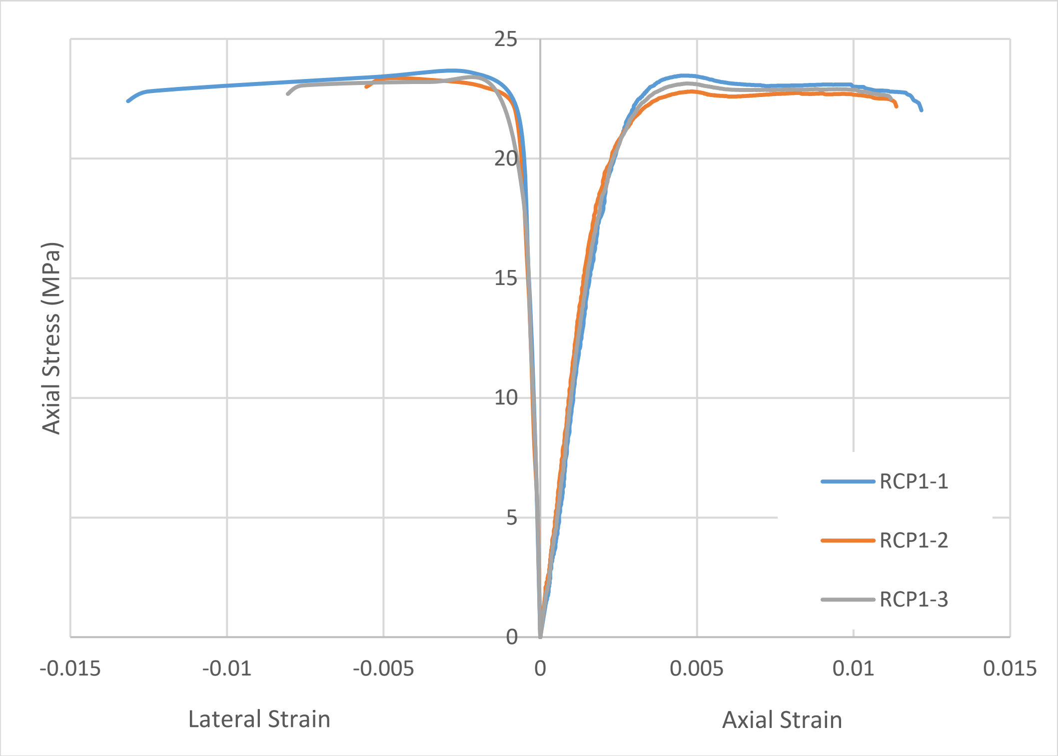


Figure 4.4. Stress-strain curves of the specimens in the RCP1 group

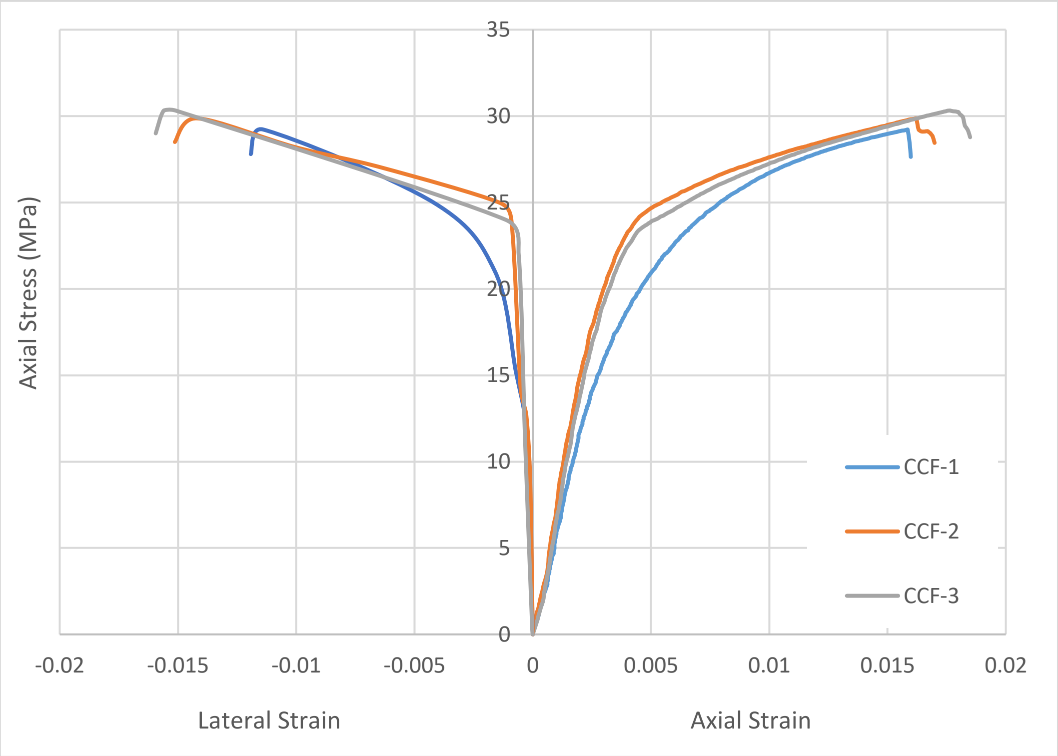


Figure 4.5. Stress-strain curves of the specimens in the CCF group

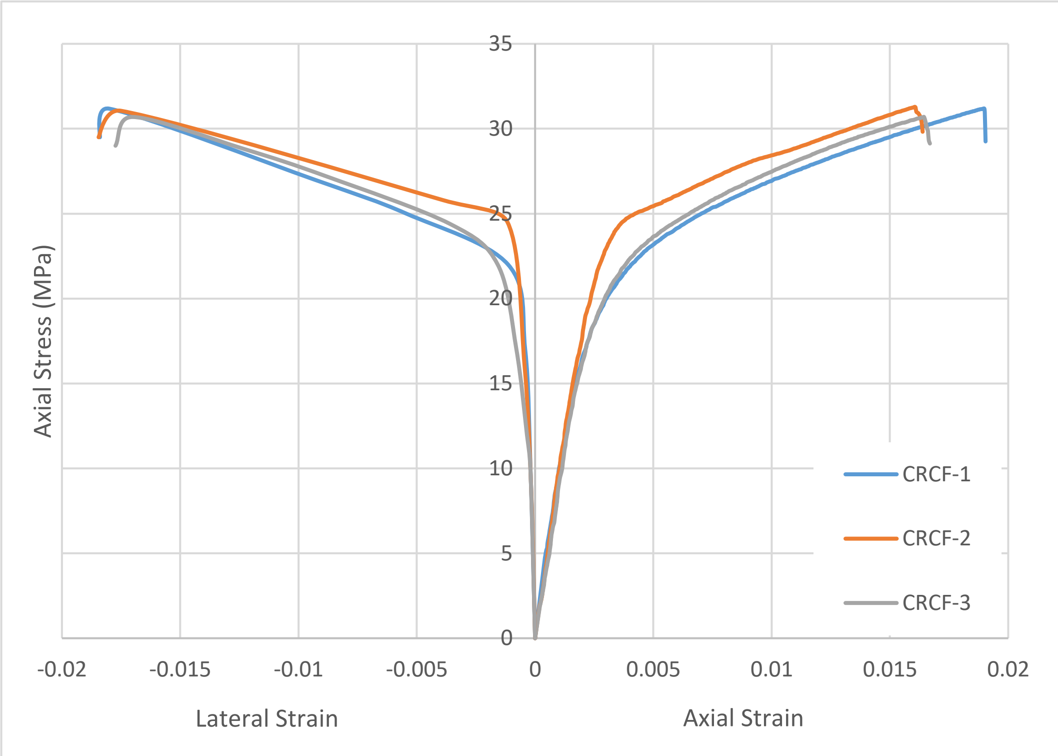


Figure 4.6. Stress-strain curves of the specimens in the CRCF group

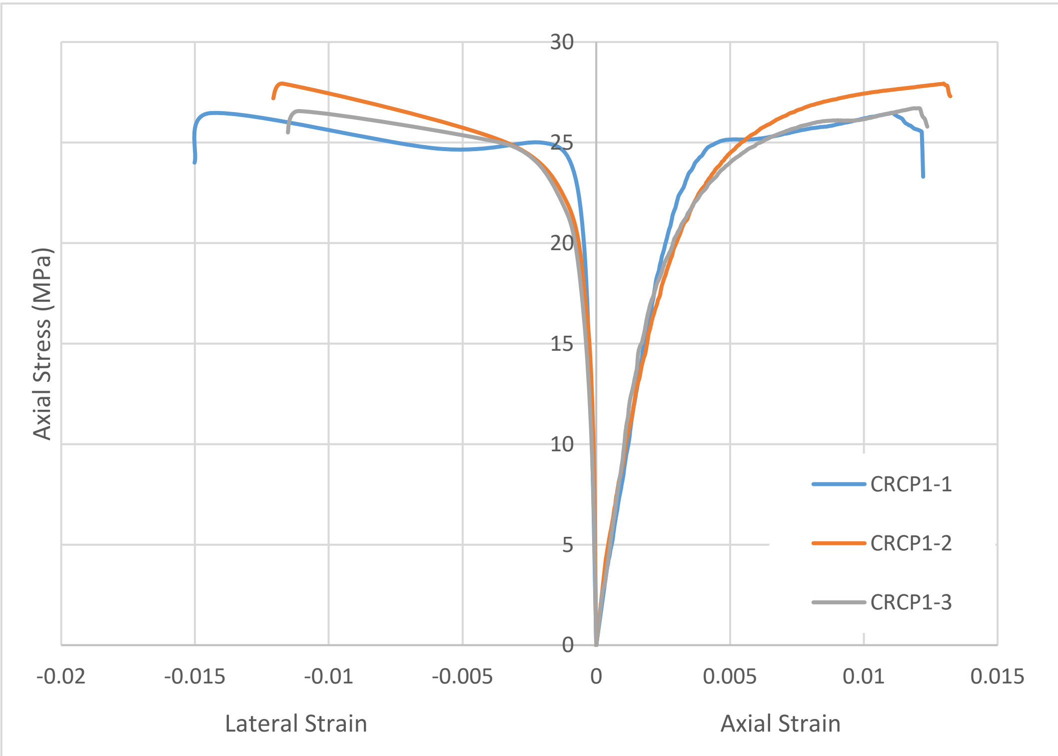


Figure 4.7. Stress-strain curves of the specimens in the CRCP1 group

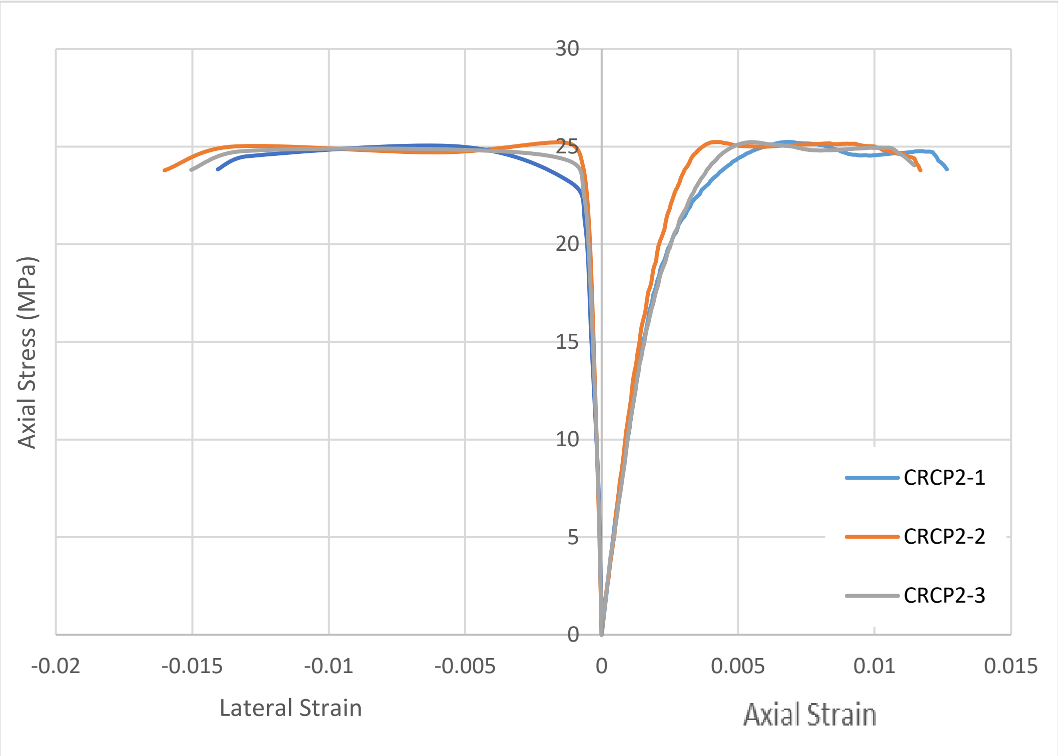


Figure 4.8. Stress-strain curves of the specimens in the CRCP2 group

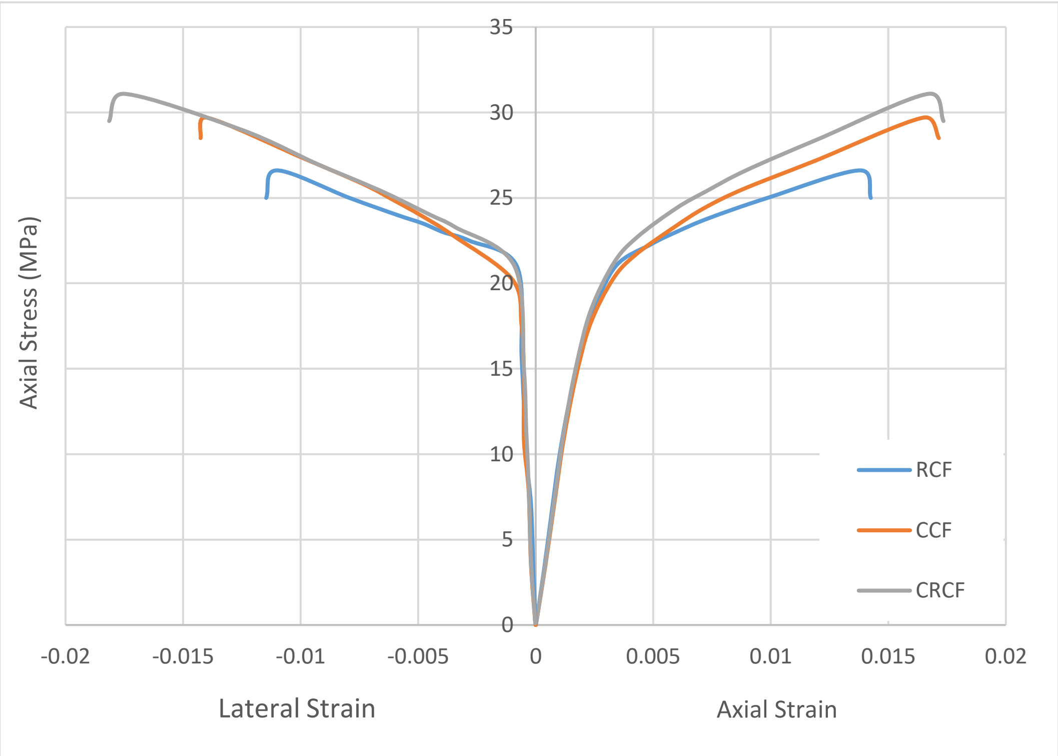


Figure 4.9. Average stress-strain curves of the test groups with fully wrapping

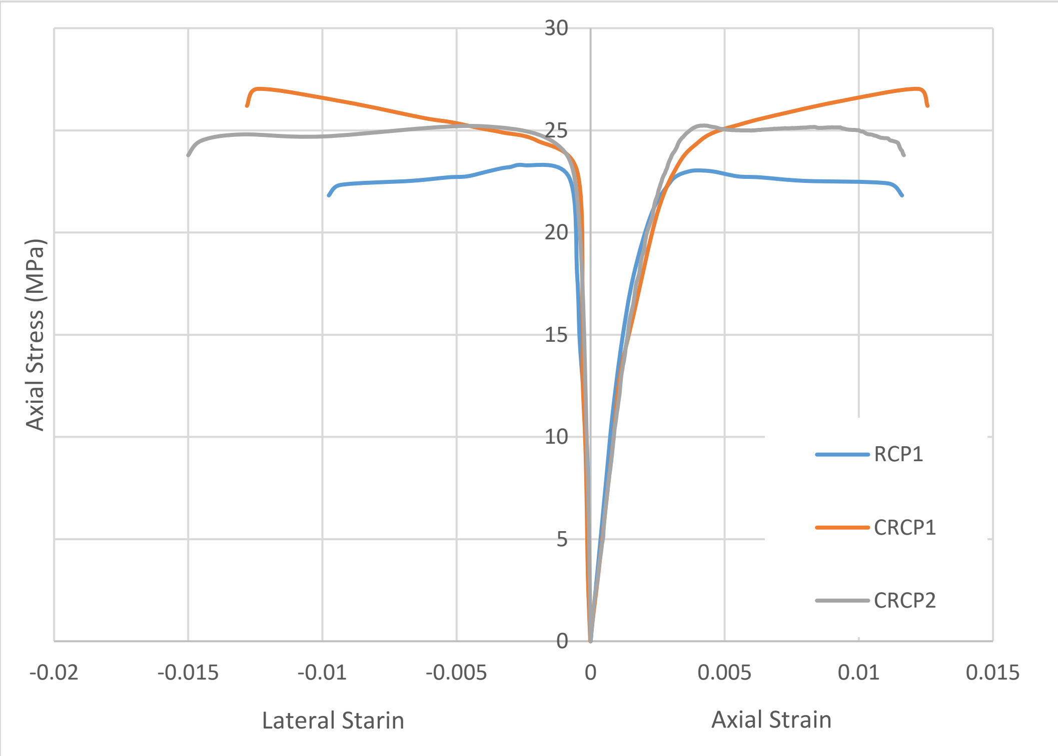


Figure 4.10. Average stress-strain curves of the test groups with partial wrapping

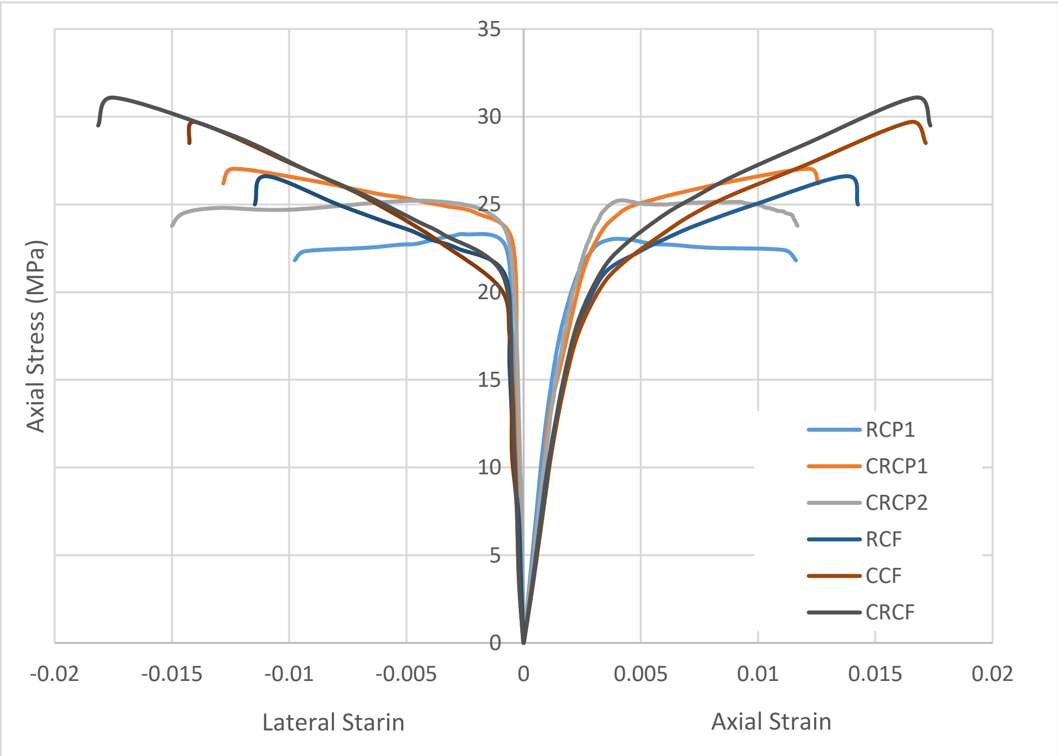


Figure 4.11. Average stress-strain curves of all the test groups

5. DISCUSSION

5.1. General Introduction

In this chapter the effect of both shape modification methods and different wrapping methods on the stress-strain behaviour of the confined specimens is going to be discussed.

5.2. Effect of the Shape Modification Techniques

The shape modification techniques succeeded to improve the confinement efficiency of the GFRP-composite when compared to the square sections with rounded corners (Figure 4.9 and 10). A considerable improvement in the axial strength and strain could be obtained by the applied circularization.

There is no significant difference between the overall axial stress-strain response of both shape modification techniques. However, the actual rupture strain for the proposed circularization technique (i.e. as applied in the CRC test groups) was much higher than the previous technique (i.e. as applied in the CCF test group) (Figure 4.9). This resulted in slightly higher strength- and strain-enhancement ratio in the specimens where the proposed circularization technique was applied. The use of other FRP composites with higher mechanical properties (i.e. such as carbon FRP) may provide a higher enhancement.

Furthermore, the proposed shape modification technique did not increase the column size too much compared with the original size of the column where the considerable increase in the cross-sectional area was a questionable factor of the previous technique. Moreover, in real practice, the size may decrease more by refining the sharp edges as much as possible. In addition, less GFRP was used, where the difference in the amount of the GFRP sheets between the two shape modification techniques was about 15%. Therefore, the proposed shape modification technique is considered to be more economical.

5.3. Effect of the Wrapping Methods

The full wrapping method provided better enhancement in the axial strength and strain. However, partial wrapping can be considered as more economical. Besides, the difference between the strength- and strain-enhancement obtained by the two wrapping methods was not quite significant (Figure 4.11).

The suggested circularization technique provided better axial response for the partial wrapping. The specimens in the CRCP test groups reached higher ultimate strength compared to those in RCP1 test group. It should be noted that this was even valid when lower amount of GFRP was used with larger spacing in the group CRCP2 (Figure 4.11). Moreover, the improvement in the axial strength of the circularized specimens which were partially wrapped (CRCP1) was even higher, although slightly than the fully wrapped square specimens with rounded corners (RCF).

6. THEORETICAL INVESTIGATION

6.1. General Introduction

Many design-oriented models of FRP confined concrete have been generated to predict either the ultimate strength and strain capacity. Besides, some of these models can also provide the overall response under compressive stresses. These models were validated by the experimental results in the previous studies. The predictions of the selected models are compared with the tests results of this study as explained in the following parts. However, it is worth to discuss the behaviour of the confined and unconfined concrete column under the axial load before this comparison.

6.2. Behaviour of the Concrete Column Under Axial Load

The confinement significantly affects the behaviour of the concrete column under the axial load. Therefore, the behaviour of the unconfined concrete column is presented at the first. Then the effect of confinement on the behaviour of the column is discussed. At the end, the factors that affects the confinement efficiency are reviewed briefly.

6.2.1. Behaviour of the Unconfined Concrete Column

Generally, the columns are designed for a specific compression load. When the compression load is applied vertically on the column, the concrete column is compressed and shortened. The amount of the shortening is called as the axial displacement.

Relying on Poisson's ratio law, the column tends to expand laterally after a certain axial stress level (Figures 6.1a and b). Finally, the column fails and the failure mechanism depends on the properties of the concrete. For instance, the normal strength concrete fails suddenly with con shape (Figure 6.1c) while the high strength concrete column fail explosively with shear failure (Figure 6.1d).

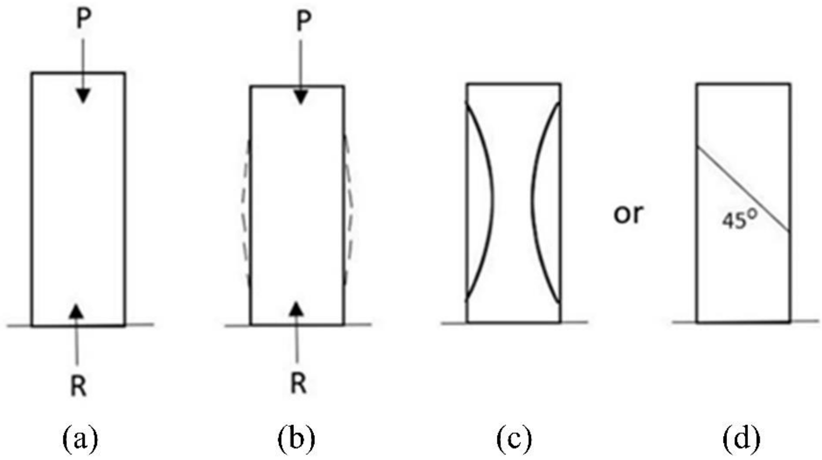


Figure 6.1. The concrete column behaviour under axial loading, a) beginning of the test, b) starting the lateral expansion, c) failure mode of the normal strength concrete and d) failure mode of the high strength concrete

6.2.2. Behaviour of the FRP Confined Concrete Column

The behaviour of the FRP confined-concrete column can be summarized as follows. At a certain point above the limits of elasticity of the concrete, the fibers of the composite material stretch along the hoop direction as a result of the lateral expansion of the concrete. This leads to a passive confining pressure applied on the column surfaces (Figure 6.2). It is worth noting that this confining pressure is ideally assumed as uniformly distributed along the circumference which may not be the case in practice. Nevertheless, the confining pressure enhances the load-carrying capacity and the ductility of the column as well. At a certain point, fibers reach their tensile strain caapcity which ends by the failure of the column (Figures 6.3). However, experimentally proved that the fiber ruptured before reaching its maximum tensile strength. Because of the confining pressure, the concrete column fails suddenly and explosively. The failure mode depends on the properties of the confinement material (Lam and Teng, 2003a). Besides, many factors may affect the efficiency of the composite material as having been discussed widely in the literature review.

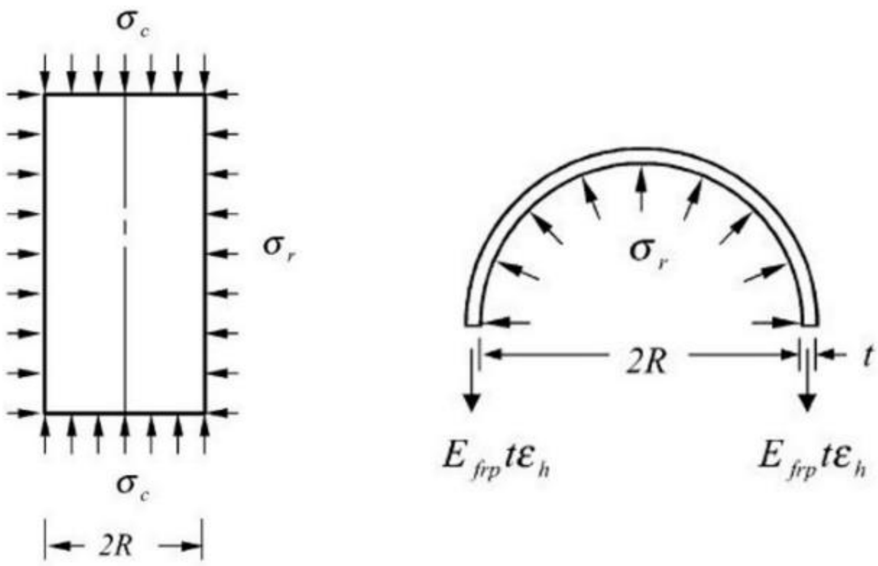


Figure 6.2. The confinement mechanism of FRP, Lam and Teng (2003a)

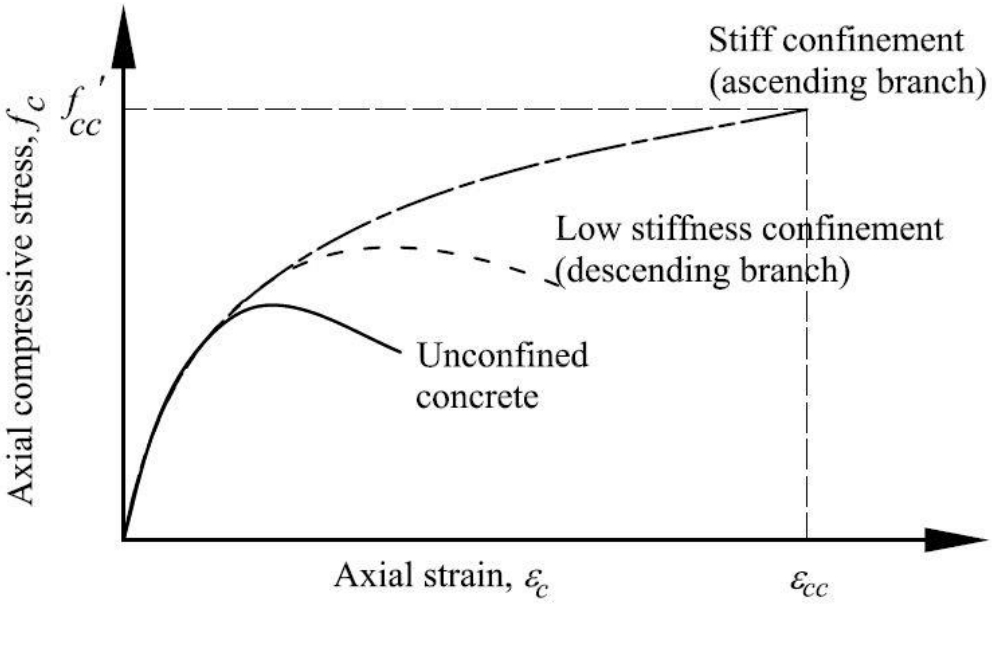


Figure 6.3. Behaviour of the unconfined and FRP confined-concrete column, Pham, T.M. (2014)

6.2.3. The Difference in the Behaviour of the Concrete Confined by Full and Partial Wrapping

Instead of the fully wrapping of the column, partial wrapping can be conducted for an economical purpose. However, the confining pressure that may be provided by partial wrapping is expected to be less in comparison to fully wrapping.

It is worth to mention that the confining pressure in the partial wrapping is valid on an effective confined area. On the other hand, the effective confinement area at the clear spacing is less than effective confinement area at the FRP ring position. An arcing action takes place along the unconfined region between the FRP strips where effective confined area reduces (*fib, 2001*), (Figure 6.4).

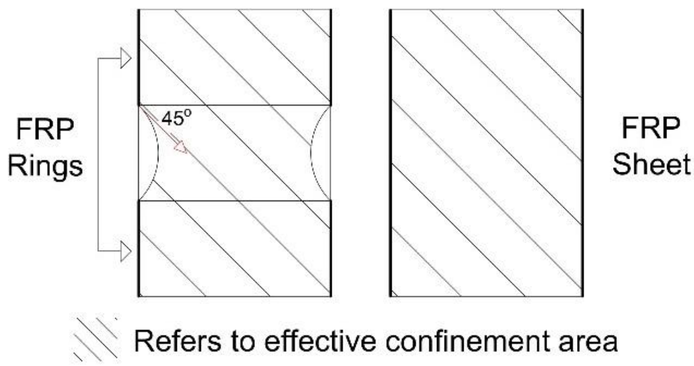


Figure 6.4. Confinement mechanism of both partial and fully wrapping

6.2.4. Parameters Affecting FRP Efficiency

It was previously discussed in the literature review that the efficiency of the FRP as a confinement material is affected by many parameters. Here, the effect of each parameter is summarized in (Table 6.1). It should be mentioned that all other parameters are assumed as constant while defining the effect of each specific parameter in (Table 6.1).

Table 6.1. Parameters affecting the efficiency of the FRP Shell

Parameter	Column cross-section	Details
Cross-section shape	-	FRP is most efficient with the circular cross-section. The efficiency is higher in square sections compared to rectangular sections.
Cross-section size	Square	Efficiency of FRP decreases when the cross-sectional dimension is larger than 350 mm
	Circular	Unreliable when the diameter is less than 50 mm
Existence of Steel reinforcement	Square	The stirrups may provide extra confining pressure but the buckling of the longitudinal reinforcement may cause a sudden failure
	Circular	
Corner radius	Square	Increase in the corner radius leads to increase the FRP efficiency
	Rectangular	
Aspect ratio	Rectangular	Increase the aspect ratio leads to decrease the FRP efficiency
	-	
Concrete Strength	Square and Rectangular	Increase the concrete strength leads to decrease the FRP efficiency
	Circular	

Method of wrapping	Square and Rectangular	None (FRP-tube, we lay-up, single or multilayers)
	Circular	
FRP thickness	Square and Rectangular	Increase in the thickness leads to more enhancement in the axial strength and less for the axial strain
	Circular	
FRP type	Square and Rectangular	CFRP more efficient, but more expensive
	Circular	
Slenderness	Square	Insignificant effect
	Circular	
Fibre orientation	Square	FRP is considered to be more efficient when the orientation angle is parallel to the hoop direction in case of axial load
	Circular	
Partial wrapping	Square	More economical than fully wrapping but the spacing should not be excessive
	Circular	
Non-uniform wrapping	Square	Increases enhancement
	Circular	
Eccentric loading	Square	Decreases FRP efficiency
	Circular	
Hollow column	Square	FRP is more efficient with solid section
	Circular	
Circularization technique	Square	Increases FRP efficiency
	Rectangular	

Pre-tension technique for the FRP	Square	Increases FRP efficiency
	Circular	
Pre-loading of the column	Square	Decreases FRP efficiency
	Circular	

6.3. Analytical Calculations

Many design-oriented models have been proposed to assess the axial behaviour of FRP confined concrete. Among these, the design-oriented models suggested by Lam and Teng, (2003a, 2003b) are considered to be the most reliable models to predict the maximum axial strength and ultimate axial strain of the confined concrete column (Ozbakkaloglu et al., 2013). Therefore, the theoretical investigations of this study are conducted using only the mentioned models.

6.3.1. Prediction of the Maximum Axial Stress and Strain of the Circular Cross-section

The suggested model by Lam and Teng (2003a) was proved by Ozbakkaloglu et al. (2013) to be the most accurate model to predict the ultimate axial strength and strain for the FRP confined-concrete column. In the model, the maximum axial strength can be estimated by the Eqn. 2.

$$\frac{f'_{cc}}{f'_{co}} = 1 + k_1 \frac{f_{lu.a}}{f'_{co}} \quad (2)$$

Where f'_{cc} is the maximum axial stress of the confined concrete column, f'_{co} is the maximum axial stress of the unconfined concrete column, k_1 is the confinement effectiveness coefficient, and $f_{lu,a}$ is the provided confining pressure by the FRP-composite.

The confinement effectiveness coefficient was taken as 3.3 as a constant value by Lam and Teng, (2003a). However, Teng et al. (2007) magnified the value to 3.5. The confining pressure can be found by the Eqn. 3 (Figure 5.2). It should be noted that the uniform confining pressure is assumed on the section to obtain this expression.

$$f_{lu.a} = \frac{2E_{frp}t\varepsilon_{h,rup}}{d} \tag{3}$$

Where E_{frp} is the modulus of elasticity of the FRP-composite, t is the thickness of the layer and for multilayer, t is multiplied by the number of the layers, $\varepsilon_{h,rup}$ is the actual rupture strain from the test and d is the diameter of the specimen. When the actual rupture strain could not be provided, the value of the rupture strain ε_{frp} from the coupon test should be multiplied by the FRP efficiency factor, k_e. The efficiency factor of the FRP was taken to be 0.586 by Lam and Teng (2003a) depending on a large database.

The maximum axial strain of the confined concrete column can be calculated by Eqn. 4 that was proposed by Lam and Teng (2003a).

$$\frac{\varepsilon_{cu}}{\varepsilon_{co}} = 1.75 + 12\left\{\frac{f_{lu.a}}{f'_{co}}\right\}\left\{\frac{\varepsilon_{h,rup}}{\varepsilon_{co}}\right\}^{0.45} \tag{4}$$

Where ε_{cu} and ε_{co} are the maximum axial strain of the confined concrete column and the axial strain at the peak stress of the unconfined concrete column respectively.

6.3.2. Prediction of the Maximum Axial Stress and Strain of the Rectangular Cross-section

Experiments proved that the behaviour of the square/rectangular column is significantly different than the circular column. And the proposed models for the circular cross-section cannot be used directly to predict the maximum axial stress and strain of the confined rectangular column. Therefore, Lam and Teng 2003b, proposed a new design-oriented model for the square/rectangular columns. The proposed model is taking into account that not all cross-sectional area is going to be confined by the FRP as shown in (Figure 6.5).

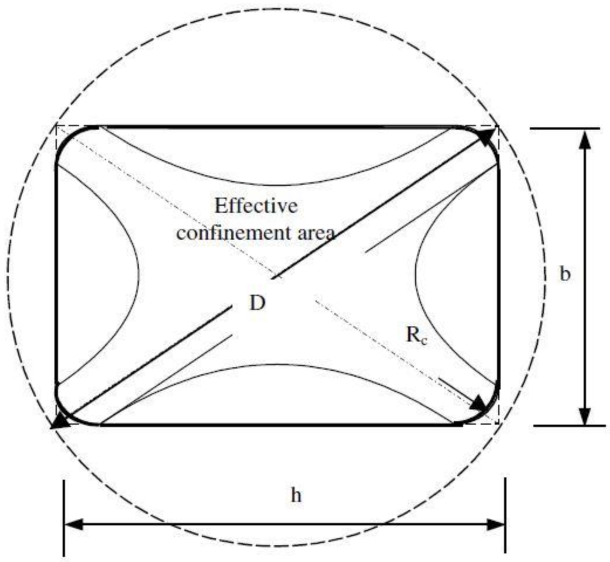


Figure 6.5. Effectively confined area in the rectangular cross-section column, (Lam and Teng 2003b)

As a result, shape factors were suggested. In the model, the maximum axial stress can be estimated by Eqn. 5.

$$\frac{f'_{cc}}{f'_{co}} = 1 + k_1 k_{s1} \frac{f_{lu.a}}{f'_{co}} \tag{5}$$

Where k_1 is the confinement effectiveness coefficient was taken 3.3, ks_1 is the shape factor and it can be found by Eqn. 6.

$$k_{s1} = \left\{\frac{A_e}{A_c}\right\}\left\{\frac{b}{h}\right\}^{\alpha} \tag{6}$$

Where *h* and *b* are the column dimensions (h ≥ b). α is a constant was taken 2. A_e/A_c is the effective confinement area ratio, and it can be found by Eqn. 7.

$$\frac{A_e}{A_c} = \frac{1-((b/h)(h-2R_c)^2+(h/b)(b-2R_c)^2/(3A_g)-\rho_{sc}}{1-\rho_{sc}} \tag{7}$$

Where R_c is the corner radius and ρ_{sc} is the cross-sectional area ratio of the longitudinal steel reinforcement. A_g is the gross area of the column section with rounded corners and it can be found by Eqn. 8.

$$A_g = bh - (4-\pi){R_c}^2 \qquad (8)$$

$f_{lu,a}$ is the ultimate confining pressure and it can be calculated by Eqn. 9.

$$f_{\ lu.a} = \frac{2E_{frp}t\varepsilon_{h,rup}}{D} \qquad (9)$$

It is worth to mention that the diameter D is the diagonal distance of the section (Figure 6.5) which can be estimated by Eqn. 10.

$$D = \sqrt{h^2 + b^2} \qquad (10)$$

The maximum axial strain of the confined concrete column can be calculated by Eqn. 11 which was proposed by Lam and Teng (2003b) as follows:

$$\frac{\varepsilon_{cu}}{\varepsilon_{co}} = 1.75 + k_1 k_{s2} \left\{\frac{f_{\ l.a}}{f'_{\ co}}\right\} \left\{\frac{\varepsilon_{h,rup}}{\varepsilon_{co}}\right\}^{0.45} \qquad (11)$$

Where k_1 was taken 12 and k_{s2} is the shape factor and it can be found by Eqn. 12.

$$k_{s2} = \left\{\frac{A_e}{A_c}\right\} \left\{\frac{h}{b}\right\}^{\beta} \qquad (12)$$

Where β has a constant value that was assumed as 0.5 by Lam and Teng (2003b).

In the case of the partial wrapping, the confining pressure is multiplied by the vertical confinement effectiveness coefficient. The coefficient proposed by Mander et al. (1988) for steel stirrups was utilized here for the partial FRP confinement as presented in Eqns. 13,14

For the circular cross-section.

$$k_v = \left\{1 - \frac{s\prime}{2D}\right\}^2 \qquad (13)$$

For the square cross-section

$$k_v = \left\{1 - \frac{s\prime}{2b}\right\}\left\{1 - \frac{s\prime}{2h}\right\} \quad (14)$$

Where *s'* is the clear spacing between two adjacent FRP rings.

6.4. Validation of the Test Results

The axial strength and ultimate strain capacity of the GFRP confined specimens with circularization were estimated by utilizing Lam and Teng (2003a) model. On the other hand, Lam and Teng (2003b) model was used for the prediction of the ultimate conditions of the GFRP confined concrete with square sections. In the case of partial wrapping, the coefficient suggested by Mander et al. (1988) was integrated to the Lam and Teng (2003a, 2003b) models. Furthermore, the actual rupture strain is considered as average of four strain gauges.

Table 6.2. presents the comparison of the ultimate conditions attained during the tests of GFRP confined specimens with those predicted by the models. It should be noted that the experimental results are presented as the average values of each group and indicated by subscription “E” On the other hand, the model predictions are presented with a subscription of “A”.

Table 6.2. Results of the theoretical investigations

Group	$f'_{cc,E}$ MPa	$\varepsilon_{cu,E}$	$f'_{cc,A}$ MPa	$\varepsilon_{cu,A}$	$\frac{f'_{cc,E}}{f'_{cc,A}}$	Error %	$\frac{\varepsilon_{cu,E}}{\varepsilon_{cu,A}}$	Error %
RCF	26.7	0.0143	25.12	0.0079	1.06	+6	1.81	+81
RCP1	23.14	0.0116	24.53	0.0074	0.94	-6	1.57	+57
CCF	29.8	0.0172	27.64	0.0109	1.08	+8	1.57	+57
CRCF	31.09	0.0174	30.6	0.0149	1.02	+2	1.17	+17
CRCP1	27.03	0.0126	27.09	0.0101	0.99	-1	1.25	+25
CRCP2	25.24	0.0119	27.36	0.0108	0.92	-8	1.1	+10

There is a good agreement between the test results and model predictions in terms of the axial strength of GFRP confined concrete (Figure 6.6). The success in the model predictions is the same for both models, either for the circular and square sections. It may be stated that the use of vertical confinement effectiveness coefficient suggested by Mander et al. (1988) originally for the steel stirrups resulted in a slight underestimation of the axial strength of partial GFRP confined concrete.

The model predictions in terms of axial strain capacity were not as successful as axial strength (Figure 6.7). In the case of CRC test groups (either fully or partially wrapped), the ultimate axial strain estimations were close to the experimental results (i.e. with an average of 17% difference). However, there is a significant divergence between the test results and model predictions in terms of strain capacity which may reach to 81% in the RCF test group.

Overall, the axial strength and strain capacity predictions of the model was more successful in the case of CRC test group where circularization was applied on the sections with rounded corners. This success in the model predictions may be related with the more uniform confinement observed in this group as explained in “Chapter 4.3”. It should be recalled that the expressions of the utilized models were generated with a uniform confining pressure assumption.

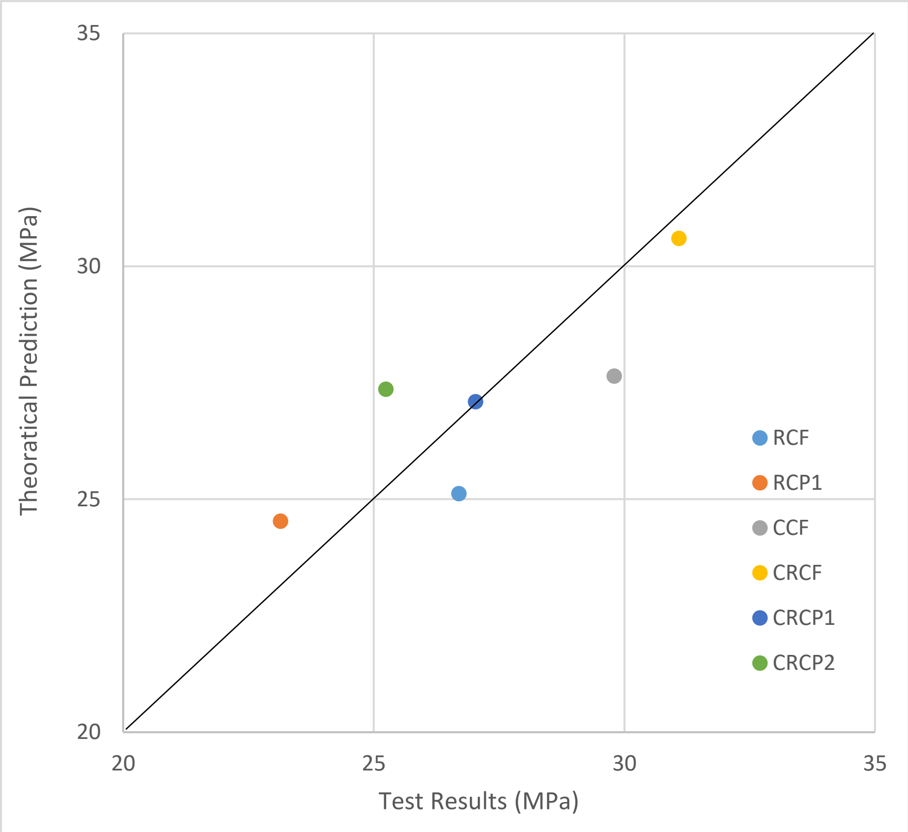


Figure 6.6. Comparison of the axial strength from the test results and model predictions

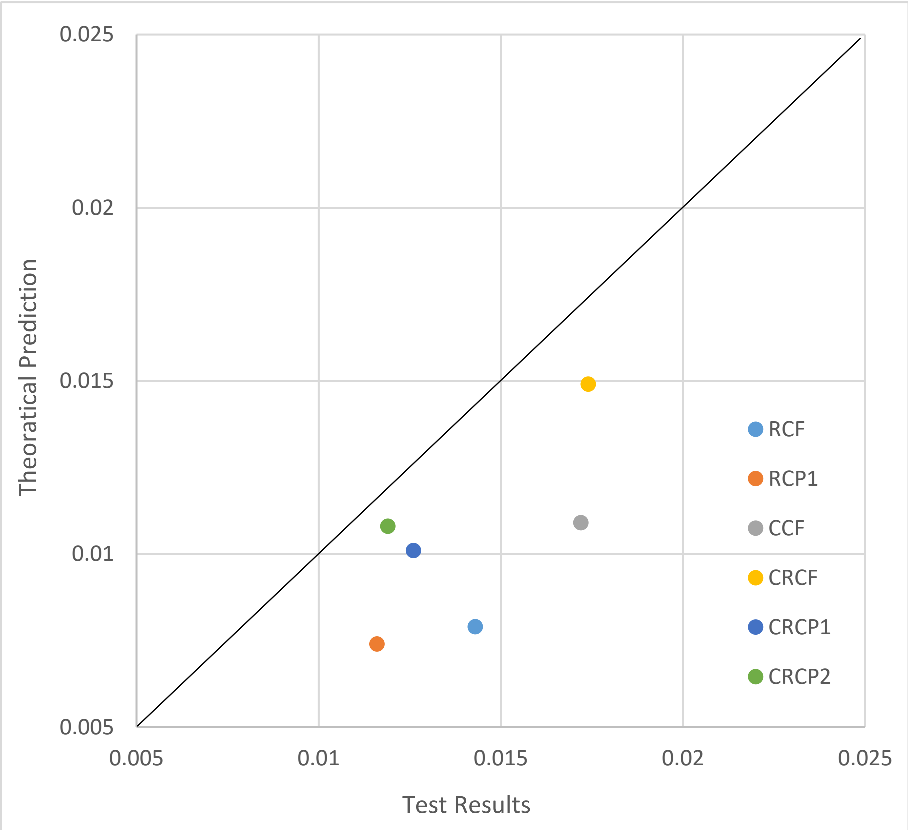


Figure 6.7. Comparison of the ultimate axial strains from test results and model predictions

7. CONCLUSION AND RECOMMENDATIONS

7.1. General Introduction

The aim of this study is to assess shape modification technique which is proposed to enhance the confinement efficiency of the FRP confined concrete column with less increase in the cross-sectional sizes. Furthermore, the behaviour of the modified column with different wrapping techniques was evaluated. The following conclusions were drawn from the experimental study and the theoretical investigation. These conclusions should not be generalized without due judgement or unless supported by further experimental findings.

1- A remarkably higher axial strength- and strain-enhancement could be obtained by the GFRP confinement when the proposed shape modification method was used in comparison to the specimens with square sections. The proposed technique succeeded to decrease the cross-sectional sizes of the column compared with the previous shape modification technique. The reduction in the cross-sectional sizes can be increased by refining the sharp corners as much as possible. Moreover, decreasing the cross-sectional sizes leads to reduce the amount of GFRP that is used to repair the column.

2- Obviously, the actual rupture strain was increased significantly, where the strain efficiency factor of the modified specimens by the proposed technique exceeded the efficiency factor of the previous shape modification technique. The more uniform confining pressure distribution on the section that was obtained by the proposed circularization method is believed to contribute to these higher rupture strain values.

3- The partial wrapping allowed to enhance the axial strength and ultimate strain capacity of the modified specimen confined by GFRP. Moreover, the partial wrapping provided a close enhancement compared with the square specimen fully wrapped by the GFRP. That means an economic benefit can be obtained by conducting the shape modification technique. However, increasing the clear spacing between the GFRP rings results in the reduced enhancement.

4- The proposed design-oriented model by Lam and Teng (2003a, 2003b) succeeded to provide an accurate prediction for the concrete specimen fully wrapped with the GFRP. In addition, the combined use of the suggested vertical confinement effectiveness coefficient by Mander et al. (1988) and the model of Lam and Teng (2003a, 2003b) allowed to obtain a good agreement between the experimental and theoretical results for the concrete column partially wrapped with GFRP.

Relying on the previous studies (Hadi et al., 2013; Zeng et al., 2017) more enhancement can be obtained by using the proposed shape modification technique compared with square cross-section if the composite materials with higher mechanical properties are used instead of GFRP (i.e. such as carbon FRP). The proposed shape modification technique may be highly recommended when the increase in the cross-sectional dimensions of the members where circularization is to be applied is an issue.

More investigations are recommended to be carried out to assess the proposed shape modification method with inner steel reinforcement. Moreover, different loading conditions are recommended to be conducted such as flexural test, etc.

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SCIENTIFIC ETHICAL STATEMENT

I hereby declare that I composed all the information in my master's thesis entitled SHAPE MODIFICATION OF SQUARE COLUMN SECTIONS TO IMPROVE THE EFFECTIVENESS OF FRP CONFINEMENT within the framework of ethical behaviour and academic rules, and that due references were provided and for all kinds of statements and information that do not belong to me in this study in accordance with the guide for writing the thesis. I declare that I accept all kinds of legal consequences when the opposite of what I have stated is revealed.

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